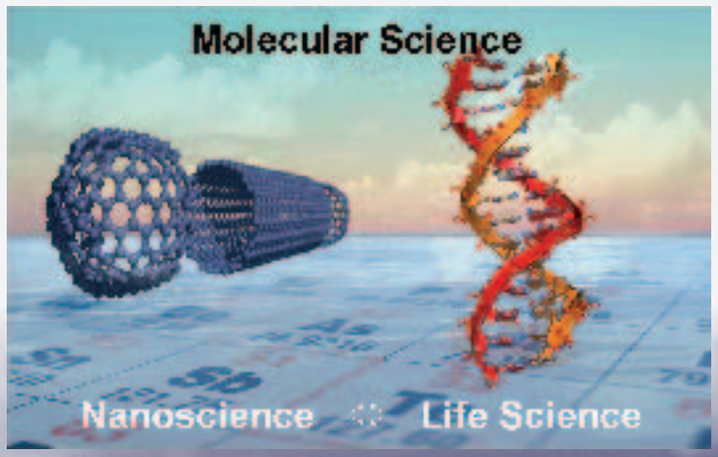
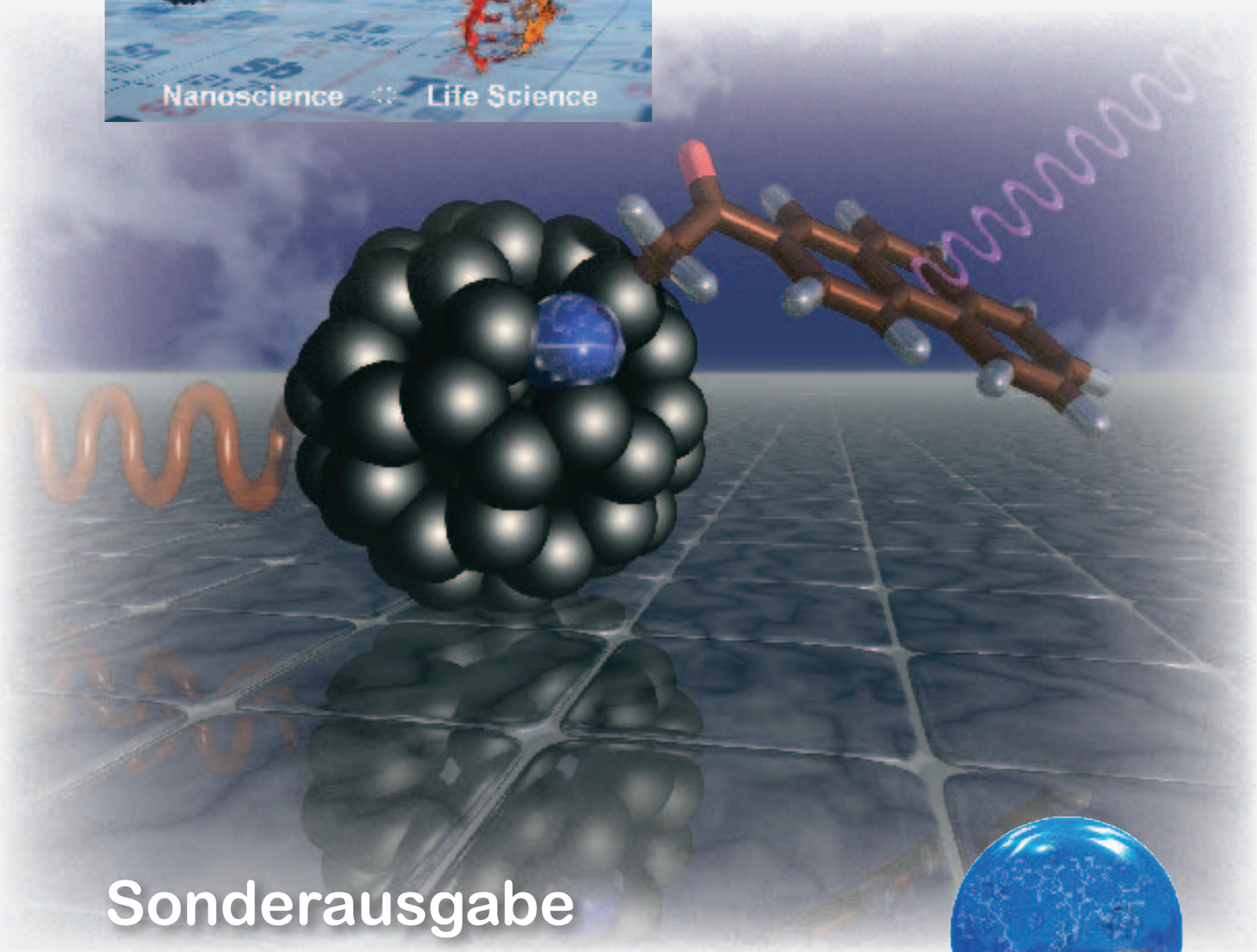
Chemie in Erlangen



Friedrich-Alexander-Universität
Erlangen-Nürnberg



Sonderausgabe
Bunsentagung 2006

Werte schaffen durch Innovation

Auch nach 120 Jahren an Erfahrung sind wir immer noch ausgesprochen neugierig - für unsere kommenden Generationen.

Boehringer Ingelheim hat sich seit 1885 bis heute in einem globalen Markt seinen Charakter als ein unabhängiges familiengeführtes Unternehmen bewahrt. Forschung ist unsere treibende Kraft, die von vielen Forschungszentren rund um den Globus ausgeht. Als Pharmaunternehmen setzen wir Erfolg gleich mit der kontinuierlichen Einführung von therapeutischen Innovationen. Mit mehr als 36.000 Mitarbeitern weltweit arbeiten wir daran, die Aussichten auf ein gesünderes Leben Realität werden zu lassen.

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Boehringer
Ingelheim

Editorial

Hans-Peter Steinrück
Physikalische Chemie

Ulrich Nickel
Physikalische Chemie

Dirk Guldi
Physikalische Chemie

Die 105. Hauptversammlung der Deutschen Bunsen-Gesellschaft für Physikalische Chemie e. V., kurz B*unsentagung 2006*, findet vom 25. bis 27. Mai 2006 in Erlangen an der Friedrich-Alexander-Universität Erlangen-Nürnberg statt. Die Friedrich-Alexander-Universität ist mit mehr als 25.700 Studierenden, 11 Fakultäten, 265 Lehrstühlen, 89 Instituten und 22 Kliniken die zweitgrößte Universität Bayerns, und ist damit ein gewichtiger Faktor in Forschung und Lehre weit über die Region hinaus. Ihr hohes wissenschaftliches Potential macht die Friedrich-Alexander-Universität zu einem leistungsfähigen Partner für Wirtschaft und Kultur in der Europäischen Metropolregion Nürnberg, in der Akteure aus Politik, Wirtschaft, Wissenschaft, Verwaltung, Kultur und Sport auf Vernetzung und Kooperation setzen. Rund 2,5 Millionen Menschen leben in der Metropolregion, die zu den 10 großen Wirtschaftszentren in Deutschland gehört. Mit einem Ausgabevolumen von über 600 Millionen Euro stellt die Universität einen wesentlichen Wirtschaftsfaktor dar. Das über die Jahre gewachsene breite Fächerangebot der Friedrich-Alexander-Universität bietet die einzigartige Chance, interdisziplinäre, über Fakultätsgrenzen hinweg arbeitende Kompetenzzentren und Zentralinstitute einzurichten. Neun der elf Fakultäten, einschließlich der Naturwissenschaftlichen Fakultäten, der Medizinischen und der Technischen Fakultät sind in Erlangen angesiedelt, wo die Universität mit mehr als 10.000 Mitarbeitern nach Siemens den zweitgrößten Arbeitgeber darstellt.

Die Chemie und Pharmazie stellen einen der besonders leistungsstarken Bereich der Friedrich–Alexander-Universität Erlangen-Nürnberg dar, der sich besonders durch seine stark interdisziplinäre Ausrichtung sowohl in der Forschung als auch in der Lehre auszeichnet. Derzeit sind die Institute für Chemie und Pharmazie sowohl im Stadtzentrum als auch im Südgelände der Universität angesiedelt; hier findet auch die Bunsentagung 2006 statt. In den nächsten Jahren sollen die verschiedenen Standorte in einem Neubau *Chemikum* im Südgelände der Universität zusammengeführt werden.

Das vorliegende Heft soll Ihnen einen Überblick über die aktuelle Forschung an den Instituten für Chemie und Pharmazie geben und die derzeitigen Forschungsschwerpunkte und die Vernetzung innerhalb der Universität darstellen. Wir wünschen allen Lesern viel Vergnügen bei der Durchsicht dieser Broschüre und den Teilnehmern der Bunsentagung 2006 einen anregenden und interessanten Verlauf.

Ihre
Hans-Peter Steinrück, Ulrich Nickel und Dirk Guldi
Organisatorische Leitung der Bunsentagung 2006
in Erlangen

Contents

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Dr. Heinz Behret, Frankfurt

Die junge Bunsen-Gesellschaft

Seit mehr als 110 Jahren fördern die Mitglieder der Bunsen-Gesellschaft mit erstaunlichem Einsatz die physikalische Chemie und darüber hinaus die gesamte Wissenschaft, und dies im Jahr 2006 mit vielen jungen Mitgliedern und der Wahl einer verjüngten Führung im Vorstand, im Ständigem Ausschuss, in der Geschäftsführung und in Erlangen mit einer jungen, dynamischen Truppe in der Vorbereitung der Bunsentagung. Nach Erlangen kommen Physikochemiker und Wissenschaftler aus vielen Grenzgebieten der Physik, Chemie und Verfahrenstechnik - in diesem Jahr dem Hauptthema und der Zusammenarbeit mit der DFG folgend besonders aus der Katalyse.

Heinz Behret

NEUES IN GANG SETZEN

Jede Woche etwas Anderes, etwas Neues und Spannendes aus der Physikalischen Chemie brachte die „Aktuelle Wochenschau der Bunsen-Gesellschaft“ als publikumsnahen Beitrag der DBG zum Jahr der Chemie 2003. Mitglieder der DBG aus Hochschule, Forschungseinrichtungen und Industrie haben in insgesamt 52 Wochen die Wochenschau entwickelt und aufgebaut, erreichbar über www.bunsen.de als Portal mit Anklicken „Aktuelle Wochenschau“. Aus den Beiträgen entstand ein Band „HighChem - Aktuelles aus der Physikalischen Chemie in Deutschland“, der, solange der Vorrat reicht, noch bei der Geschäftsstelle in Frankfurt kostenlos angefordert werden kann. Der Erfolg dieses Bandes war so groß, dass sich die Fachgruppe Analytische Chemie der Gesellschaft Deutscher Chemiker (GDCh) zu einem gleichen Unternehmen entschloss, und jetzt in diesem Jahr die GDCh-Fachgruppe Angewandte Elektrochemie, beide unter Mitwirkung der Bunsen-Gesellschaft.

Die Bunsentagung ist jährlich die wichtigste Plattform, über die Arbeiten der jungen, aber auch herausragender „arrivierter“ Forscher zu berichten und diskutieren, Auszeichnungen auszusprechen und gleichzeitig die Öffentlichkeit, die Nicht-Wissenschaftler, über die Tätigkeit der Wissenschaftler zu informieren. Die wissenschaftliche Gesellschaft versucht damit zum mindestens teilweise aus dem Elfenbeinturm herauszukommen und ihrer Bringschuld gegenüber der Gesamtgesellschaft gerecht zu werden.

HERAUSRAGENDES EHREN

Ehrungen im festlichen Rahmen der Bunsentagung 2006 sind die Verleihung der Ehrenmitgliedschaft, des Nernst-Haber-Bodenstein-Preises und die Verleihung des Paul-Bunge-Preises der Hans-R.-Jenemann-Stiftung.

Für richtungweisende, erfolgreiche, national und international herausragende Arbeiten, für hervorragende Wegbereiter der physikalisch-chemischen Wissenschaft und Technik und in Anerkennung besonderer Verdienste um die Förderung der physikalischen Chemie wird in Erlangen die - seltene - *Ehrenmitgliedschaft* verliehen werden. Die Zukunft der Wissenschaft und Technik liegt im Nachwuchs: Auf Anregung der Bunsen-Gesellschaft wird zur Anerkennung hervorragender wissenschaftlicher Leistungen in der physikalischen Chemie durch jüngere Wissenschaftler zum Gedenken an Max Bodenstein, Fritz Haber und Walther Nernst der *Nernst-Haber-Bodenstein-Preis* in der Festsitzung verliehen. Hans R. Jenemann, der bekannte Waagen-Spezialist, hat die nach ihm benannte Stiftung zur Förderung der Arbeiten über wissenschaftshistorische Instrumente 1990 ins Leben gerufen und der GDCh und DBG gemeinsam übertragen. Im Wechsel zwischen beiden Gesellschaften werden die Preisträger bei herausragenden Veranstaltungen geehrt, in diesem Jahr im Rahmen der Bunsentagung.

GEDÄCHTNISVORLESUNGEN ALS BLICK IN DIE ZUKUNFT

Die Gedächtnisvorlesungen der Bunsen-Gesellschaft sind dem Andenken berühmter Physiko-Chemiker gewidmet. Mit der *Bonhoeffer-Eucken-Scheibe-Vorlesung* werden sowohl Wissenschaftler aus der Industrie als auch aus der Academia besonders geehrt, wobei die jeweiligen Vorlesungen aktuelle Ergebnisse und eben immer eine wissenschaftliche Zukunftsschau bringen.

Die *Wilhelm-Jost-Gedächtnisvorlesung,* gemeinsam mit der Akademie der Wissenschaften zu Göttingen, wird an den Orten des Wirkens von Wilhelm Jost jährlich von herausragenden Physiko-Chemikern auf Vorschlag der Bunsen-Gesellschaft gehalten. Die *Theodor-Förster-Gedächtnisvorlesung* wird zu Ehren des berühmten Photochemikers Theodor Förster gemeinsam mit der GDCh beschlossen und getragen, ebenso der *Weller-Preis* für jüngere Wissenschaftler auf dem Gebiet der Photochemie.

PCCP-Titelblatt

Neben der Henry *von Böttinger-Stiftung* betreut die Bunsen-Gesellschaft die ebenfalls als Stiftung eingerichtete *Bonhoeffer-Eucken-Scheibe-Vorlesung* als eine zur Nachahmung und Zustiftung empfohlene Aktivität von Mitgliedern aus Hochschule und Industrie. Der Förderung insbesondere der jüngeren Wissenschaftler dienen die *Robert Bunsen-Stiftung* und die *Leo Gans-Cassella-Stiftung*, wobei die zweite Stiftung die Herkunft aus der früheren CASSELLA AG belegt. Spenden und Zustiftungen zu all den genannten Stiftungen, so auch zur Förderung des wissenschaftlichen Nachwuchses in der Robert Bunsen-Stifung, dienen der Nachwuchsförderung und sind ganz besonders willkommen.

DER ANFANG

In Deutschland wurde unter Mitwirkung von H. J. van't Hoff und W. Nernst, insbesondere auch des späteren Nobelpreisträgers Wilhelm Ostwald, 1894 die erste Gesellschaft zur Pflege der neuen Wissenschaft Physikalische Chemie, anfangs unter dem Namen „Deutsche Elektrochemische Gesellschaft", gegründet. Ähnliche Gründungen folgten in anderen Ländern erst später, auch in Amerika und in England erst später, so die Electrochemical Society und die Faraday Society. Wilhelm Ostwald wurde auch der erste Vorsitzende der neuen Gesellschaft. 1902, also keine zehn Jahre nach der Gründung, wurde die Gesellschaft zu Ehren des ein Jahr vor der Jahrhundertwende verstorbenen Robert W. Bunsen in „Deutsche Bunsen-Gesellschaft für Angewandte Physikalische Chemie" umbenannt und trägt den jetzigen Namen seit über einem halben Jahrhundert.

DIE PUBLIKATION

Die wichtigste wissenschaftliche Publikation der Bunsen-Gesellschaft wurde gemeinsam mit den chemischen Gesellschaften aus England, Italien und den Niederlanden ins Leben gerufen wurde : „PHYSICAL CHEMISTRY CHEMICAL PHYSICS **PCCP**, zunächst als das Wissenschaftsjournal der europäischen chemischen Gesellschaften, heute getragen von mehr als einem Dutzend wissenschaftlicher Gesellschaften Die Royal Society of Chemistry brachte ihre Zeitschrift Faraday Transactions, die DBG ihre langjährigen Berichte der Bunsengesellschaft für Physikalische Chemie ein. PCCP war von Start an die erfolgreiche europäische und internationale Zeitschrift und hat folgerichtig im neuen Layout den Untertitel „An International Journal". Persönliche Mitglieder der Bunsen-Gesellschaft erhalten die Zeitschrift unmittelbar vom Verlag zu einem sehr niedrigen Sonderpreis.

Die Bunsen-Gesellschaft hat rund 1.800 Mitglieder, die im Hochschulbereich, in der Industrie und in Forschungsinstituten, aber auch im Forschungsmanagement, hauptsächlich in Deutschland aber auch im Ausland tätig sind. Die Mitglieder erhalten im Rahmen des Mitgliedsbeitrags seit 1999 das „BUNSEN-MAGAZIN". Es bringt Sonderbeiträge, Artikel, Meinungen, Buchbesprechungen, Tagungsankündigungen und die Nachrichten der Bunsen-Gesellschaft mit den Personalia.

DIE DEUTSCHE FORSCHUNGS-GEMEINSCHAFT UND DIE BUNSENTAGUNG IN ERLANGEN

Die wissenschaftliche Hauptversammlung der Gesellschaft, die „Bunsentagung" wurde in den letzten Jahren durchweg von 700 oder mehr Teilnehmern besucht, darunter fast 200 Studenten und jüngere Forscher. Neben der nicht hoch genug anzusetzenden nationalen Bedeutung spielen die Bunsentagungen in der internationalen Entwicklung der physikalisch-chemischen Forschung eine herausragende Rolle. Außer Plenar- und Hauptvorträgen von eingeladenen, international bekannten Fachleuten zum jeweiligen Hauptthema werden sowohl Poster als auch Kurzvorträge aus dem gesamten Bereich der Physikalischen Chemie präsentiert. Die Tagung selbst findet jedes Jahr in einem anderen Ort statt, nach 1973 bereits zum zweiten Mal 2006 in Erlangen und als Dokumentation des Standes der Forschung gemeinsam mit der DFG.

Das Hauptthema der Bunsentagung 2006 umfasst die heterogene Katalyse. Die Deutsche Forschungsgemeinschaft

belegt mit ihrem Sonderforschungsbereich ein weltweit untersuchtes Thema der Grundlagenforschung und Anwendung in der Industrie, Verkehr, im täglichen Leben, wobei die praktische Bedeutung der Katalyse auch in Zukunft zweifellos weiter zunehmen wird. Betont wird der Anwendungsaspekt durch das in die Bunsentagung integrierte Industrie-Symposium über industrielle Anwendungen.

Neben den Hauptversammlungen werden jährlich internationale Diskussionstagungen veranstaltet, bei denen der Fortschritt auf einem speziellen aktuellen Gebiet - oft auch hier in der Zusammenarbeit und mit der Unterstützung der DFG - diskutiert wird. Die Publikation von Ergebnissen dieser „Discussion Meetings“ erfolgt durchweg in PCCP. Sehr erfolgreich sind die „Bunsen-Kolloquien“, meist eintägige und in einfacher Form abgehaltene Treffen, die spezielle, eng eingegrenzte Themen, auch gemeinsame Grenzthemen mit anderen wissenschaftlichen Gesellschaften behandeln.

Andreas Förster

gewählt. Für die Jahre 2007 und 2008 steht nun die Wahl bei der Mitgliederversammlung in Erlangen zu einer weiter verjüngten Führung an, junge Kandidaten aus Hochschule und Industrie haben im Falle ihrer Wahl ihre aktive Mitarbeit im Ständigen Ausschuss zugesagt. Bedeutend verjüngt ist weiter die Geschäftsführung: Seit Jahresbeginn ist Dr. Andreas Förster, Dechema, Frankfurt, als stellvertretender Geschäftsführer tätig, Mitte des Jahres wird der seit 1979 wirkende Geschäftsführer die Funktion ganz an Dr. Förster übergeben. Wurde lange Jahre die technische Zusammenarbeit mit der GDCh in der Doppelfunktion von Dr. Heinz Behret getragen, so ist nunmehr in den nächsten Jahren über Dr. Förster diese Doppelfunktion mit der Dechema vorhanden. Die wissenschaftliche Zusammenarbeit aller drei Gesellschaften, Dechema, GDCh und DBG soll davon nur gewinnen.

DIE JUNGE GESELLSCHAFT

Der Vorstand der Deutschen Bunsen-Gesellschaft für Physikalische Chemie besteht aus dem Ersten und Zweiten Vorsitzenden und dem Schatzmeister. Der Erste Vorsitzende stammt abwechselnd aus den Bereichen Hochschule und Industrie: Für die Jahre 2005 und 2006 wurde von der Mitgliederversammlung Prof. Dr. Michael Dröscher, Degussa AG, Düsseldorf, zum Ersten Vorsitzenden gewählt. Zweiter Vorsitzender ist satzungsgemäß sein Vorgänger Prof. Dr. Klaus Funke, Universität Münster. Zum Schatzmeister hat die Mitgliederversammlung Prof. Dr. Wolfgang Grünbein, Clariant,

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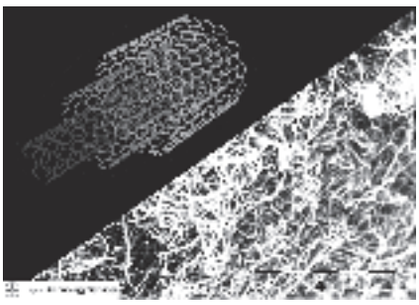
Bayer setzt in der Nanotechnologie neue Standards

Neuartiges Produktionsverfahren ermöglicht zahlreiche Anwendungsmöglichkeiten



Die Nanotechnologie ist zweifellos eine der Schlüsseltechnologien des 21. Jahrhunderts. Ihr gesamtes wirtschaftliches Potential lässt sich gegenwärtig gleichwohl nur erahnen. Verschiedene Prognosen verdeutlichen allerdings ihre bereits mittelfristig enorme ökonomische Bedeutung. So veranschlagen Schätzungen von Marktforschungsinstituten das weltweite Umsatzpotential nanomodifizierter Produkte schon im Jahr 2010 auf mehr als 700 Milliarden Euro. Dabei sind längst noch nicht alle Anwendungsmöglichkeiten der Nanotechnologie vollständig erforscht.

Bayer hat als Erfinderunternehmen die Bedeutung der Nanotechnologie früh erkannt und treibt die Entwicklung in diesem Bereich weiter zielstrebig voran. Von den rund zwei Milliarden Euro, die Bayer allein im laufenden Jahr in Forschung und Entwicklung investiert, fließt ein erheblicher Teil in diese Technologie. Doch haben bereits heute alle relevanten Bereiche bei Bayer die Nanotechnologie erfolgreich genutzt, um neue Produkte und Verfahren zu entwickeln. Viele davon stehen an der Schwelle zur Marktreife oder werden schon mit großem Erfolg angewandt.

Gegenwärtig konzentrieren sich die Forschungs- und Entwicklungsprojekte von Bayer auf vier Bereiche. Auf dem Sektor Nanopartikel und -additive hat Bayer mit Dispercoll S beispielsweise ein nanoskaliges Additiv entwickelt, das die Eigenschaften und die Verarbeitung von wässrigen Klebstoffen deutlich verbessert. Im Bereich Nanoschichten und -oberflächen werden Carbosilanvernetzer entwickelt, die besonders kratzfeste, witterungsbeständige und säureresistente Oberflächenbeschichtungen ermöglichen. Interessant sind solche Systeme etwa für Autoklarlacke oder als Hard Coat von Kunststoffbauteilen. Überaus vielversprechend sind zudem die Forschungsergebnisse in den übrigen Bereichen Nanoelektronik und Nanobiotechnologie.

Kohlenstoff-Nanoröhrchen (Carbon Nanotubes, CNTs) stehen aufgrund ihrer außergewöhnlichen Eigenschaften und ihres breiten Einsatzspektrums seit langem im Zentrum der nanotechnologischen Forschung. Bayer-Forschern ist es nun gelungen, ein Verfahren zur industriellen Produktion von Nanoröhrchen zu entwickeln. Mit der Fähigkeit, erstmals eine Materialreinheit von konstant über 99 Prozent zu gewährleisten, hat Bayer die Tür zum industriellen Einsatz dieser winzigen Alleskönner weit aufgestoßen und sich im internationalen Wettbewerb entscheidende Vorteile gesichert. Bayer ist nunmehr in der Lage, unter dem Markennamen Baytubes® weltweit nanoskalige Materialien für eine Fülle von Anwendungsmöglichkeiten anzubieten.

Mit der Erschließung dieser revolutionären Spitzentechnologie ist ein hohes Maß an Verantwortung verbunden - sowohl gegenüber den Mitarbeitern, als auch gegenüber Kunden und der Gesellschaft. Denn entscheidend für den Erfolg neuer Technologien ist auch ihre Akzeptanz in der Gesellschaft. Entsprechend wichtig ist der Dialog über Ziele, Anwendungen, Nutzen und Sicherheitsaspekte. Bayer führt daher einen intensiven Meinungsaustausch mit Politik und Wissenschaft und hat spezifische Forschungsinitiativen der chemischen Industrie mit initiiert.

So ist Bayer in Arbeitsgruppen der nationalen und internationalen Chemieverbände wie dem Verband der chemischen Industrie e.V. (VCI), der DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., dem European Chemical Industry Council (CEFIC), dem American Chemistry Council (ACC) und dem International Council of Chemical Associations (ICCA) engagiert. Im Rahmen des vom Bundesministerium für Bildung und Forschung (BMBF) geförderten Projekts "NanoCare" erarbeiten Unternehmen und renommierte wissenschaftliche Institute in enger Kooperation Methoden für die Messung und Charakterisierung der Nanomaterialien, für toxikologische Untersuchungen sowie Arbeitsplatzmessungen und deren Bewertung. Neben der Bereitstellung dieser Ergebnisse in einer Online-Datenbank fördern Informationsveranstaltungen und Publikationen den Dialog mit der Öffentlichkeit.

Winzige Alleskönner

Kohlenstoffnanoröhren (CNTs) können die Eigenschaften verschiedener Materialien verbessern.

Produkt	Vorteil durch CNTs
leitfähige Polymere	elektrostatische Lackierung
mehrschichtige Benzinschläuche	keine elektrostatische Aufladung, höhere Dichtigkeit
Sportgeräte	größere Stabilität beim Schlag
leitfähige Folien und Träger	antistatische Verpackungen, z. B. für Elektronikbauteile
Lithium-Ionen-Batterien	erhöhte Stromspeicherkapazität
Keramikbauteile von Turbinen (in der Zukunft)	verbesserte Wärmeleitfähigkeit

Weitere Infos: nanotech@bayermaterialscience.com

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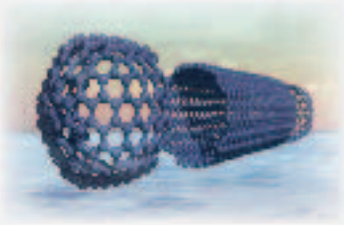
Chemistry and Pharmacy in Erlangen



Naturwissenschaftliche Fakultät II (Fakultät für Biologie, Chemie und Pharmazie)

The Faculty for Natural Sciences II (Naturwissenschaftliche Fakultät II) is one of eleven faculties at the Friedrich-Alexander-Universität Erlangen-Nürnberg. It consists of the separate research and teaching units ***Biology*** and ***Chemistry and Pharmacy***. All of them cooperate strongly with other faculties within the University, especially with the faculties for Medicine, Technical Sciences, Natural Sciences I (Mathematics and Physics) and Natural Sciences III (Earth Sciences). The cooperation range from joint research projects and interdisciplinary research centers to extensive exchange of undergraduate and graduate courses.

Institutes for Chemistry and Pharmacy

The organization chart summarizes the Institutes for ***Chemistry*** (Anorganische Chemie, Organische Chemie, Physikalische und Theoretische Chemie) and ***Pharmacy*** (Pharmazie und Lebensmittelchemie). Altogether 23 research and teaching Professors hold appointments – covering the areas of Chemistry/Molecular Science and Pharmacy/Food Chemistry. Further support comes from 24 permanent and 55 non-permanent scientific staff members. In addition, externally funded research grants total on average to ca. 4.5 Million Euro per year, which help in financing 75 additional scientists. All members of the institutes publish more than 200 articles per year in highly ranked international journals.

Major research activities at the Institutes of Chemistry and Pharmacy

The research activities of the Institutes of ***Chemistry*** and ***Pharmacy*** cover a wide spectrum that ranges from basic to applied research in the areas of chemistry, biology, pharmacy, and pharmaceutical science. These are strongly linked to each other, have a manifold of interactions and interdisciplinary research projects within the University (Sonderforschungsbereiche, Graduiertenkollegs) and with other national and international institutions (DFG-Schwerpunktprogramme, EU, BMBF, Volkswagenstiftung, DAAD, Humboldt-Stiftung, Bayerische Forschungsförderung, etc.). Consequently, the Institutes of ***Chemistry*** and ***Pharmacy*** create the *molecular bridge* between the Faculties for Medicine and Technical Sciences.

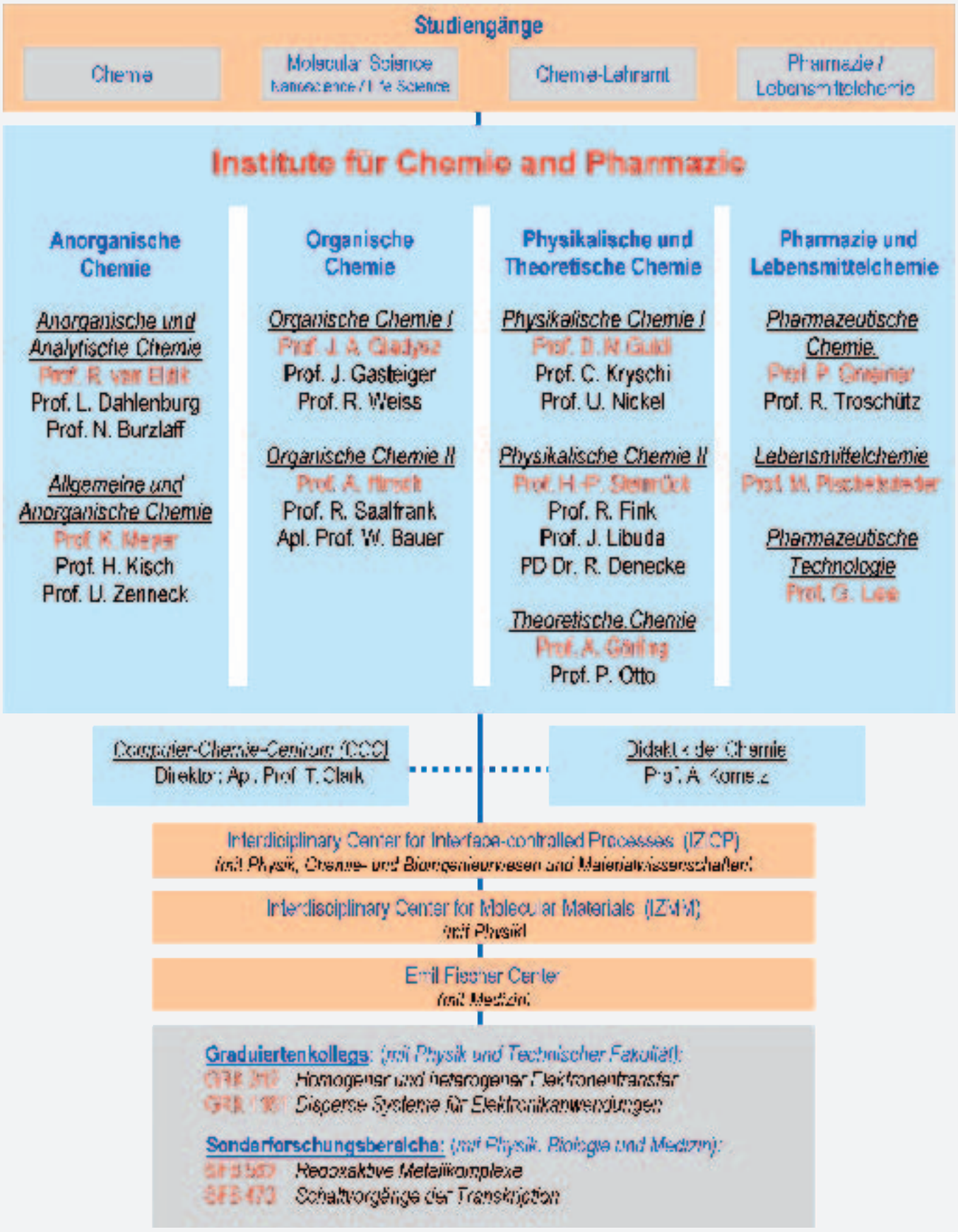
Current research objectives concentrate on two major areas:

MOLECULAR MATERIALS – metal complexes, electron transfer, nanostructures, modeling, and catalysis

The synthesis and characterization of molecular materials are of central interest to the research activities in the various institutes of ***Chemistry***. Hereby, as an important class of materials redox-active metal complexes constitute the major thrust of SFB 583. These are used, for example, to catalyze chemical reactions. Also, carbon-rich conjugated π-systems, which exhibit unprecedented materials properties, such as mechanical strength, molecular magnetism and electrical conductivity, are of interest. Additional incentives in the studies of metal complexes and alternative molecular architectures are also their supramolecular assembly and integration into hierarchically ordered nanostructures. Many of these tailored materials undergo photoinduced charge separation processes between redox-active subunits. Consequently, new systems are developed, which will help to solve fundamental challenges of the future, such as the shortage of energy and other resources. A specific strength of the chemical research in Erlangen is the computer assisted determination and modeling of molecular architectures, of their properties and transitions.

BIOACTIVE MOLECULES – Neurotropic Agents, Biologicals, and Protein Conjugates

Within the context of the subject *Bioactive Molecules,* novel neurotropic agents are designed, synthesized and examined for of their activity towards signaling proteins. As target proteins, G-protein coupled neuroreceptors, Tet-repressors (SFB 473) as well as prion proteins are addressed. To examine target protein modifications occurring during food treatment but also *in vivo* under pathological conditions, chemical changes are detected and functional consequences are analyzed by means of biological tests. For the understanding of effects of large-scale processes during the preparation of therapeutic proteins on protein folding and aggregation, stabilization, particle formation, and drying rate of biotechnologically obtained proteins are explored.


Studiengänge
Chemie
Molecular Science
Nanoscience / Life Science
Chemie-Lehramt
Pharmazie / Lebensmittelchemie
Institute für Chemie and Pharmazie
Anorganische Chemie
Anorganische und Analytische Chemie
Prof. R. van Eldik
Prof. L. Dahlenburg
Prof. N. Burzlaff
Allgemeine und Anorganische Chemie
Prof. K. Meyer
Prof. H. Kisch
Prof. U. Zenneck
Organische Chemie
Organische Chemie I
Prof. J. A. Gladysz
Prof. J. Gasteiger
Prof. R. Weiss
Organische Chemie II
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Apl. Prof. W. Bauer
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Theoretische Chemie
Prof. A. Görling
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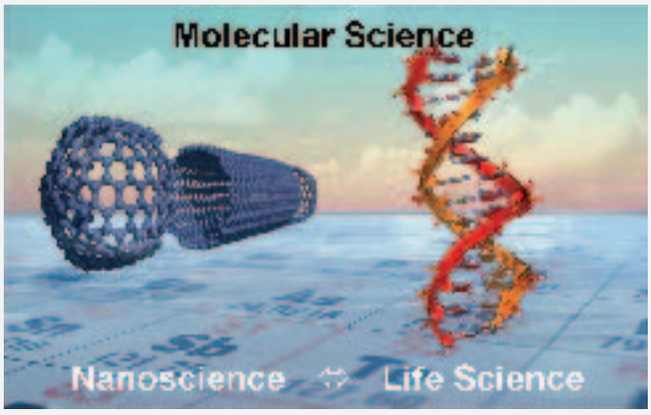
Pharmazie und Lebensmittelchemie
Pharmazeutische Chemie
Prof. P. Gmeiner
Prof. R. Troschütz
Lebensmittelchemie
Prof. M. Pischetsrieder
Pharmazeutische Technologie
Prof. G. Lee
Computer-Chemie-Centrum (CCC)
Direktor: Ap. Prof. T. Clark
Didaktik der Chemie
Prof. A. Kornelz
Interdisciplinary Center for Interface-controlled Processes (IZ CP)
mit Physik, Chemie- und Biorgenieurwesen und Materialwissenschaften
Interdisciplinary Center for Molecular Materials (IZMM)
mit Physik
Emil Fischer Center
mit Medizin
Graduiertenkollegs: (mit Physik und Technischer Fakultät)
Homogener und heterogener Elektronentransfer
Disperse Systeme für Elektronikanwendungen
Sonderforschungsbereiche: (mit Physik, Biologie und Medizin)
Redoxaktive Metallkomplexe
Schaltvorgänge der Transkription

Education at the Institutes of Chemistry and Pharmacy

The institutes provide the following programs of study:

- Chemie Diplom – BSc/MSc (start: WS 2006/07)
- Molecular Science – Bachelor (start: WS 2001/02)
- Molecular Science – Master (start: WS 2004/05)
- Chemie Lehramt – Gymnasium / Realschule
- Chemie Lehramt – Grundschule / Hauptschule
- Pharmazie – Staatsexamen
- Lebensmittelchemie – Staatsexamen

In compliance with the Bologna recommendation, the former Diplom-Studiengang Chemie will be replaced by a consecutive Bachelor/Master program. The new program, which will commence with the beginning of the Wintersemester 2006/07, is conceptualized as a three-year program, for the Bachelor part, and a two-year program, for the Master program.



www.chemie.uni-erlangen.de/Molecular-Science/

The consecutive interdisciplinary Bachelor/Master program ***Molecular Science*** was successfully started at the Faculty for Natural Sciences II in WS 2001/02 with the Bachelor program; the Master program followed in WS 2004/05. After the initial phase of 4 semesters there are two options within the ***Molecular Science*** Bachelor degree program: *Molecular Nanoscience* or *Molecular Life Science*. During the master program, the course of study is intended to provide students with an education in *Nanotechnology or Life Science* by choosing the modules *Molecular Nanoscience* or *Drug Discovery*.

Each program emphasizes practical experience in addition to traditional course work.

Altogether, about 1120 students are educated and trained in the aforementioned programs – in 2005 about 350 beginners have been registered. In addition, the Institutes for ***Chemistry*** are involved in the education of twelve other Diploma or BSc/MSc programs ranging from medical to technical sciences: per year more than 1200 students from other programs attend classes and lab courses in the various fields of chemistry.

With respect to the education of future school teachers there exists a close cooperation with the Faculty of Education – Didactics of Chemistry.

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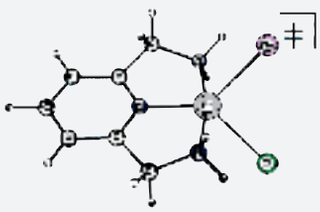
Mechanistic studies in coordination chemistry.
Application of high pressure techniques

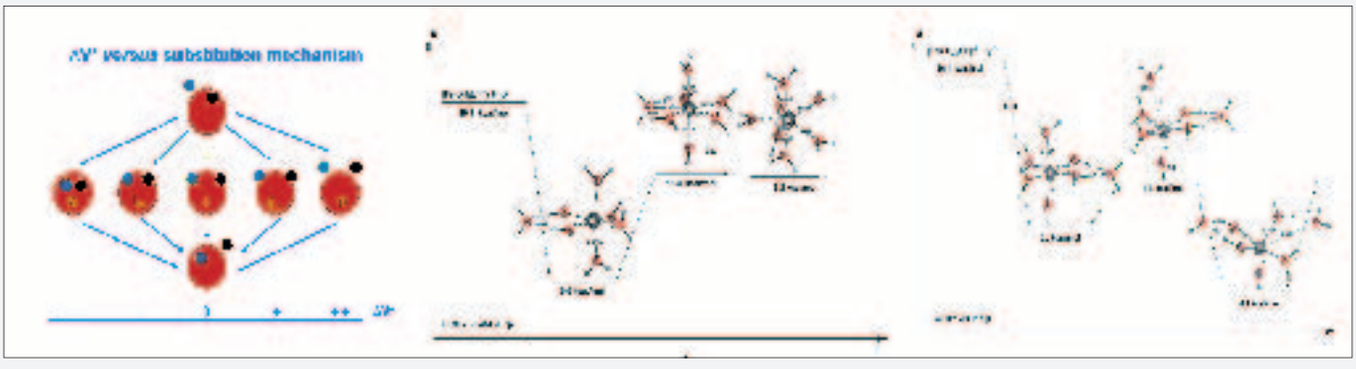
The principal goal of our work is to elucidate the mechanisms of chemical reactions in solution, focusing on the reactivity of inorganic, bioinorganic and organometallic systems in which the coordination sphere of the metal complex is the controlling factor. The studied systems include fundamental solvent exchange reactions, ligand substitution processes, the activation of small molecules such as O_2, H_2O_2, CO_2, SO_2, NO, H_2 and C-H bonds, and electron transfer reactions. In these studies we focus on the application of kinetic and thermodynamic high pressure techniques to construct volume profiles for the reactions under investigation, on which basis further mechanistic insight into the intimate nature of the transition state can be obtained. Where possible we collaborate with theoretical chemists in order to validate the proposed transition state structures.



Das grundlegende Ziel unserer Arbeit ist die Bestimmung von Reaktionsmechanismen in Lösung. Im Fokus sind dabei Anorganische, Bioanorganische und Organometallische Systeme in denen die Koordinationssphäre des Metallkomplexes ein bestimmender Faktor ist. Die untersuchten Systeme beinhalten fundamentale Lösemittelaustausch-Reaktionen, Ligandensubstitutions-Prozesse, die Aktivierung kleiner Moleküle wie O_2, H_2O_2, CO_2, SO_2, NO, H_2 und C-H-Bindungen, und Elektronen-Transfer-Prozesse. In diesen Untersuchungen liegt der Schwerpunkt in der Anwendung kinetischer und thermodynamischer Hochdruck-Techniken um Volumenprofile für die betrachteten Reaktionen zu erstellen. Auf der Basis der so erhaltenen Informationen ist es möglich einen tieferen mechanistischen Einblick in die Natur des Übergangszustandes zu erhalten. Wenn möglich arbeiten wir mit theoretischen Chemikern zusammen um vorausgesagte Übergangszustände durch theoretische Berechnungen zu bestätigen.

Fundamental importance of solvent exchange reactions

Vacant coordination sites in metal complexes are usually occupied by solvent molecules in the presence of a coordinating solvent. In such cases, the reactivity of the complex is controlled by the lability of the coordinated solvent molecules. Thus, solvent exchange reactions in which coordinated and bulk solvent molecules exchange in a dynamic process, are of fundamental importance in describing the chemical behaviour of the complex in solution, and in many cases control the rate and mechanism of reactions that involve the displacement of the coordinated solvent molecules. The rate of a solvent exchange reaction is usually followed by isotope labelling, for instance using ^{17}O-NMR techniques for the study of water exchange reactions. The solvent exchange rate constant is a measure of the reactivity/lability of the complex under investigation, but does not reveal anything about the intimate nature of the solvent exchange process. Here the application of high pressure NMR techniques has been very fruitful since the pressure dependence of such a symmetrical reaction immediately reveals information on bond formation and bond breakage during the exchange process. On the basis of these data the solvent exchange process can be described in terms of associative (A), dissociative (D) and interchange (I) mechanisms, where the interchange process can be more

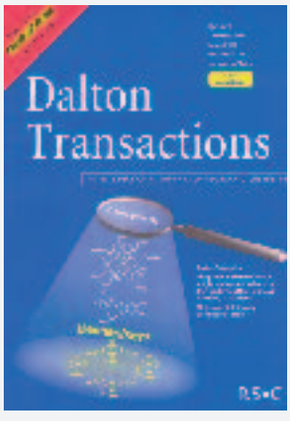


associative (I_a) or more dissociative (I_d) as shown in the following scheme.

Accordingly, water exchange reactions on $[Fe(H_2O)_6]^{3+}$ shows a small negative volume of activation that supports the operation of an I_a mechanism, whereas water exchange on $[Fe(H_2O)_5OH]^{2+}$ shows a small positive volume of activation in line with an I_d mechanism. Thus deprotonation of a coordinated solvent molecule can induce a much faster solvent exchange reaction as a result of the *trans* labilization effect induced by coordinated hydroxide, and is accompanied by a changeover in mechanism from more associative to more dissociative, respectively. Recent theoretical calculations clearly underline the validity of this claim and the displayed energy profiles not only show the decrease in the activation barrier that accompanies the deprotonation step, but also the changeover in mechanism from associative to dissociative, respectively.

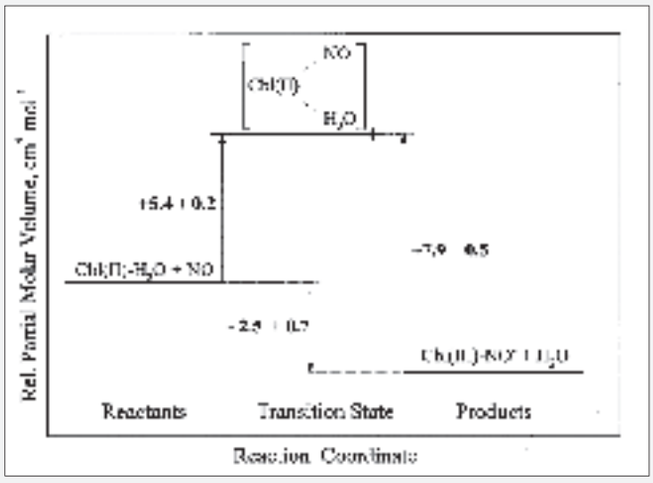
Tuning the rate and mechanism of ligand substitution reactions

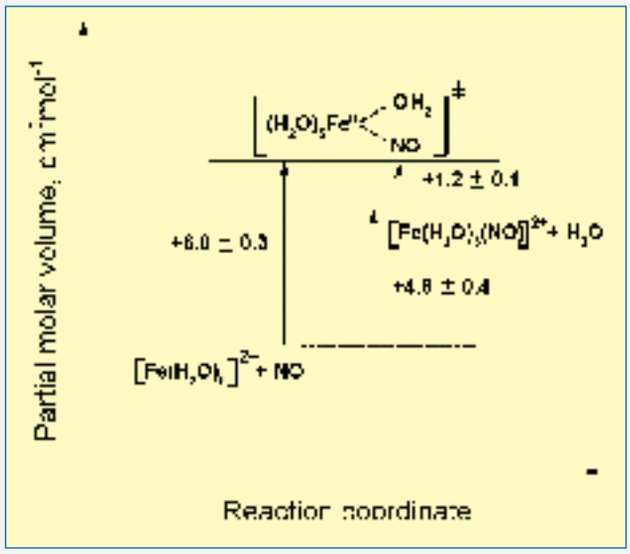
The rate and mechanism of solvent and ligand substitution reactions are controlled by the nature of the metal centre, the influence of spectator ligands and chelates, the spin state of the metal centre, the pH of the solution, and the coordination ability of the solvent in case it participates in the substitution process. The introduction of metal-carbon bonds has a strong *trans* labilization effect and is expected to induce a dissociative substitution process in the *trans* position of an octahedral complex. This was shown to be the case for the co-enzyme vitamin B_{12} where the C-bonded adenosyl ligand labilizes the dimethylimidazole group in the *trans* position. A systematic study on a series of modified co-enzyme B_{12} systems in which the adenosyl group was displaced by C_2H_5, CH_3, CH_2CF_3, CHF_2, CH_2CN, CF_3, and CN, clearly showed a systematic decrease in labilization along the series of complexes. Model Co(III) complexes were also studied to account for the observed labilization effects as a function of the Co-C bond strength and electronic effects. The work was cited on two cover pages[1,2] of *Dalton Trans*. and *Eur. J. Inorg. Chem*.



Mechanistic studies on NO activation

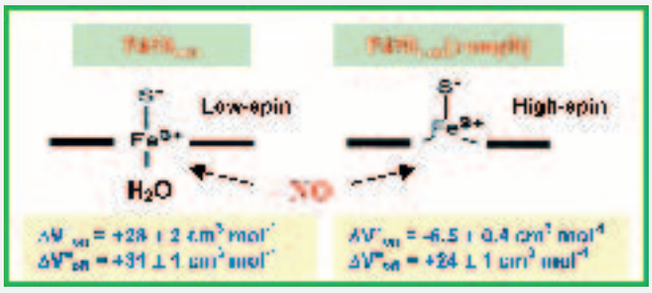
NO plays an important role in many biological and environmental processes. We have over the past 5 years undertaken detailed studies of the activation of NO by Fe, Co and Ru complexes. Some of these were model coordination compounds, whereas others were biological molecules such as Vitamin B_{12a} and cytochrome P450. Our studies were initiated by claims in the literature that aquacobalamin (Vitamin B_{12a}) can bind NO and inhibit the biological functions of NO. Based on our earlier experience with the substitution behaviour of aquacobalamin, we studied the details of the reaction and surprisingly found that NO does not bind to aquacobalamin at all. The observed reactions could all be accounted for in terms of the coordination of nitrite present as impurity in aqueous NO solutions. Subsequent work showed that reduced cobalamin, a five-coordinate Co(II) complex, binds NO very effectively to form the corresponding Co^{III}-NO^- species according to a dissociatively activated process that involves a weakly coordinates water molecule as shown in the following volume profile.[3]



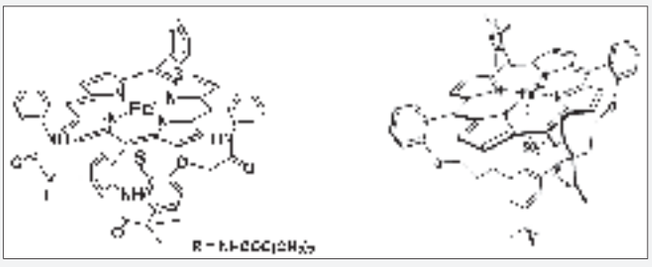


In another study, a classical undergraduate text book reaction was revisited. This concerns the brown-ring test for nitrate that involves the binding of NO to aquated Fe(II) to form a brown-green Fe-NO complex, of which the exact nature is very speculative. Our detailed study not only revealed that the final product is an Fe^{III}-NO^- instead of the generally believed Fe^{I}-NO^+ species, but also that NO undergoes a dissociative substitution reaction with the aquated Fe(II) complex as shown by the volume profile given above.[4]

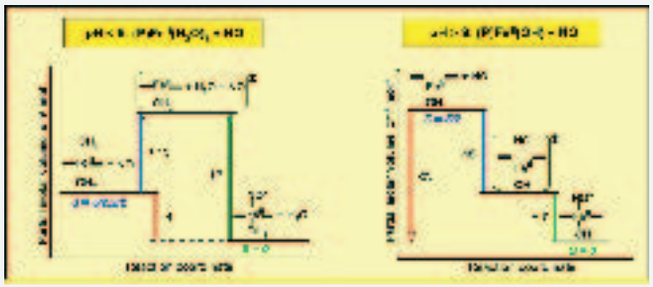
Following this work we studied the reversible binding of NO to metmyoglobin in which NO displaces the axial coordinated water molecule on the Fe(III) centre to form Fe^{II}-NO^+ as reaction product. In the case of cytochrome P450, the interaction of NO with both the six-coordinate, low-spin aqua complex and the five-coordinate, high-spin intermediate that is formed on the binding of a substrate molecule, were studied in an effort to gain further insight into the catalytic cycle of P450 and the role of the resting states. The following schematic picture shows the drastic difference in the activation parameters found for the binding of NO, and demonstrates that the low-spin, six-coordinate complex follows a dissociative mechanism, whereas the high-spin, five-coordinate complex binds NO according to an associative mechanism.[5]



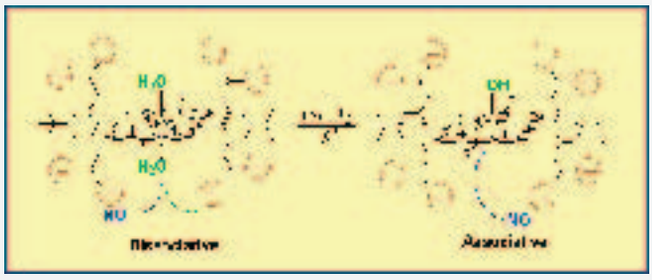
More recently, the model complexes shown below were used to mimic the catalytic activity of cytochrome P450, and their interaction with NO was studied in a comparative way. Both complexes are high-spin, five-coordinate Fe(III) in non-coordinating solvents and low-spin, six-coordinate Fe(III) in the presence of coordinating solvents such as methanol and acetonitrile.[6]

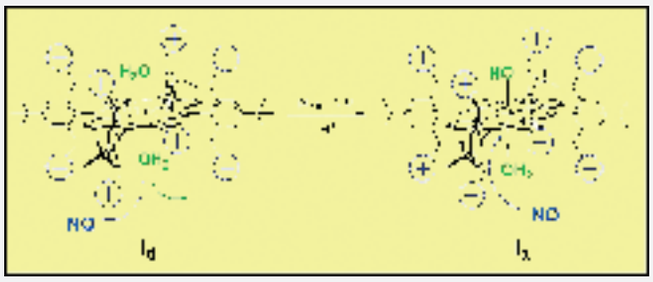


These model complexes are not water soluble, and presently the search is for water-soluble model complexes for P450. In a first approach, a water soluble Fe(III) porphyrin system was selected in which the porphyrin carries an overall charge of 4- and the coordinated water molecules have a pK_a value of 7. The reactivity and spin state of this complex can be tuned through a change in pH in such a way that this model complex mimics the reactivity of the two ground state cytochrome P450 species mentioned above. The reported volume profiles for the binding of NO clearly show a changeover in mechanism on going from the six-coordinate diaqua complex to the five-coordinate hydroxo complex at high pH.[7]



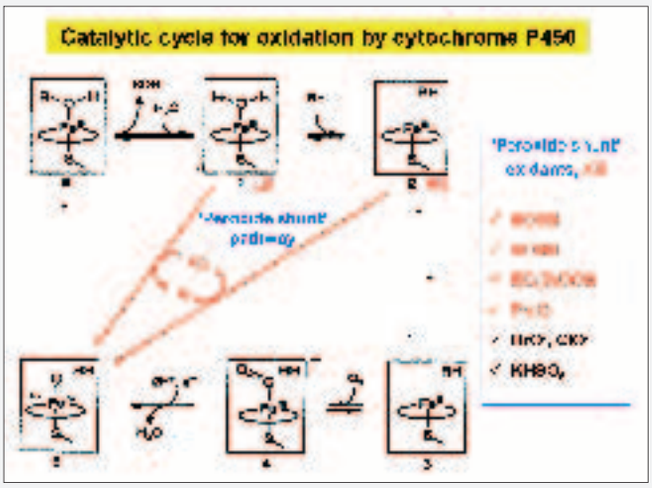
Along these lines, Dr. Norbert Jux (Organic Chemistry) synthesized a series of highly charged water soluble Fe(III) porphyrin complexes that carry negatively and positively charged substituents on the porphyrin chelate. These complexes showed a similar changeover in mechanism for the binding of NO as a function of pH as shown below.[8]



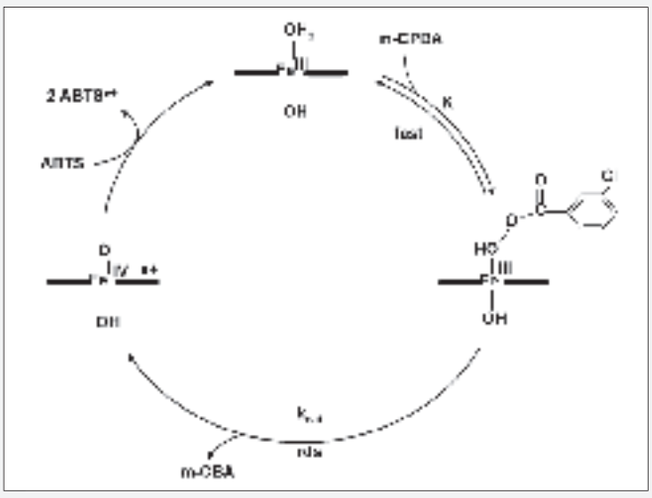


Mechanistic studies on peroxide activation

For the catalytic cycle of P450, the overall reaction for the oxidation/hydroxylation of RH to ROH is given by RH + O_2 + $2e^-$ + $2H^+$ → ROH + H_2O. We are interested in the actual oxygen transfer step **5** → **6** and have initiated studies on this process by adopting the peroxide shunt pathway with different peroxides as demonstrated in the scheme presented below. The resting states **1** and **2** are capable of reacting in a substitution controlled process with different peroxides to produce the $(P^+)Fe^{IV}(=O)$ species **5**. The initial step of the reaction is expected to be very similar to the reactions with NO reported above.



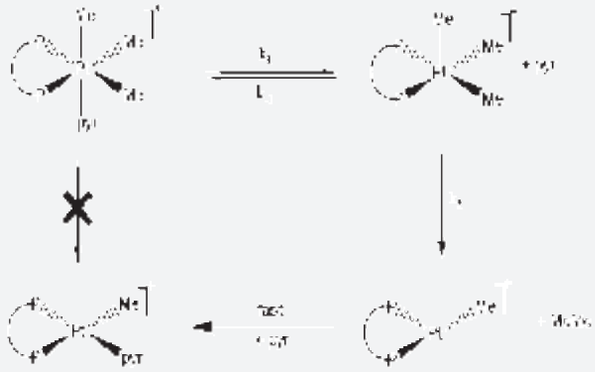
Our work on model porphyrin complexes with H_2O_2, cumene hydroperoxide and m-chloroperoxybenzoic acid has demonstrated that we are able to identify the individual reaction steps of the catalytic cycle with the kinetic techniques, including high pressure (up tp 200 MPa) and low temperature (down to -90 °C) stopped-flow measurements, at our disposal. The reactivity of $(P^+)Fe^{IV}(=O)$ was studied by using efficient traps such as ABTS for this species and resulted in the formulation of the catalytic cycle shown below.

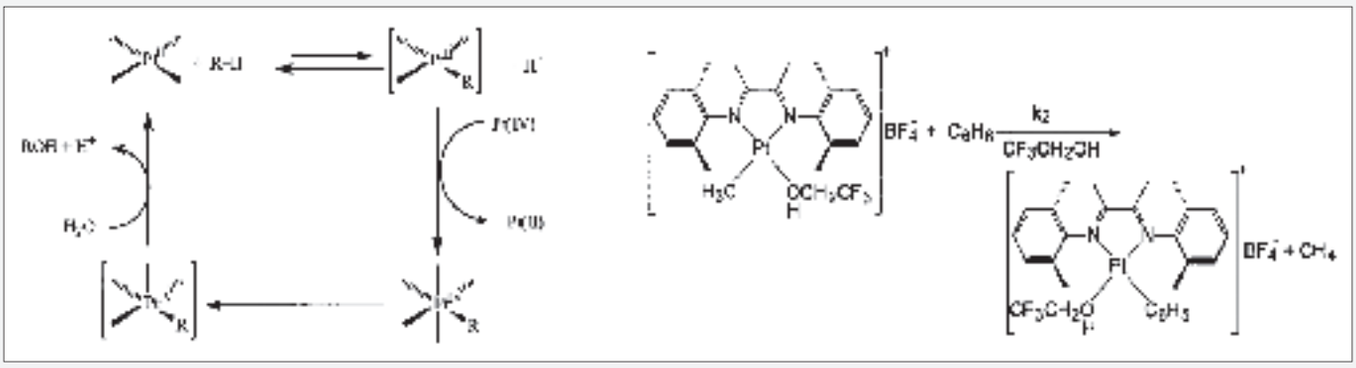


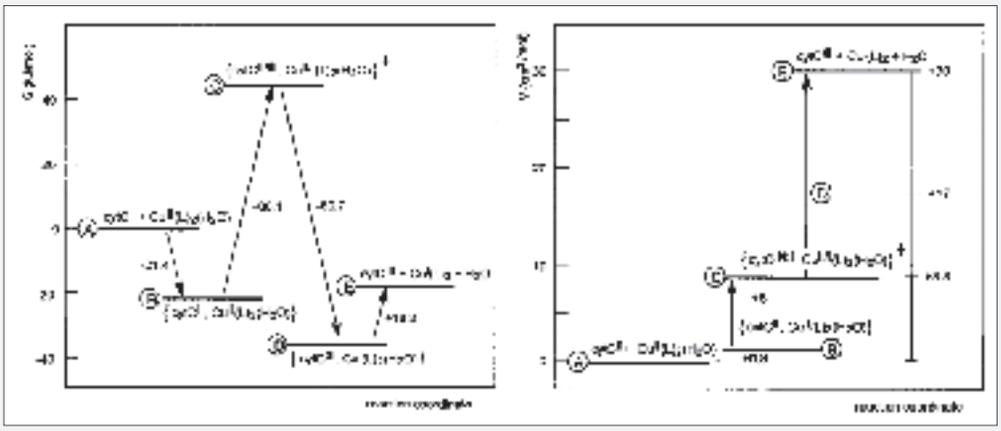
Mechanistic studies on C-H activation

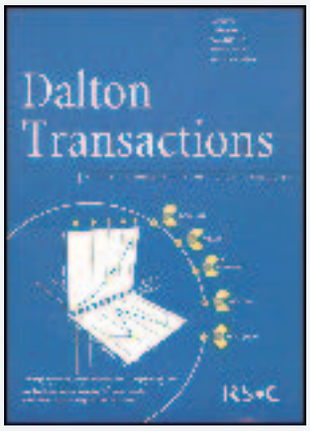
Activation of C-H bonds by organo-transition metal complexes has attracted much attention as a route to directly utilize alkanes as chemical feedstocks. The Shilov system, which consists of aqueous solutions of Pt(II) and Pt(IV) salts that convert alkanes to mixtures of the corresponding chlorides and alcohols under mild conditions, has been extensively studied. Results from several groups support the multi-step catalytic mechanism depicted in the scheme given below, where the key first step, the actual C-H bond activation, involves reaction of alkane with a Pt(II) complex. A key question concerns how the reacting hydrocarbon enters the Pt(II) coordination sphere. A detailed study of the reaction system presented in the scheme (right), revealed that benzene displaces methane in an associative manner as supported by a significantly negative volume of activation.[9]

In a follow-up study, the reductive elimination of ethane from a cationic trimethylplatinum(IV) complex was studied as the microscopic reverse of a C-H activation reaction. The rate and activation parameters for C-C coupling revealed that dissociation of pyridine to form a five-coordinate intermediate controls the reductive elimination reaction as shown in the following scheme. The rate-







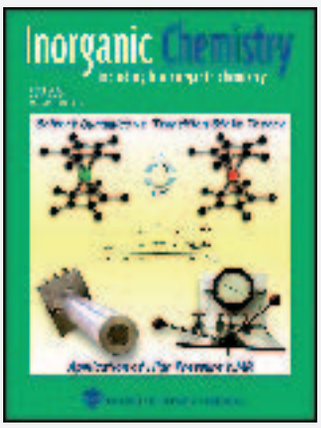


determining step involves C-C coupling and release of ethane accompanied by coordination of pyridine. The reverse C-C activation will also involve the formation of a five-coordinate transition state similar to that proposed for the activation of benzene above. The work was recently cited on the cover[10] of *Inorg. Chem*.

Mechanistic studies on outer-sphere electron transfer reactions

^{1}H-NMR spectroscopy was used to study the outer-sphere self-exchange reaction of $[Fe(Cp^*)_2]^{0/+}$ in different solvents as a function of temperature and pressure. A newly developed ‚narrow bore' high pressure probe (see picture)[11] was used to study the pressure dependence of the reaction up to 200 MPa in order to distinguish between a solvent dynamic and transition state controlled self-exchange reaction. The reported activation volumes underline the validity of a transition state controlled electron transfer reaction.[12]

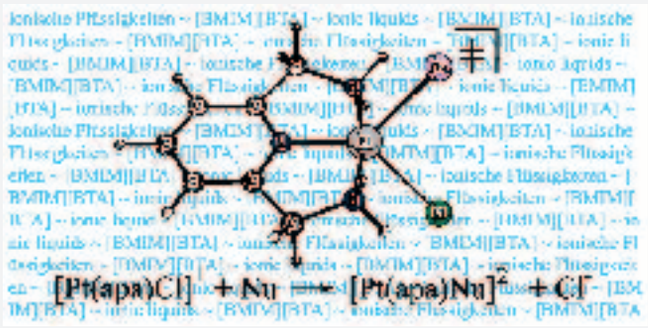
In another study the outer-sphere electron transfer reaction between an anionic Cu(II) complex and cationic cytochrome c Fe(II) was studied and mechanistic information on precursor-formation, electron transfer and successor-decomposition, could be obtained from a combination of kinetic and



electrochemical measurements as a function of temperature and pressure. From these data it was possible to construct free energy and volume profiles for the overall process shown below. For the first time it was possible to construct a three dimensional energy-volume-reaction coordinate profile for the reaction, which was featured on the cover[13] of *Dalton Trans.*

Mechanistic studies in ionic liquids

In recent years, ionic liquids have become a popular research area that is expected to grow as a result of their potential industrial application. Not only are such liquids interesting in terms of applications in separation technology, but also to improve the solubility of weakly soluble gases and to enhance the catalytic activity of metal complexes. A fundamental question, however, does remain. Do ionic liquids really behave as 'normal' solvents, or are there unknown aspects that could affect the substitution behaviour of square planar Pt(II) complexes? Ligand substitution reactions of square-planar complexes of d^8 metal ions such as Pt(II) and Pd(II) play a fundamental role in many chemical processes, for instance in the treatment of tumours and in homogeneous catalysis. We have therefore studied the kinetics of a typical ligand substitution reaction (see scheme) in the ionic liquid [BMIM]BTA as a function of the entering nucleophile concentration, temperature and pressure. The reported rate and activation parameters indicate that the studied ionic liquid behaves perfectly well as solvent, and that changes in the polarity of the transition state play a minor role in the selected ionic liquid.[14]



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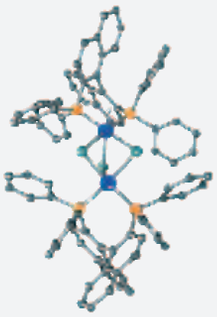
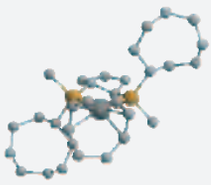
Coordination Chemistry and Homogeneous Catalysis with Chiral Bis(phosphines), Aminophosphines and Aminoalcohols

Asymmetric catalysis continues to be a field of chemical research actively pursued in both academic and industrial laboratories. It provides one of the most cost-effective and ecologically harmless methods for the preparation of numerous structurally diverse compounds as enriched or pure enantiomers, such as pharmaceuticals, agrochemicals, animal health products, flavors and fragrances. In this area, the development of new chiral ligands and complexes is of fundamental importance because the activity of a homogeneous catalyst originates from the central metal and the enantioselectivity of the metal-catalyzed reaction is brought about by the ancillary ligands attached to that metal. Against this background, we have designed a class of optically active bis(phosphines) with structural components that are easily and systematically interchanged and allow access to >C=C< hydrogenation catalysts with stereodiscriminating properties determined by, e.g., the spatial orientation of P-substituents being equal or pairwise different in steric demand and the combination of C- and P-chirogenic stereoelements in matched (or mismatched) fashion. Additional activities have focussed on the catalytic potential in asymmetric >C=O hydrogenation of optically active metal complexes bearing bidentate aminophosphine and aminol ligands which are derived from diastereomeric (pseudo)ephedrine precursors and from amino acids, respectively.





Nach wie vor ist die asymmetrische Katalyse ein Gebiet chemischer Forschung, welches in Universitäts- wie auch in Industrielaboratorien mit Nachdruck bearbeitet wird. Sie bietet eine der kostengünstigsten und umweltverträglichsten Methoden zur Darstellung zahlloser strukturell unterschiedlicher Verbindungen als angereicherte oder reine Enantiomere - so etwa von Pharmazeutika, Agrochemikalien, verterinärmedizinischen Produkten, Aromen und Duftstoffen. Dabei ist die Entwicklung neuer chiraler Liganden und Komplexe von grundsätzlicher Bedeutung, denn die Aktivität eines Homogenkatalysators geht vom Zentralmetall aus, während die daran gebundenen Hilfsliganden die Enantioselektivität der metallkatalysierten Reaktion bestimmen. Vor diesem Hintergrund haben wir eine Klasse optisch aktiver Bis(phosphine) mit Strukturbausteinen entworfen, die in systematischer Weise leicht gegeneinander ausgetauscht werden können. Sie erlauben Zugang zu >C=C<-Hydrierkatalysatoren mit stereodifferenzierenden Eigenschaften, die z.B. von der räumlichen Ausrichtung paarweise gleich oder unterschiedlich raumerfüllender P-Substituenten und dem Zusammenwirken C- und P-chirogener Stereoelemente in aufeinander abgestimmter (oder einander zuwiderlaufender) Kombination abhängen. Weitergehende Aktivitäten richten sich auf optisch aktive Metallkomplexe mit Aminophosphin- und Aminol-Liganden, welche von diastereomeren (Pseudo)ephedrinen sowie von Aminosäuren abgeleitet sind, und deren Anwendbarkeit in der katalytischen >C=O-Hydrierung.

Asymmetric >C=C< Hydrogenation with Enantiopure Cyclopentane-based P_2 Ligands

Analogous to the preparation of $Cl_2PC_2H_4PCl_2$ from ethylene, white phosphorus, and phosphorus trichloride, racemic *trans*-1,2-$C_5H_8(PCl_2)_2$ (**L^{Cl}**) is easily obtained on a 100 g scale by heating cyclopentene with P_4 and PCl_3 at 220 ºC in an autoclave. Resolution into the (*S*,*S*) and (*R*,*R*) enantiomers involves initial reaction of the racemate with either enantiomer of diisopropyltartrate to furnish two of the four possible diastereomeric bis(dioxaphospholanes) as isomerically pure crystals (Figure 1). Reduction with $LiAlH_4$ then affords the bis(primary phosphine) 1,2-$C_5H_8(PH_2)_2$ (**L^{H}**) as resolved (*S*,*S*) and (*R*,*R*) enantiomers and subsequent oxidation of the P-H bonds with $(Cl_3CO)_2CO$ („triphosgene“) allows for the routine preparation of either antipode of the multi-purpose P-Cl reagent **L^{Cl}**.[1]
One of the most useful features of the abundance of optically active diphosphorus ligands[2] that have been obtained by reacting **L^{Cl}** or **L^{H}**, as either mirrage isomer, with *C*, *N*, or *O* nucleophiles and alkenes, respectively, is their adjustability which enables the possibility of influencing the enantioselectivity by varying the substituents on the phosphorus atoms. Many of these enantiopure ligands have therefore been examined by us[1] and others[3,4] for their utility in Rh-catalyzed asymmetric hydrogenations of standard enamide substrates such as (acetylamino)acrylic and –cinnamic acid or their alkyl esters. The main purpose of these investigations was to reveal potential correlations between the outcome of the hydrogenation reactions and structural properties of the metal complexes in order to elucidate the factors governing the stereoselectivity of the catalysts.

Thus, distinct matched-mismatched effects have been observed to occur for >C=C< hydrogenations catalyzed by rhodium complexes possessing diastereomeric *C*,*P*-chirogenic bis(phosphines) of the $C_5H_8\{P(CH_3)(cyclo\text{-}C_8H_{15})\}_2$ type, where it is the two stereoisomers with opposite configuration

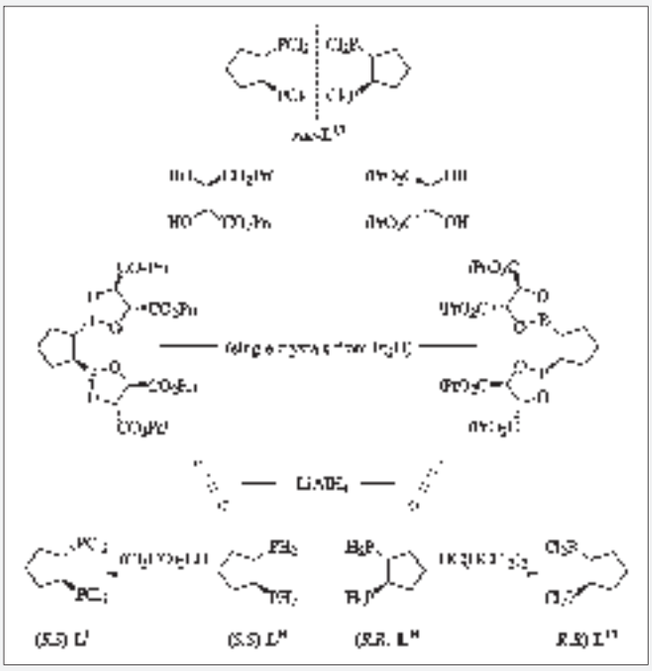


Figure 1. Resolution of *rac*-$C_5H_8(PCl_2)_2$ into its (*R,R*) and (*S,S*) enantiomers via (*R,R*)- and (*S,S*)-$C_5H_8(PH_2)_2$.

at the carbon and phosphorus atoms of the free ligands (*i.e.*, like *C,P* configuration in the metal complexes) that represent the beneficial matched combination of stereochemical elements (up to 90% *e.e.*) while the R_C,R_C,R_P,R_P and S_C,S_C,S_P,S_P isomers (*i.e.*, those with unlike *C,P* configuration as coordinated ligands) must be looked at as their disadvantageous counterparts (less than 30% *e.e.*).[1] The major stereochemical difference between two structurally characterized Rh(I) (pre)catalysts exhibiting the superior and, repectively, inferior

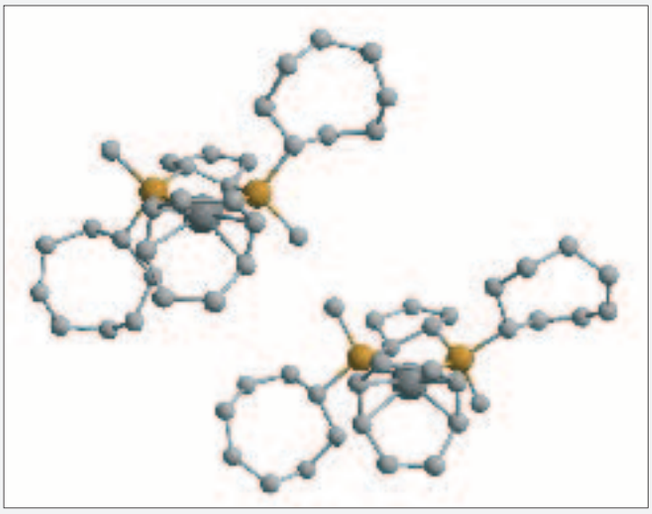


Figure 2. Perspective views of (a) [(COD)Rh{(R_C,R_C,R_P,R_P)-C_5H_8[P(CH_3)(*cyclo*-C_8H_{15})]$_2$}]$^+$ (top) and (b) [(COD)Rh{(S_C,S_C,R_P,R_P)-C_5H_8[P(CH_3)(*cyclo*-C_8H_{15})]$_2$}]$^+$ (bottom) showing the axial and, resp., equatorial octyl alignment of the matched (λ-shaped) and mismatched (δ-shaped) catalysts.

enantiodiscriminating properties arises from the contrasting orientations of the sterically demanding cyclooctyl groups with respect to the R- Rh- P coordination plane; these are axial in the former (Figure 2a) but tend to be equatorial in the latter (Figure 2b).

It is the (alkyl)hydride-forming insertion of the substrate in short-lived diastereomeric dihydrido enamide intermediates as depicted in Figure 3, which has been identified as the enantiodetermining irreversible step of asymmetric hydrogenation with catalysts bearing *P*-chirogenic ligands with substituents being pairwise different in steric demand.[5] This step is controlled in an enantiofacially discriminating fashion by repulsive interaction, in two diagonally arranged „coordination quadrants“, between the carboxyl group and the more bulky *P*-bound residues:

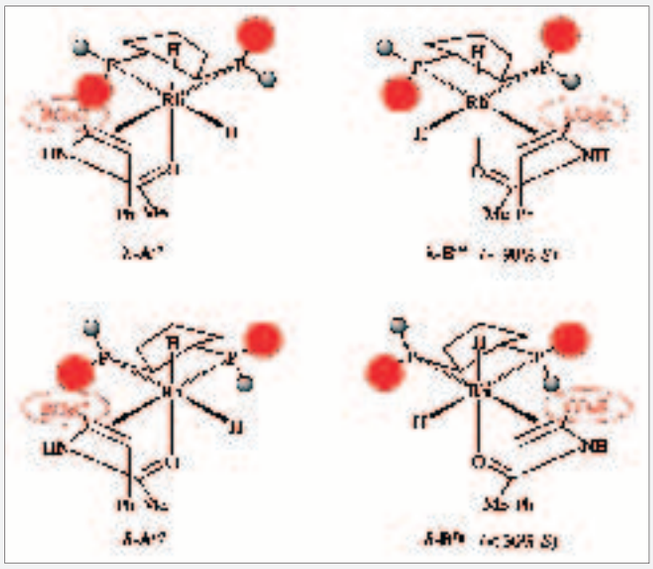


Figure 3. Possible diastereomers of cationic rhodium dihydrido enamide intermediates with C_5H_8{P(CH_3)(*cyclo*-C_8H_{15})}$_2$ ligands in matched and mismatched configuration (interfering cyclooctyl and carboxyl groups drawn in red).

For λ-shaped matched (pre)catalyst [(COD)Rh{(R_C,R_C,R_P,R_P)-C_5H_8[P(CH_3)(*cyclo*-C_8H_{15})]$_2$}]$^+$, the axial arrangement of its cyclooctyl rings results in steric blocking of *only* the top right and bottom left quadrants. This makes λ-**B**^{ax} lower in energy than λ-**A**^{ax} so that shielding of these two quandrants leads to preferential bonding of the substrate through its *re* face giving (*S*)-amino acids in high optical yield as observed. As a consequence of their distinct equatorial alignment, the spatially expanded cyclooctyl groups of δ-shaped mismatched (pre)catalyst [(COD)Rh{(S_C,S_C,R_P,R_P)-C_5H_8[P(CH_3)(*cyclo*-C_8H_{15})]$_2$}]$^+$, on the other hand, not only fill out the two top right and bottom left quandrants but slightly penetrate into the adjacent parts of the coordination sphere as well, thereby contributing to some *unwanted shielding* of the upper left and lower right quadrants. Hence, the degree of *favorable quadrant-blocking*, thought to make δ-**B**^{eq} more readily accessible than δ-**A**^{eq}, is much less effective with

the latter complex and results in largely decreased *e.e.*'s for the (*S*) hydrogenation product as found by experiment.[1]

Homogeneous Hydrogenation of Ketones with Aminophosphine Ligands Derived from (Pseudo)ephedrine Precursors

Metal complexes containing both *P* and *N* donor ligands have been dominating the field of homogeneous hydrogenation of organic carbonyl compounds for several years. Noyori's optically active ruthenium complexes $[RuCl_2(binap)(1,2\text{-diamine})]$ in particular have been found to be excellent enantioselective catalysts for the reduction by H_2 of simple ketones, if activated by an excess of strong base.[6] Heterolytic cleavage of dihydrogen by deprotonation of short-lived η^2-H_2 intermediates with the help of an internal base has been shown to be a key step involved in the catalytic cycle. Such intramolecular heterolytic H_2 splitting occurs across the polar metal-amide bond of initially formed amine-amido hydrido complexes, $[RuH(P\cap P)(HN\cap NH_2)]$, to reversibly give diamine dihydrides, $[RuH_2(P\cap P)(H_2N\cap NH_2)]$, as the catalytically active species. From these, $H^{\delta-}/H^{\delta+}$ equivalents are transferred simultaneously to the ketonic substrate, once the carbonyl group has come into close contact with the second coordination sphere of the catalyst through an unconventional Ru-$H^{\delta-}\cdots>C^{\delta+}=O^{\delta-}\cdots H^{\delta+}$-N „metal-ligand bifunctional" interaction.[7] A different type of a highly enantioselective >C=O hydrogenation catalyst is examplified by Zhang's „Rh-PennPhos" system, composed of *in situ* generated [(COD)Rh{(*R*,*S*,*R*,*S*)-Me-PennPhos}]Cl and up to one equivalent of a weakly coordinating base of moderate strength. This catalyst is believed to support the homogeneous hydrogenation of ketones following the classic pathway of homolytic scission of the H_2 molecule by oxidative addition with subsequent insertion of the ketone into one of the Rh-H bonds.[8]

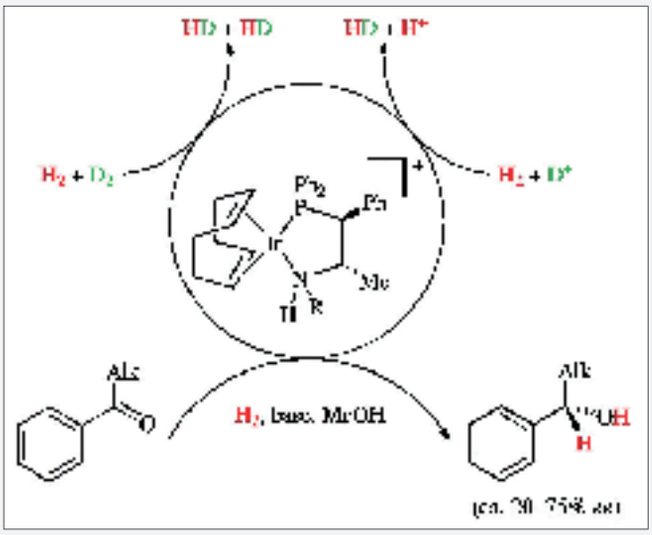
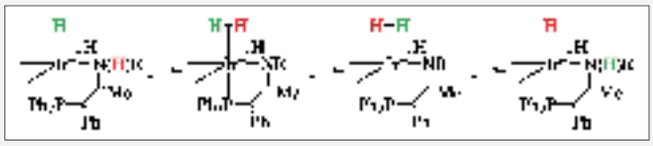


Figure 4. Catalytic >C=O hydrogenation and H_2/D^+ and H_2/D_2 exchange catalyzed by cationic $[(COD)Ir\{P\cap N(H)R\}]^+$ complexes.

Against this background, our recent activities have focussed on the catalytic potential in asymmetric >C=O hydrogenation of a class of optically active β-aminophosphine complexes of Ir^I, $[(COD)Ir\{Ph_2PCH(Ph)CH(Me)N(H)R\}]BF_4$ (R = H, alkyl), having a chelated d^8 metal center (as found in Zhang's catalyst) embedded in a *P*,*N*-dominated coordination environment (which is a substantial characteristic of the Noyori systems). An important further aspect of our work with these complexes arose from our interest to elucidate whether the dihydrogen molecule is activated during catalysis by homolytic or heterolytic H-H bond breaking.

All the above $[(COD)Ir\{P\cap N(H)R\}]BF_4$ complexes will act as catalysts for the direct hydrogenation of alkyl aryl ketones if combined under H_2 with an alkaline base in methanol (both of which are essential) to produce the corresponding 1-arylalkanols with modest to moderate enantioselectivity (~ 20-75% *e.e.*); Figure 4.[9] The base-free amido complexes $[(COD)Ir\{P\cap NR\}]$ display similar catalytic activity to the combined systems $[(COD)Ir\{P\cap N(H)R\}]BF_4$-KOH. The ability of both the cationic β-amino- and the neutral β-amidophosphino complexes to undergo oxidative H_2 addition and the observation of H_2/D^+ as well as H_2/D_2 exchange processes during catalysis (Figure 4) provides evidence for a mechanism involving reversible proton-to-hydride transfer and heterolytic H_2 cleavage on $Ir^+(H)_2$-N(H)R and $(\eta^2\text{-}H_2)IrH$-NR tautomers:[9]



Current and Future Activities

In continuation of the work described above, *P*,*N*-coordinated Ru^{II} complexes are being actively investigated which differ from the advanced Noyori systems, where the central metal is always coordinated to two phosphorus and nitrogen atoms of one bis(phosphine) and one diamine ligand, in two ways: either their coordination spheres are made up of one chelating bis(phosphine) and one aminophosphine to form $P\cap P/P\cap N$ derivatives as examplified by Figure 5a, or their structural motif features pairwise $P\cap N$ coordination of two aminophosphine ligands such as, *e.g.*, in Figure 5b.[10]

Also included are cationic $Rh^{I/III}$ and $Ir^{I/III}$ catalysts representing coordinatively saturated or unsaturated counterparts of $[RuCl_2(binap)(1,2\text{-diamine})]$ (*e.g.*, Figure 6a)[11][12] as well as Rh^I and Ir^I complexes bearing optically active aminol ligands, such as depicted in Figure 6b.[13]

These and similar complexes are being studied for their ability to serve as (pre)catalysts either for the direct hydrogenation of ketones by molecular H_2 or for the transfer of H^+ and H^- equivalents from solvents such as Me_2CHOH or HCO_2H to the

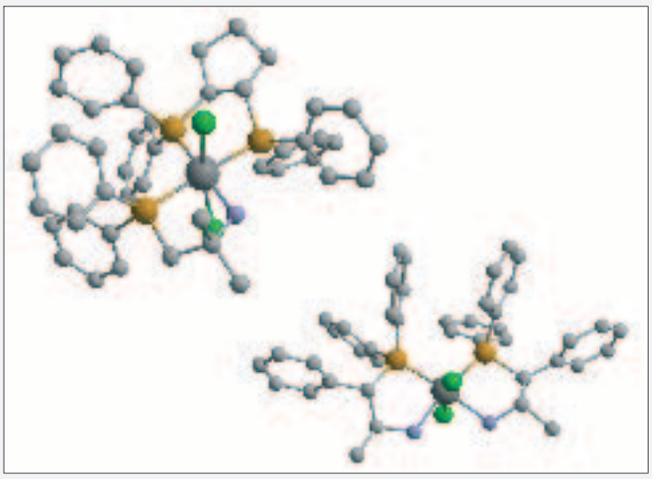


Figure 5. Perspective views of (a) *trans*-[$RuCl_2${(*S*,*S*)-$C_5H_8(PPh_2)_2$}($Ph_2PCH_2CMe_2NH_2$)] (top) and (b) *trans*-[$RuCl_2${(*S*,*S*)-$Ph_2PCH(Ph)CH(Me)NH_2$}$_2$] (bottom).

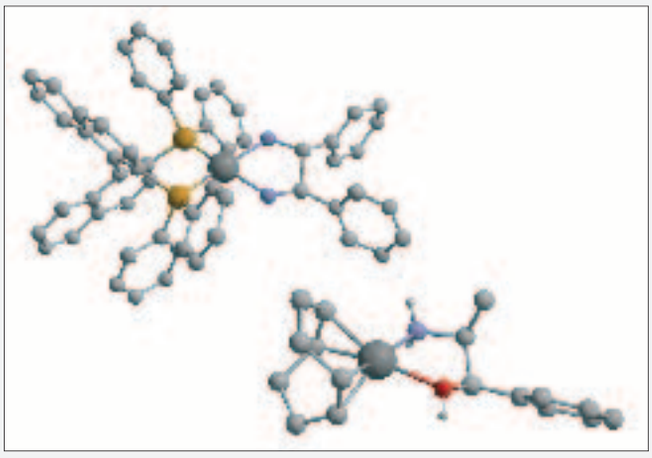


Figure 6. Perspective views of (a) [Ru{(*R*)-binap}(*R*,*R*)-$NH_2CH(Ph)CH(Ph)NH_2$)]$^+$(top)and(b)[(COD)Rh{(*R*,*S*)-$HOCH(Ph)CH(Me)NH_2$}]$^+$ (bottom).

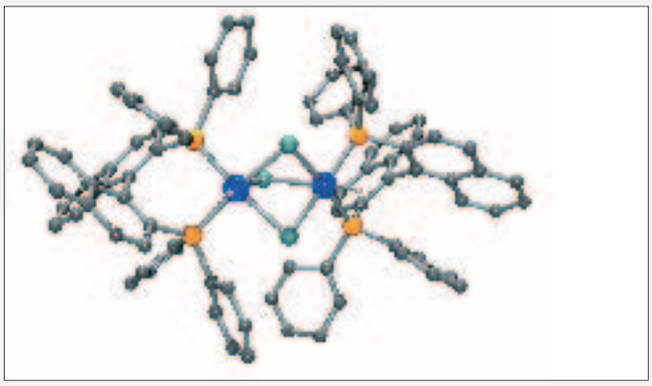


Figure 7. Perspective view of [{(*R*)-binap)}$_2Ir_2H_2(\mu\text{-}Cl)_3]^+$.

>C=O double bond. So far, enantioselectivities of up to 87% have been obtained with an *in situ* catalyst composed of [{(*R*)-binap)}$_2Ir_2H_2(\mu\text{-}Cl)_3]^+$ (Figure 7), (*R*,*R*)-$H_2NCH(Ph)CH(Ph)NH_2$, and activating base.[12]

Acknowledgments

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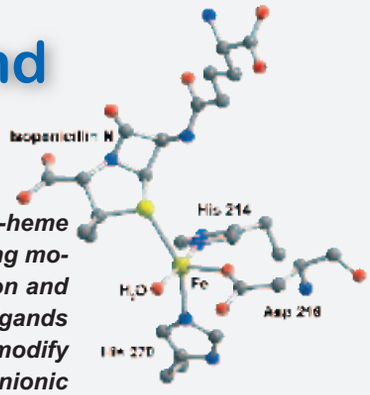
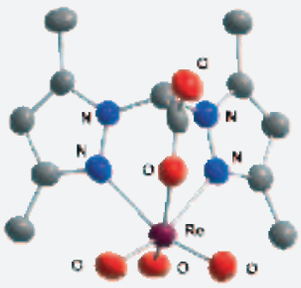
Prof. Dr. Nicolai Burzlaff

The N,N,O Motif in Coordination and Bioinorganic Chemistry



The N,N,O binding motif is the key aspect of our research. This motif is found in many non-heme iron enzymes as well as in some zinc enzymes, for example the gluzincins, as metal binding motif. Thus, to mimic this motif is the purpose of most of our model complexes for these iron and zinc enzymes. Small organic κ^3-N,N,O ligands such as various bis(pyrazol-1-yl)acetato ligands are applied for this purpose. These ligands can be tailored with bulky substituents to modify their steric hindrance and with solid phase linkers for solid phase fixation. Some of these anionic κ^3-N,N,O ligands, we developed, are also quite useful in organometallics and coordination chemistry and allow a chemistry comparable to that of cyclopentadienyl (Cp) or hydrido(trispyrazol-1-yl)borato ligands (Tp). This includes future potential applications in radiopharmaceuticals. Furthermore, new chiral enantiopure N,N,O tripod ligands have been developed starting from cheap compounds of the Chiral Pool. Finally, we try to investigate the biocatalytic pathways of the non-heme iron dioxygenases by pseudo kinetic protein crystallography.



Ausgangspunkt unserer Forschung ist das N,N,O-Bindungsmotiv. Dieses Metall-bindende Motiv findet sich in zahlreichen Nicht-Häm-Eisen-Enzymen wie auch in einigen Zink-Enzymen, z. B. den Gluzinkinen. Ziel der meisten unserer Eisen- und Zink-Komplexe ist es, dieses Motiv nachzubilden. Hierfür werden kleine κ^3-N,N,O-bindende Liganden, wie z. B. verschiedene Bis(pyrazol-1-yl)acetato-Liganden, eingesetzt. Diese Liganden können bezüglich ihres sterischen Anspruchs quasi maßgeschneidert werden. Auch sind Variationen mit Linkern für die Festphasenfixierung möglich. Einige dieser anionischen κ^3-N,N,O-Liganden sind zudem in der Organometall- und Koordinationschemie einsetzbar und erlauben eine Chemie, die mit der von Cyclopentadienyl- (Cp) oder Hydrido(trispyrazol-1-yl)borato-Liganden (Tp) vergleichbar ist. Dies geht hin bis zu möglichen Anwendungen in Radiopharmazeutika. Zudem wurden von uns neue chirale N,N,O-Tripod-Liganden enantiomerenrein dargestellt, ausgehend von preisgünstigen Naturstoffen aus dem Chiral Pool. Schließlich bearbeiten wir auch die Aufklärung von Biokatalysezyklen der Nicht-Häm-Eisen-Dioxygenasen mittels pseudokinetischer Proteinkristallographie.

Bioinorganic model complexes for mononuclear, non-heme iron dependent oxidases and oxygenases

In the past decade, protein structures of several mononuclear non-heme iron(II) enzymes were solved, such as isopenicillin N synthase (IPNS), taurine dioxygenase (TauD) (Fig. 1) and many more 2-oxoglutarate dependent iron enzymes.

In plenty of these iron(II) dependent enzymes two iron binding histidines and one aspartate or glutamate - the so called 2-His-1-carboxylate facial triad - are conserved throughout the whole family of enzymes.

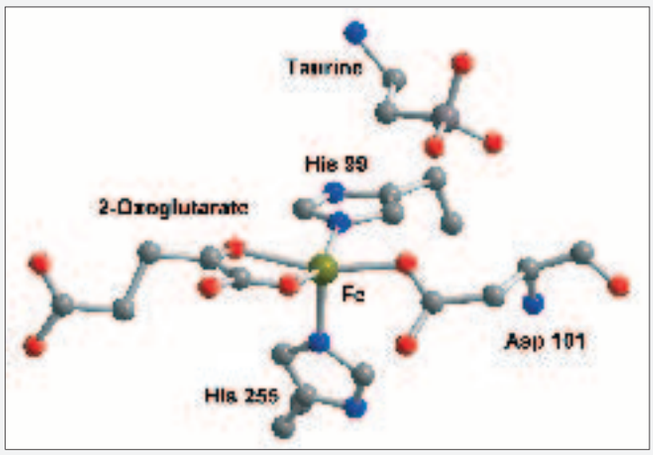


Figure 1: Active site of TauD, a mononuclear 2-oxoglutarate dependent non-heme iron(II) dioxygenase (PDB code: 1GY9).[1]

Bis(pyrazol-1-yl)acetato, bis(3,5-dimethylpyrazol-1-yl)acetato and recently also bis(*N*-methylimidazol-2-yl)propionato ligands can mimic this 2-His-1-carboxylate facial triad found in the active sites of these oxidases and oxygenases.[2-4] With iron (Fig. 2) and ruthenium (Fig. 3) models bearing these ligands and even more bulky analogues we try to mimic certain steps in the catalytic cycle and the biosynthesis of the enzymes by biomimetic reactions. Many inherited diseases are caused by malfunction of these enzymes. Therefore, coordination of substrates or substrate analogues and inhibitors to the models are also investigated. Furthermore, some of the model complexes are tested for their catalytic activity in oxidation reactions such as epoxidation.

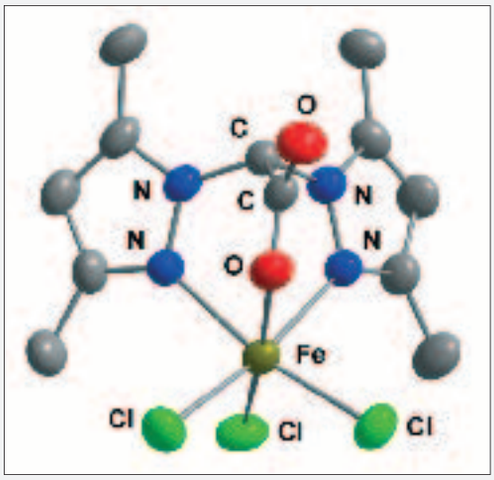


Figure 2: An iron model complex bearing the bis(3,5-dimethylpyrazol-1-yl)acetato ligand.[3]

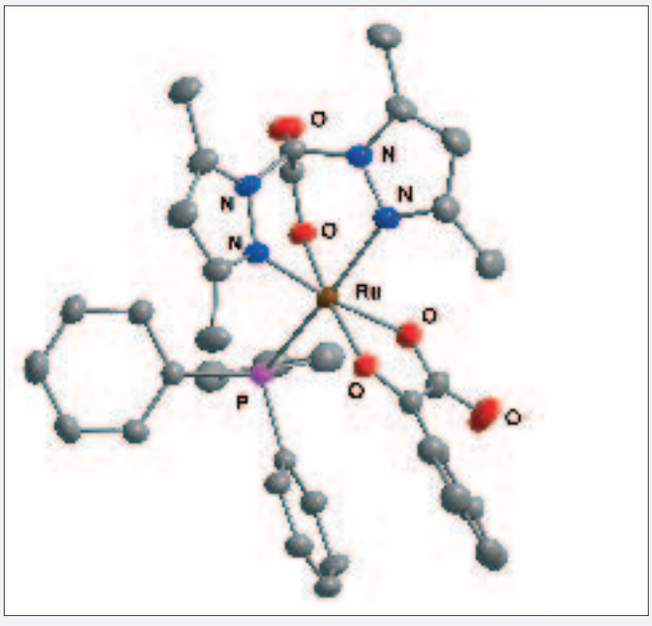


Figure 3: A ruthenium model complex as mimic for 2-oxoglutarate dependent iron dioxygenases.[4]

Bioinorganic model complexes for zinc peptidases and proteases

Several zinc peptidases and proteases that are relevant to medicine bind zinc in the active site by two histidines and one glutamate or aspartate. The *angiotensine converting enzyme* (ACE), a key enzyme in the regulation of the blood pressure, is a prominent example. With zinc bis(pyrazol-1-yl)acetato complexes we developed structural models for these active sites.[2,5] Our current interest focuses on the coordination of protease inhibitors to the zinc models and the construction of functional models. These inhibitors bear typical zinc binding groups (ZBGs) such as carboxylates, thiols or hydroxamic acids as well as new potential ZBGs. Thus, the new developed zinc protease models serve as tools to develop and test new ZBGs. Zinc alkyl complexes (Fig. 4) as precursors allow an easy access to these model complexes.

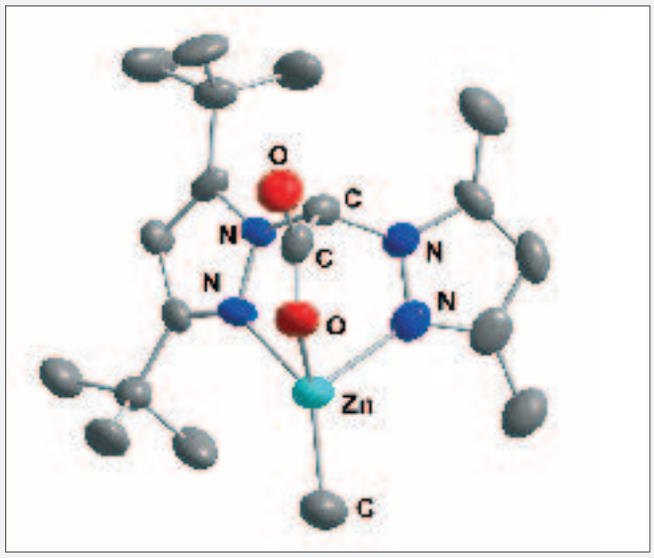


Figure 4: A racemic zinc methyl complex, a versatile precursor for zinc protease models.[5]

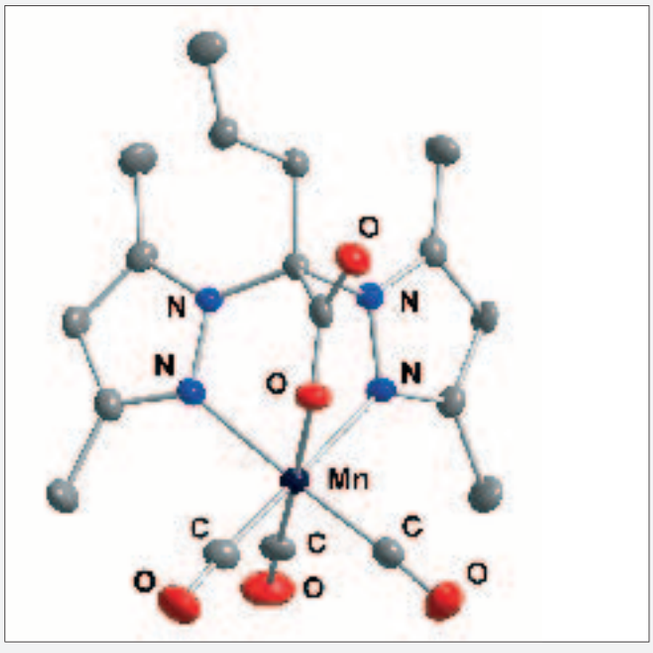


Figure 5: Manganese complex with a bis(3,5-dimethylpyrazol-1-yl)acetato ligand bearing an allyl linker.[6]

Ligands with solid phase linkers

We are able to add linkers such as an allyl linker (Fig. 5) or a hydroxymethyl group for solid phase fixation to the bis(pyrazol-1-yl)acetato ligands.[6]

This should allow the future application of these ligands in solid phase synthesis and *imprinted polymers*. Especially, a separation of the metal centres on the solid phase similar to the separation of the active sites in enzymes might be achieved by this method, without adding bulky groups to the ligands.[6] Recently, we even succeeded in fixing a bis(*N*-methylimidazol-2-yl)propionato ligand to a Merrifield resin.

Coordination chemistry of *N,N,O* ligands

By some exemplary coordination experiments and organometallic complexes we can prove that bis(pyrazol-1-yl)acetato and bis(N-methylimidazol-2-yl)propionato ligands are as versatile for coordination chemistry as cyclopentadienyl ligands (Cp) or hydrido(trispyrazol-1-yl)borato ligands (Tp). Various manganese and rhenium tricarbonyl as well as rhenium trioxo complexes have been obtained.[7-9] Especially, the rhenium trioxo complexes (Fig. 6) open a potential application of the bis(pyrazol-1-yl)acetato ligands in ^{99m}Tc radiopharmaceuticals.

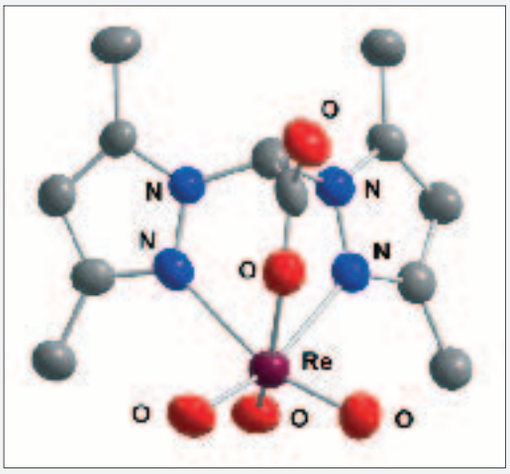


Figure 6: A rhenium trioxo complex.[8]

So far, in all ^{99m}Tc radiopharmaceuticals $^{99m}TcO_4^-$ has to be reduced to a lower oxidation state in order to produce a stable ^{99m}Tc-complex for clinical application. The formation of the rhenium trioxo complexes bearing bis(pyrazol-1-yl)acetato ligands is achieved by reaction of perrhenic acid with the ligands, thus indicating that a rather simple synthesis of a ^{99m}Tc complex might also be possible directly from $^{99m}TcO_4^-$.
Furthermore, several ruthenium carbene, vinylidene, allenylidene, hydride and hydrogen complexes have been synthesised.[10,11]

Chiral enantiopure *N,N,O* tripod ligands

Chiral facially coordinating tripod ligands play an important role in stereoselective synthesis. Usually, the chirality of these ligands originates from three different donor groups that are bound to a bridging atom with a non-coordinating group, atom or lone pair. For asymmetric induction two problems have to be solved: (a) enantiomeric purity, and (b) a stable configuration of the stereogenic centres. Often C_3-symmetric ligands with three identical, chiral donor groups are applied, though the application of these ligands is rather limited due to their steric hindrance. Recently, we reported on a general concept to obtain new enantiopure facially binding ligands, that are less hindered, from C_2-symmetric precursors. Starting from cheap *Chiral Pool* compounds such as (+)-camphor or (-)-menthone new chiral enantiopure tripod ligands for coordination chemistry have been developed. The syntheses of these ligands are performed in only a few steps. No separation of enantiomers or diastereomers is necessary.[12,13]

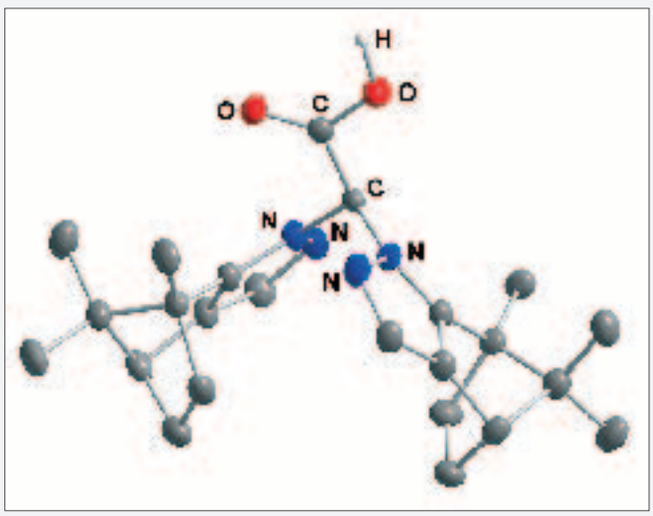


Figure 7: An enantiopure N,N,O ligand derived from (+)-camphor.[12]

Crystallography

Whenever possible, the model complexes are characterised by X-ray structure analysis. This allows a comparison of the structural models with the geometries of the active site of the enzymes. In addition to this everyday small molecule crystallography we are also active in the field of pseudo kinetic protein crystallography (Fig. 8).[14-17] In these experiments protein crystals of iron oxygenases are pressurised with the oxygen substrate. After a defined time the crystals are frozen in liquid nitrogen, thereby trapping the reaction in the crystal. The analysis of X-ray datasets obtained from these crystals allows some sort of snap shot view inside the mechanism of the iron oxygenases.

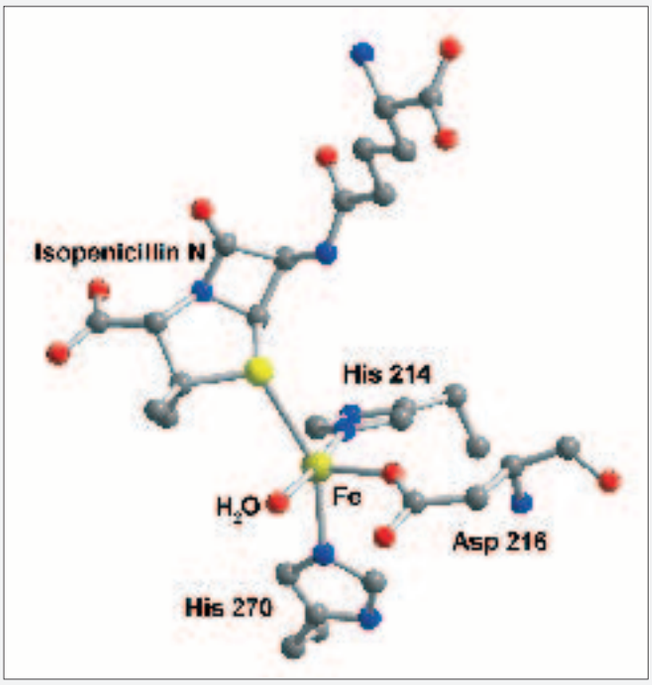


Figure 8: Molecular structure of the active site of isopenicillin N synthase (IPNS) with a bound IPN product deduced from a pseudo kinetic protein crystallography experiment (PDB code: 1QJE).[14]

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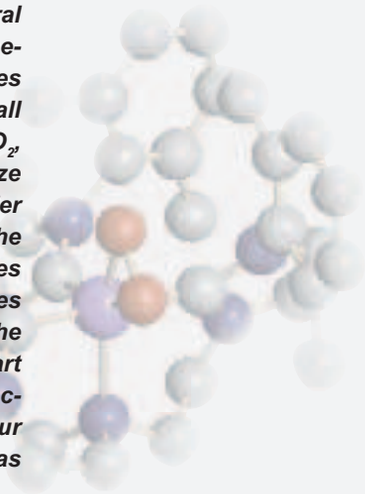
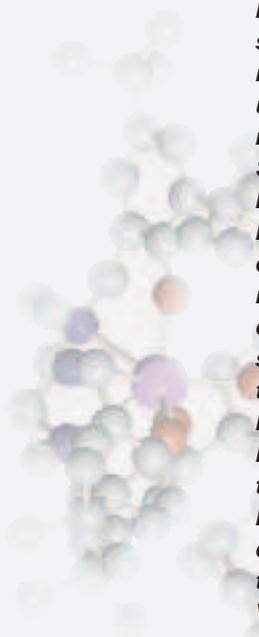
Prof. Dr. Karsten Meyer

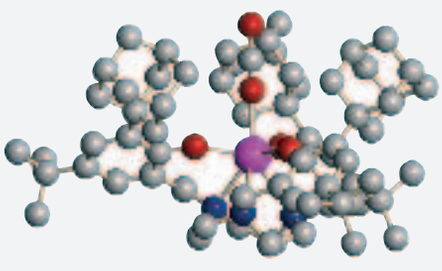
Small Molecule Activation with Electron-Rich Metal Complexes in Sterically Demanding Ligand Environments



The inorganic chemistry in the Meyer laboratory bridges the field of classical coordination chemistry with fields of supramolecular, organometallic, and bioinorganic chemistry. The general research focuses on the synthesis of new chelating ligands and their transition and actinide metal coordination complexes. These complexes often exhibit unprecedented coordination modes and unusual electronic structures and consequently, show enhanced reactivities towards small molecules of industrial and biological relevance, such as organic azides and H_2, N_2, CH_4, CO, CO_2, NO_x, O_2, O_3, P_4 etc. Small molecule activation and atom or group transformation to functionalize important organic and inorganic precursor molecules is the ultimate goal of our research. In order to achieve this goal, the coordination chemistry of a range of early transition metals as well as the relatively unexplored uranium chemistry is being investigated. Single-crystal diffraction studies in conjunction with a battery of spectroscopic methods such as SQUID magnetization studies as well as EPR, Mößbauer, electronic and X-ray absorption spectroscopy is applied to study the electronic properties and reactivities of these new species. Synthetic chemistry is at the heart of our research but modern computational methods are applied to elucidate the electronic structures and origin of reactivity of our newly synthesized molecules. In general, the research in our laboratory allows for learning a variety of inorganic and organic synthetic techniques as well as the theory and application of a large number of spectroscopic and computational methods.



Die Forschungsinteressen im Arbeitskreis Meyer zielen darauf ab, Brücken zwischen der klassischen Koordinationschemie und den aktuellen Gebieten der supramolekularen, bioanorganischen und Organometallchemie zu schlagen. Dabei steht die Synthese neuer Chelatliganden und ihrer Koordinationsverbindungen mit Übergangsmetallen und Actiniden im Vordergrund. Oftmals weisen diese Komplexe ungewöhnliche Koordinationsmodi sowie besondere elektronische Strukturen auf. Dies führt zu erhöhter Reaktivität gegenüber kleinen Molekülen, die von industrieller und biologischer Bedeutung sind. Als Beispiele dafür stehen etwa organische Azide, aber auch H_2, N_2, CH_4, CO, CO_2, NO_x, O_2, O_3, P_4 usw. Im Vordergrund unserer Forschung steht die Aktivierung dieser Moleküle sowie die Übertragung von Atomen oder Atomgruppen mit dem Ziel der Funktionalisierung wichtiger organischer und anorganischer Vorläufermoleküle. Um dieses Ziel zu erreichen, wird nicht nur die Koordinationschemie einer Reihe früher Übergangsmetalle untersucht, sondern darüber hinaus auch die weitgehend unerforschte Chemie von Urankomplexen. Einkristallstrukturanalysen werden im Zusammenspiel mit einem ganzen Arsenal an spektroskopischen Methoden wie SQUID-Magnetisierungs-Untersuchungen, EPR-, Mößbauer-, elektronischer und Röntgenabsorptionsspektroskopie dazu verwendet, die elektronischen Eigenschaften und Reaktivitäten der neu synthetisierten Spezies zu untersuchen. Während die präparative Synthese im Mittelpunkt unserer Chemie steht, kommen zugleich moderne rechnerische Verfahren zur Anwendung, um die elektronischen Strukturen und die Ursachen für die Reaktivität der neu synthetisierten Moleküle zu ergründen. Die Mitarbeit in unserem Arbeitskreis ermöglicht es nicht nur, eine Vielzahl anspruchsvoller anorganischer und organischer Synthesetechniken anzuwenden, sondern auch Theorie und Praxis moderner Spektroskopiearten und Rechenverfahren zu erlernen.



Coordinatively Unsaturated Metal Complexes in Low-Oxidation States[1,2]

Sterically encumbering ligands are used increasingly to synthesize coordinatively unsaturated, highly reactive metal complexes. Steric constraint imposed by customized spectator ligands often translates into molecular and electronic structure changes as it directly impacts the coordination mode and me-

tal-ligand orbital interactions; the latter being particularly important in atom transfer chemistry. Compared to complexes with less customized ligands, unsaturated metal ions with molecularly engineered ligand environments often show altered and increased reactivity as a result of steric pressure imposed by the ligand. As a result, sterically tailored, highly reactive metal complexes very successfully achieve a wide variety of unprecedented small molecule activation and atom transfer chemistry of great fundamental and industrial importance.[1,2]

Carbon Monoxide and Carbon Dioxide Activation at Low-Valent Uranium Centers[3-7]

Carbon dioxide has been implicated as a main contributor to global warming, because of its role in radiative forcing. However, due to the vastness of its supply, CO_2 also represents an abundant renewable carbon resource for the production of fine chemicals and clean fuels. Interest in metal-mediated multi-electron reduction of carbon dioxide therefore remains high but, due to the molecule's inherent thermodynamic stability, the development of metal catalysts that achieve CO_2 activation and functionalization is challenging. Particularly intriguing for synthetic chemists is the discovery of relatively simple coordination complexes that bind CO_2 and facilitate its reduction. Chemists have isolated and structurally characterized several synthetic metal complexes of CO_2, such as Aresta's archetypal $[(Cy_3P)_2Ni(CO_2)]$ (*Cy* = cyclohexyl) and Herskowitz's $[(diars)_2M(CO_2)(Cl)]$ (*diars* = *o*-phenylenebis(dimethylarsine), M = Ir, Rh), featuring the bidentate η^2-**CO**O and C-bound η^1-**C**O_2 binding modes, respectively.

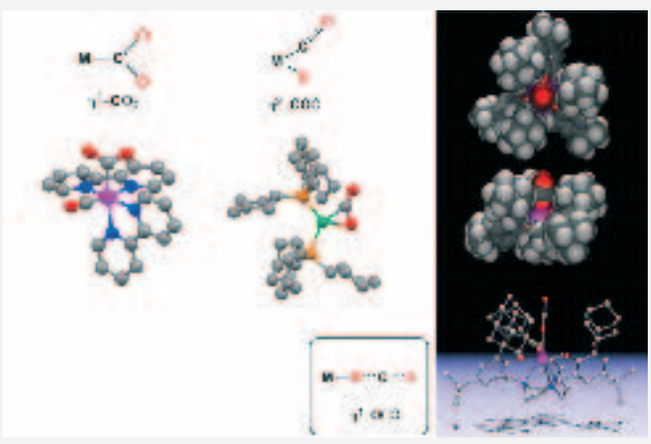


Figure 1: Coordination modes of carbon dioxide in transition metal complexes (left) and the previously unprecedented linear, O-coordinated h^1-CO_2 motif bound to uranium (right).

The most significant CO_2 activation process occurs naturally during photosynthesis. It was proposed that during photosynthetic CO_2-fixation, an oxygen-coordinated CO_2 ligand (η^1-**O**CO) is enzymatically reduced by ribulose bisphosphate carboxylase/oxygenase (*rubisco)*. Oxygen-coordination appears to be an indispensable step for C-functionalization in this system. However, definitive structural characterization of inorganic coordination complexes with a linear oxygen-bound η^1-**O**CO coordination mode has remained elusive. Recently, our laboratory has isolated and structurally characterized a synthetic uranium complex that binds and activates CO_2 in the previously unknown η^1-O-bound form (Figure 1). In this new complex, sterically encumbering adamantane groups enforce the unusual coordination mode. From bond lengths, magnetization data, vibrational, as well as X-ray and UV/vis/NIR electronic absorption spectroscopy we concluded that upon CO_2 binding, the electron-rich U(III) ion is oxidized to U(IV) and CO_2 is reduced (activated) by one electron. The study of this and related transition metal complexes that bind, reduce, and -most importantly - help functionalize CO_2 may someday lead to the development of simple compounds that can convert excess CO_2 into useful chemicals.

Electron-Rich Metal Complexes of Tripodal N-Heterocyclic Carbene Ligands[8-10]

Compounds containing divalent carbon centers have sparked the interest of organic, inorganic, and theoretical chemists like no other single class of molecules in chemistry. This is probably due to their fascinating molecular and electronic structures, challenging syntheses, and versatile properties. The study of carbene compounds has proven to be rewarding for material scientists as well as preparative chemists and has resulted in promising materials, such as single molecule magnets, liquid crystals, and a new generation of catalysts for organic synthesis. The latter is especially true for metal complexes of imidazol-2-ylidenes. These N-heterocyclic carbenes (NHCs) are important ligands in organometallic chemistry. Chelating NHC ligands reportedly yield especially stable complexes, and thus, have many advantages over conventional catalysts. Much of our research focuses on the synthesis and coordination chemistry of polydentate percarbene ligands anchored to either a tri-functionalized arene moiety (Figure 2, bottom) or

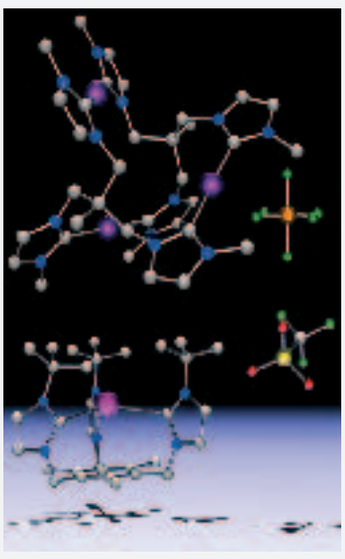


Figure 2: D_3 symmetrical trinuclear group 11 complexes of a C-anchored tris-carbene ligand provided insights into the nature of the metal-carbene bond (top) and a mononuclear thallium species as a ligand-transfer reagent for a mesitylene-anchored tris-carbene chelator (bottom).

single atoms such as the non-coordinating carbon (Figure 2, top). These previously unknown tripodal N-heterocyclic carbene ligand systems with a carbon anchor provide access to synthetic routes for the isolation of a new generation of potentially catalytically active metal-carbene complexes.

Traditionally, NHC ligands are almost exclusively referred to as pure sigma-donors when coordinated to metal ions. Only few theoretical studies on transition metal NHC complexes have been reported. In some cases, the existence of metal-to-ligand π-backbonding was suggested but the magnitudes of such interactions were reported to be minimal. We computed the electronic structure of our newly synthesized, highly symmetrical group 11 carbene complexes. Interestingly, the careful analysis of the molecular orbitals reveals remarkable and significant π-backbonding features in the carbene-metal-carbene entities, and we can now conclude that the $R_2C \leftarrow ML_n$ π backdonation in complexes with N-heterocyclic carbenes is not substantially lesser than in classical Fischer carbene complexes. It is this electronic flexibility of the NHCs that allows us to synthesize complexes, in which the NHC ligands stabilize not only moderate to high oxidation states (via σ-donation) but also very electron-rich, and thus, exceedingly reactive metal complexes (stabilized via π-backbonding).

Accordingly, we shifted our synthetic focus to mononuclear transition metal complexes of a sterically encumbering tripodal carbene ligand with an anchoring and stabilizing nitrogen atom (Figure 3).

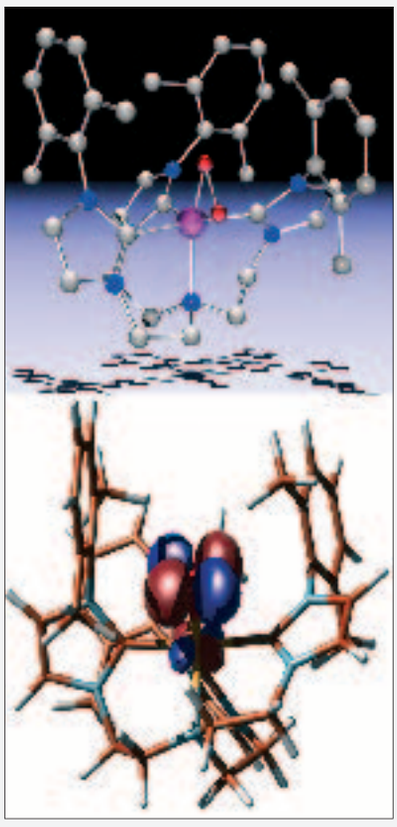


Figure 3: High-valent cobalt complexes with activated dioxygen ligands react with electron-deficient substrates to transfer the oxygen atom (top). DFT studies show that the HOMO in these complexes is an almost pure O_2 π*-orbital (bottom).

Mononuclear transition metal tris-carbene complexes were synthesized by employing aryl-derivatized, N-anchored tripodal NHC ligand with low-valent iron, cobalt, nickel and copper precursors. Electron-rich and coordinatively unsaturated Co(I) compounds of this ligand activate, for instance, dioxygen and organic azides, yielding reactive Co(III) (d^6 low-spin) species. Single-crystal X-ray diffraction studies revealed a remarkably flexible tris-carbene chelator of the distorted octahedral and tetrahedral Co(III) peroxo and imido compounds. In $[(\mathbf{L2})Co(\eta^2\text{-}O_2)]^+$ (Figure 3, top) the Co ion is six-coordinate with the tripodal ligand acting as a tetradentate chelator. The dioxygen ligand is strongly activated (d_{O-O} = 1.43 Å *vs* 1.207 Å in free O_2) and binds to the Co ion side-on (η^2). DFT studies show that the HOMO is an almost pure O_2 π* orbital (Figure 3, bottom), suggesting that the O_2^{2-} ligand reacts as a nucleophile. Accordingly, this peroxo species reacts with electron-deficient organic substrates, such as benzoyl chloride, to transfer the oxygen atom.
Complexes of these ligands with the bio-relevant iron ion show particular interesting reactivities towards dioxygen binding, activation, and catalytic oxygen atom transfer chemistry. Hence, the coordination chemistry of the tris(carbene) iron and closely related systems remain a central topic of our research.

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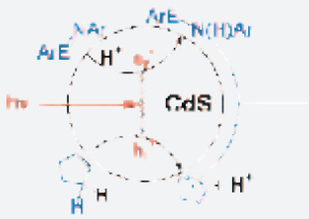
Prof. Dr. Horst Kisch

Semiconductor Photocatalysis
for Redox Utilization of Visible Light



Simple inorganic sulfidic and oxidic semiconductor powders, both modified and unmodified, are employed as efficient photocatalysts for the chemical utilization of visible light. When modified, they are active even in diffuse indoor daylight enabling degradation of air pollutants. These heterogeneous photoredox catalysts allow the electron transfer activation of oxygen and nitrogen in air and of various unsaturated organic compounds. In all these processes the semiconductor surface performs at least four key roles. It furnishes appropriate substrate adsorption sites, it promotes an efficient visible light induced charge separation, it enables an interfacial electron exchange with the substrates, and finally it supports a selective transformation of the primary redox intermediates to the stable end products. This feature resembles the working principles of photosynthesis by green plants and reveals the interdisciplinary character of semiconductor photocatalysis as a combination of photochemistry with physics, electrochemistry, and thermal heterogeneous catalysis.

Einfache sulfidische und oxidische Halbleiterpulver sind effiziente Photokatalysatoren für die chemische Nutzung von sichtbarem Licht. In modifiziertem Zustand besitzen sie selbst im schwachen, diffusen Tageslicht von Innenräumen noch genügende katalytische Aktivität, um Luftschadstoffe abzubauen. Einige dieser heterogenen Photoredoxkatalysatoren ermöglichen zudem die Elektronentransferaktivierung von Luftsauerstoff, Luftstickstoff und diverser ungesättigter organischer Verbindungen. Dabei erfüllt die Hableiteroberfläche vier Schlüsselfunktionen. Sie stellt geeignete Adsorptionsplätze zur Verfügung, ermöglicht eine effiziente lichtinduzierte Ladungstrennung, erlaubt den interfazialen Elektronenaustausch mit den Substraten und gestattet letztendlich die selektive Umwandlung der primären Redoxprodukte in stabile Endprodukte. Diese Funktionen gleichen den Prinzipien der Photosynthese grüner Pflanzen und spiegeln den interdisziplinären Charakter der Halbleiterphotokatalyse wieder, die sich im Spannungsfeld zwischen Photochemie, Physik, Elektrochemie und thermischer heterogener Katalyse bewegt.

In daily life semiconductors play a dominating role, often unnoticed even by the scientific community. From computers, mobile phones, and solar cells up to many other technical systems semiconductors execute key functions, which originate in their specific electronic structure. This opens novel applications not only in physics but also in chemistry, especially in the field of chemical solar energy conversion, wherein semiconductors enable efficient light-induced generation and separation of charges. This effect is of basic importance both in photovoltaics and photocatalysis. Whereas the former field since many years comprises an applied key technology, semiconductor photocatalysis of chemical reactions is just in the state of moving from basic to applied science[1]. An important advantage over homogeneous systems is the fact that the light-generated charges (Fig.1, processes 1 and 2) do not predominantly undergo radiative and nonradiative recombination (Fig.1, processes 4 and 5) but rather experience electron-exchange reactions (with donor and acceptor substrates; Fig.1, processes 3).

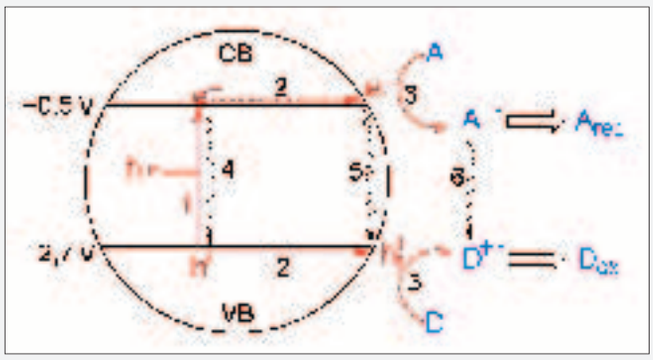


Figure 1: Schematic view of UV light driven photocatalysis at titanium dioxide. The circle symbolizes a particle, the two horizontal lines represent the upper and lower edge of the valence and conduction band, respectively.

In a few cases it could be proven that emissive (e^-, h^+) and reactive (e_r^-, h_r^+) states are different. The primary redox products $A^{-\bullet}$ and $D^{+\bullet}$ are converted into a reduced and oxidized end product. Therefore this heterogeneous system can be viewed as a functional model of photosynthesis with the important difference that in the natural system the sunlight-generated charges eventually reduce carbon dioxide and oxidize water. In our re-

search group we use visible light semiconductor photocatalysis as an efficient method for light-induced charge generation and apply it for daylight driven photooxidation, electron transfer induced organic addition reactions, and nitrogen fixation.[2)]

Photooxidation

It is well known that titania (TiO_2) upon irradiation with UV light is able to completely oxidize many organic and inorganic compounds. In the presence of air the reactive electron reduces oxygen to superoxide which through several steps is transformed to the strongly oxidizing OH radical. The latter, together with the reactive hole, oxidizes pollutants like phenols to carbon dioxide and water. Thus only air, UV-light and catalytic amounts of titania are necessary for complete removal of the pollutant. However, due to its large bandgap of 3.2 eV (390 nm) titania absorbs only about 3% of solar light. In order to utilize also the larger, visible part of solar light (λ = 400 - 700 nm), intensive research efforts are made presently to shift the photocatalytic activity of titania to this wavelength region.
In a coordination chemistry based effort we have developed a chloroplatinate(IV) complex containing titania as a ligand (Fig.2).[3)] This *n*-type semiconductor is a very efficient photocatalyst inducing complete photooxidation of various pollutants even by very weak diffuse indoor daylight (1-2 Wm^{-2} in the range of 400 – 1200 nm) Furthermore, the quasi-Fermi level can be continuously shifted more anodically upon increasing the platinum loading. Thus, a maximum shift of 0.3 eV is observed for the material loaded with 4wt%.

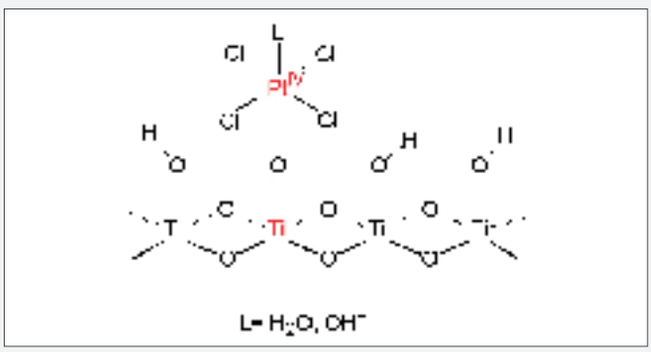


Figure 2: Simplified titania-chloroplatinate structure.

As mechanism of the photooxidation it was proposed that visible light excitation leads to homolytic Pt-Cl bond cleavage affording a Pt(III) center and an adsorbed chlorine atom. The former injects an electron to the titania conduction band, from where it reduces oxygen, whereas the latter oxidizes the pollutant. As a result Pt(IV) and chloride ligand are reformed. It is likely that a strong electronic interaction between the platinum center and titania favors electron injection over back electron transfer between Pt(III) and the adsorbed chlorine atom. This semiconducting heterogeneous titania coordination complex is one of the most efficient photocatalysts for the complete oxidation of air and water pollutants. It even mineralizes atrazine whereas all other advanced oxidation processes end up with cyanuric acid.

In a more solid state physics inspired effort nitrogen- and carbon-doped titania powders were prepared which also exhibit daylight photocatalysis.[4)] In addition to the steep onset of the titania-based band-to-band absorption at about 400 nm, these materials show a moderate preabsorption extending to 600 nm. Experimental evidence from wavelength dependent photooxidation reactions indicates that this novel absorption is connected with the presence of dopant-centered surface states located close to the valence band edge (Fig. 3).

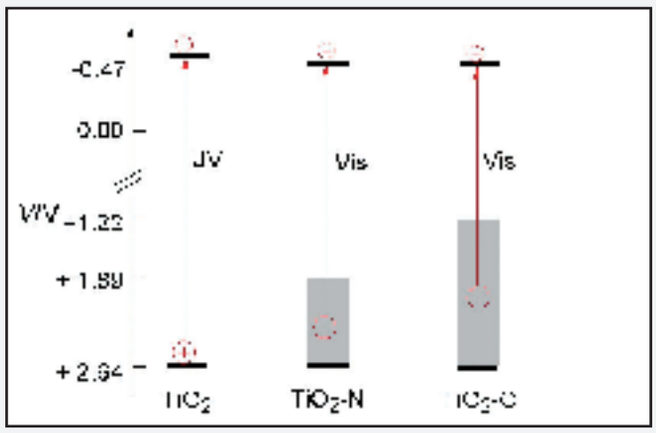


Figure 3: Band edge (bold lines) and surface state (shaded areas) positions (rel. to NHE) of undoped and carbon- and nitrogen-doped titania at pH 7.

These semiconductor powders may be easily prepared on a large scale, and since they are also active in diffuse indoor light they offer various applications in *green* environmental cleaning. It is noted that under comparable illumination conditions unmodified titania is inactive.

Organic Synthesis

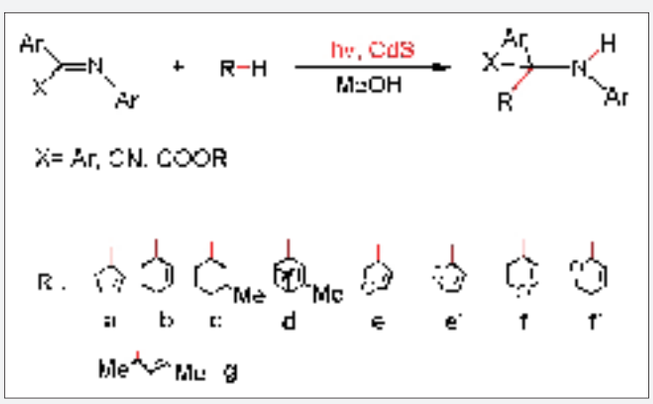


Figure 4: CdS photocatalyzed synthesis of homoallylamines.

In addition to the application of this efficient heterogeneous charge separation in photooxidation reactions, it can be utilized also for novel organic syntheses.[5)] In this case sulfidic semiconductors proved to be most active. Whereas zinc sulfide photocatalyzes a UV light induced dehydrodimerization of cyclic allyl/enol ethers, cadmium sulfide enables a visible light driven linear addition of olefins to 1,2-diazenes and imines affording novel allylhydrazines and homoallylamines, respectively (Fig. 4). These products are versatile intermediates for organic synthesis of biological active nitrogen compounds. This atom economic reaction affords novel fine chemicals in isolated yields of 40 – 80% and is a good example for the synthetic potential of semiconductor photocatalysis in the field of *green chemistry*. Solar light or cheap tungsten halogen lamps can be applied as light source and product isolation is simple since the catalyst is easily separated by filtration or centrifugation. Figure 5 summarizes the reaction mechanism of this unique addition reaction. According to this the interfacial redox reactions of the reactive

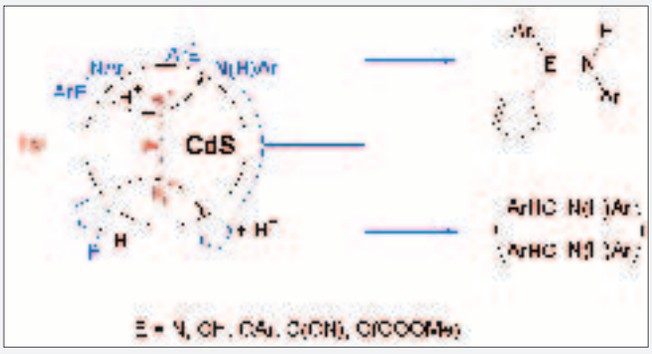


Figure 5: Mechanistic scheme of the CdS photocatalyzed addition of olefins to 1,2-diazenes and imines.

electron-hole pair afford intermediate radicals which preferentially undergo regioselective heterocoupling to the linear addition product, whereas homocoupling is observed only as a side reaction in the case of appropriate imine substitution pattern.
The *n*-type cadmium sulfide material employed in these reactions consists of micrometer sized aggregates composed of nanometer small cubic crystallites. Since isolated nanocrystals, as present in colloidal cadmium sulfide, are photocatalytically inactive, the efficient charge separation apparently is bound to the presence of the aggregate.[6)] A likely hypothesis is that intercrystallite majority carrier hopping results in charge compartmentation, thus preventing the undesired recombination which seems to predominate in the colloid due to the absence of another close crystallite.

In attempts to modify the photocatalytic activity of a semiconductor, *n*-type cadmium sulfide was supported onto silica. Only a covalent attachment induces a modest bandgap widening but a strong increase in its photocatalytic activity in these addition reactions. This originates in a longer lifetime of reactive electron-hole pairs.[7a,b)] In the case of TiO_2/SiO_2 the lifetime and activity are decreased, however.[7c)]

Nitrogen Fixation

Encouraged by some early observations that cadmium sulfide[8)] or iron-doped titania[9)] induce a photoreduction of dinitrogen to micromole amounts of ammonia, a systematic study of the titania-iron system was conducted. Preparation of thin film iron titanates of various Fe:Ti ratios by the sol-gel method indicated that a glass supported semiconducting film of the composition $Fe_2Ti_2O_7$ exhibited the best activity for ammonia formation in the presence of ethanol as reducing agent.[10)] Carbon monoxide reversibly inhibits the reaction and ammonia is oxidized by aerial oxygen to nitrate as the final product. A characteristic feature of the mechanism is the crucial first reduction step to the postulated diazene intermediate (Fig. 6). From the fact that ammonia is formed only if the film exhibits also a “photocurrent doubling” effect, it is assumed that out of the two electrons necessary for this step, one originates from electron injection by the strongly reducing intermediate hydroxyethyl radical.

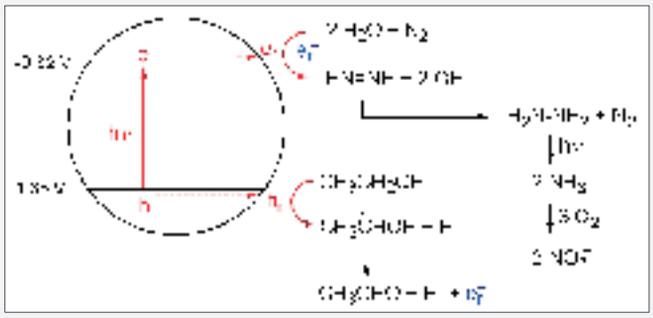


Figure 6: Mechanistic scheme of visible light photofixation of nitrogen at a nanosized iron titanate thin film.

The further reaction steps are supported by the known disproportion properties of 1,2-diazene and direct observation of intermediate hydrazine. Since ethanol can be replaced by the natural occurring reducing agent humic acid and since weathering of ilmenite may afford a corresponding photoactive surface[11)] this reaction may be a model for a *non-enzymatic* visible light induced nitrogen fixation, hitherto unknown in nature. It is known that such a reaction can occur also on rutile minerals upon UV excitation.[9b)] Geocatalytic reactions in general, irrespective if thermal or photochemical, are gaining increasing importance for the understanding of our ecosystem.[12)]

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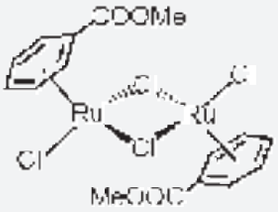
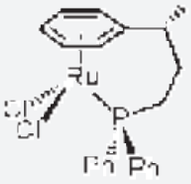
Arene Ruthenium Complexes: Selective Catalysts and Suitable Precursors for MOCVD Deposition of Thin Ruthenium Films





Arene ruthenium complexes have been established as an important class of catalytically active complexes. A general procedure is presented in this paper how to interconvert arene ruthenium complexes in the oxidation states 0 and 2+ without breaking the arene-ruthenium bond or racemization of chiral species. This allows to combine the preparative advantages of both redox states, ease of handling of Ru(II) species, for example, and the flexible ligand periphery substitution chemistry for Ru(0). Chiral (arene)Ru(II) species are catalytically active in highly enantioselective hydrogen transfer reactions, however, neither the turnover numbers TON, nor the turnover frequencies TOF are sufficient yet for commercial use.[1, 2] Our approach is based on stabilization of the catalytically active species through an additional σ-donor group of a side chain in a suitable distance to the arene ligand. This way tethered complexes are formed. If a phosphorus atom is playing the role of the σ-donor center, the reactivity of the catalyst is enhanced with respect to the established catalysts with only N- or O-σ-donor ligands.

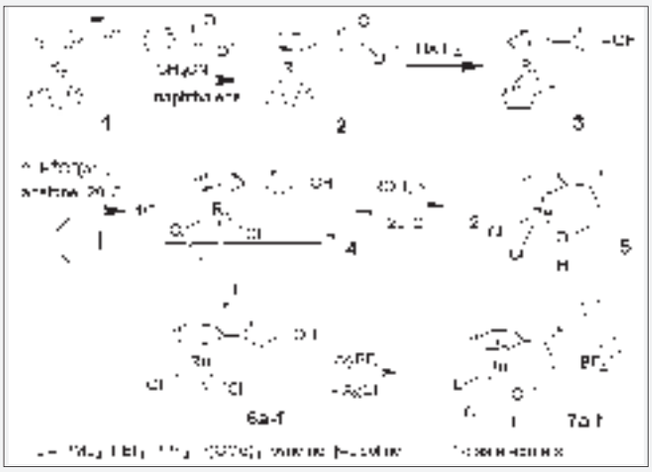
[(Arene)(diene)Ru(0)] complexes exhibit a good vapor pressure at temperatures around 100°C without decomposition. They are thus qualified as chemical vapor deposition (CVD) precursors for thin ruthenium films. Both allow reducing the CVD temperature for ruthenium film formation to 200°C or even below and may be used with precious substrates like silicon wafers with a minimized risk of damage.

Introduction

Catalytic enantioselective hydrogenation reactions of unsaturated organic molecules are a highly actual interdisciplinary research topic, as they lead to big quantities of enantiopure compounds with the help of only traces of chiral complexes. Many useful systems are already known including commercial processes, however, the chemo- and enantioselective transfer hydrogenation of the carbonyl function of enones and related compounds is still of specific interest, as it leaves C=C double bonds of the starting compounds entirely intact. Unsaturated chiral alcohols are formed by that procedure under mild and safe working conditions and many biologically active molecules belong to the class of compounds. R. Noyori found the first enantioselective catalyst for that purpose: *in situ* formed (arene)Ru(II) complexes with chiral β-diamine or β-amino alcohol co-ligands.[1] Several research groups adopted this approach, however, comparable high enantioselectivities have been obtained to date only with such (arene)Ru catalysts, which are based on exactly the same type of chiral N,N or N,O co-ligands.[2] In contrast to that, we believe that significant changes are required for the stabilization of the (arene)Ru moiety for example, to grant sufficient TON. A tether between the arene and one of the σ-donor ligands is useful in this sense, as it stabilizes such a catalyst kinetically by occupying four co-ordination places. We investigated OH, NH_2, and PR_2 groups of chiral arene side chains for that purpose. They co-ordinate to ruthenium and influence the chemical properties of the resulting complexes significantly through their σ-ligand characteristics.[3]

Tethered (arene)Ru complexes with OH or NH_2 donor functions

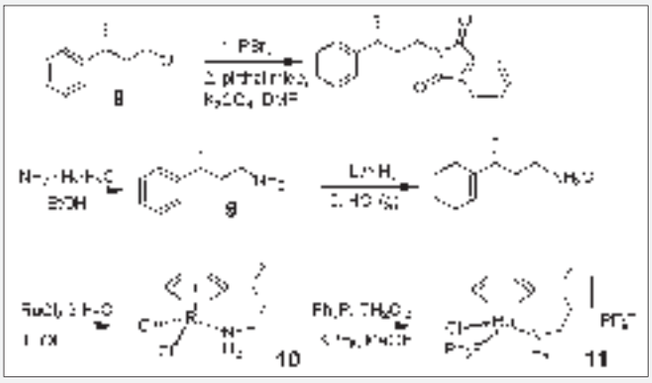
Our first synthetic approach on tethered (arene)Ru(II) complexes is based on (arene)Ru(0) complex **1**. We developed this chemistry by preparing species with chiral and functional side chains including alcohol functions.[4] Attempts to co-ordinate such an OH function in α- or β-position of the side chain to the Ru atom failed, irrespective of the oxidation state of the metal atom. So the tether had to be prolonged to a minimum of three carbon atoms between ring ligand and σ-donor center. This can be achieved by classical carbonyl chemistry at the respective (arene)Ru(0) complexes. Carbonyl functions can be introduced directly with the arene ligand if the substituent is not too bulky. Even an acidic N-H group can be tolerated at the same time, if it is shielded by substituents. [5] Enantiopure (*R*)-3-phenylmethylbutyrate complex **2** has been identified as a useful compound. It allows the reduction of its methyl ester functional group to form the target alcohol complex **3** without loss of optical activity and the Brønsted acidic OH group is situated in a proper distance to the ring ligand for an interaction with the ruthenium in the case of an electronic demand of the central metal. Oxidation of **3** by aqueous hydrochloric acid leads to the related Ru(II) complex dimer **4** and refluxing the dimer in alcohols like MeOH or EtOH leads to the tethered target species **5**. All steps work with good chemical yield and without any loss of optical activity.[6] (Scheme 1.)



Scheme 1.

Alternatively, dimer **4** can be split by P- or N-ligands to form mononuclear complexes **6a-f** which may be dehalogenated to yield the tethered, diastereomeric complex salts **7a-f**, respectively. In the last step, the metal atom forms a new stereocenter. The process is diastereoselective, (17 – 56% d.e.) however, this is not good enough for a potential enantioselective catalyst.[6]

(***R***)-3-phenylmethylbutyrate may be reduced directly to form chiral alcohol **8** and that leads to primary amine **9**. To bind **9** to Ru(II) in a direct way, it was reduced at the arene group and protonated to block the N lone pair. The reaction of the cyclohexadiene hydrochloride leads directly to the desired te-

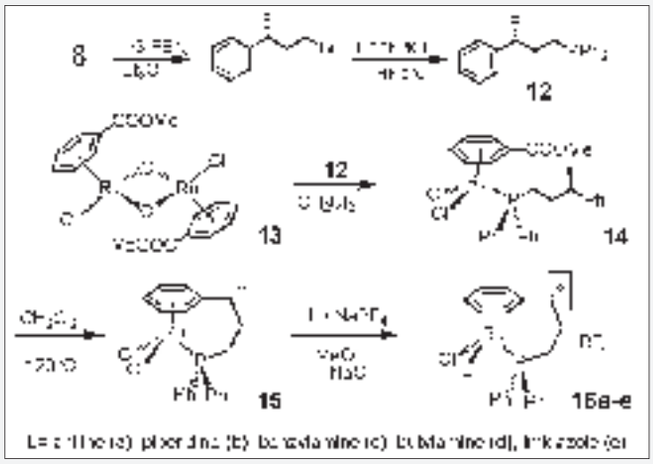


Scheme 2.

thered arene complex **10** through rearomatization of the ring and reduction Ru(III) → Ru(II). Dechlorination in the presence of PPh_3 does not need the assistance of a silver salt, but KPF_6 does the job to obtain salt **11** in reasonable 82% d.e. (Scheme 2.). Unluckily this is a kinetic value. If one reverses the introduction of PPh_3 and the tethering process, it is diminished to poor 12% d.e.. On the other hand, reactivity studies with salt **11** as a hydrogen transfer catalyst for the reduction acetophenone → phenylethanol disclosed a better reactivity then the Noyori catalysts, but poor e.e.[7]

Tethered (arene)Ru complexes with PR_2 donor functions

To maintain the activating influence of the PPh_3 ligand and introduce more restricting stereochemical conditions, PR_2 groups were regarded as the better choice for the σ-donor center of the arene side chain. One approach is based again on (*R*)-3-phenylmethylbutyrate. Alcohol **8** needs two steps only to lead to phosphine **12**, and another four for obtaining diastereomeric tethered complex salts **16**. (Scheme 3.)



Scheme 3.

As hoped for, **16a-d** are formed highly diastereoselective, (82 – 90% d.e.) only imidazole species **16e** dropped out of the series with its poor 14% d.e.. Both stereocentres of salts **16a-d** are configurationally stable over weeks or at slightly elevated temperatures.[8]

Reactivity studies with salts **16** as a hydrogen transfer catalyst for the reduction acetophenone → phenylethanol proved the designed good reactivity for the P,N σ-ligand combination even at room temperature. The process is enantioselective for **16a**, but still far away from practical use (22 – 25% e.e., depending on the conditions).

Modifications of salts **16** by replacing the PPh_2 unit by chiral phosphetane rings,[9] $OPPh_2$ groups, or SR functions [10] are all diastereoselective, however, the stereochemical properties of these classes of compounds are highly complex. As a consequence, no clear trends can be formulated in the moment for structure-property relations of the catalysts. This is part of our present research activities.

[(Arene)(diene)Ru] Complexes as MOCVD Precursors.

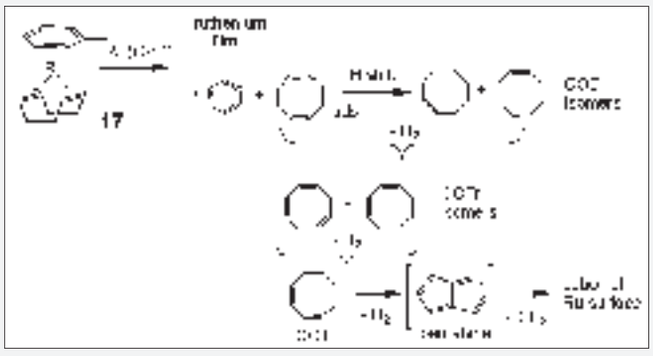
Thin metallic layers for surface protection or functional applications in microprocessors should be mechanically robust and indifferent to air and moisture for long periods even at elevated temperatures. The resistivity of conducting contacts,

for example, must not leave the range of tolerance which is required to grant the function of the unit. Ruthenium is a metal which can match these requirements. The conductivity of ruthenium dioxide is an extra advantage, as it maintains at least part of the electrical properties even in case of surface oxidation. This makes thin ruthenium films specifically attractive as electrodes in capacitors for memory chips. [11] The trend to miniaturize microelectronic devices requires highly reliable and precisely located formation processes of pure films. Thermal stress of the substrate should be minimized when it is covered with the film to create the device, as that could cause mechanical problems and diffusion processes. Several ruthenium compounds have been investigated as MOCVD precursors but an optimal Ru MOCVD-precursor has not been found yet. It is our aim to design Ru complexes as MOCVD precursors for the deposition of thin films close to or below 200°C for granting the function of precious substrates like integrated circuits, for example. π-Complexes of the general type [(arene)(diene)Ru] have suitable decomposition properties. Some results on [(1,5-COD)(toluene)Ru] **17** and [(benzene)(1,3-CHD)Ru] **18** are here presented.[12] **18** has been investigated independently from us by a Korean team, as well.[13]

MOCVD preparation of thin ruthenium films

The ruthenium films were deposited by thermolysis of **17** and **18**, respectively, in a He carrier gas atmosphere on ceramic, copper, and silicon wafer substrates. Parameters such as substrate temperature, total pressure, and mean residence time have been subject of systematic variations. Gas chromatography in combination with mass spectroscopy (GC-MS) was utilized to determine the composition of the exhaust gas and learn what has happened to the ligands through the CVD process. Examples for the CVD coating experiments of copper blocks are depicted in Fig. 1. and the coating of silicon wafers in Fig. 2.

Both precursors fulfilled our definitions as ambient temperature MOCVD precursors, as they give good results in our target temperature region around 200°C. The films are of good quality, however, some elemental carbon is always found as an impurity. In the case of precursor **17** we were able to identify catalytic C-H and C-C ruthenium surface activation processes of the diene ligand as the dominant source for carbon incorporation into the films.[12] (Scheme 4.)



Scheme 4. Ruthenium surface transformation of 1,5-cyclooctadiene under MOCVD conditions.

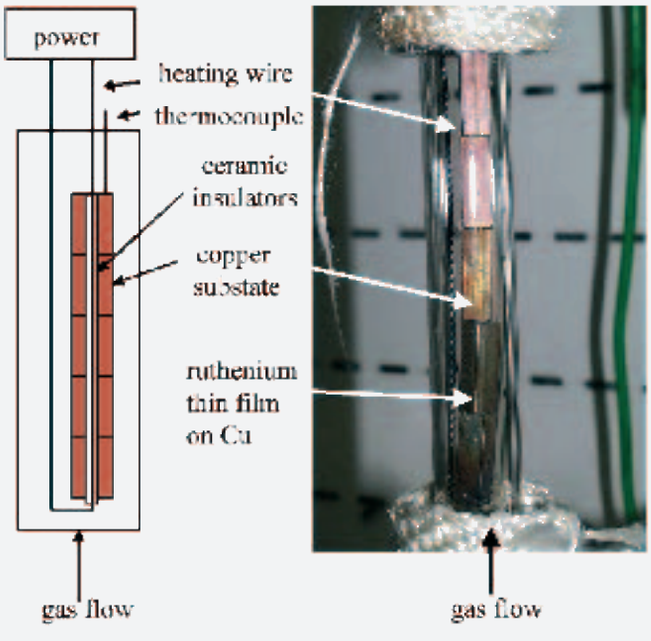


Figure 1. Coating of Cu-blocks by MOCVD with 17 as precursor.

Acknowledgements

Financial support of the projects by the Deutsche Forschungsgemeinschaft (SFB 583, GRK 312, SPP 1119) is gratefully acknowledged.

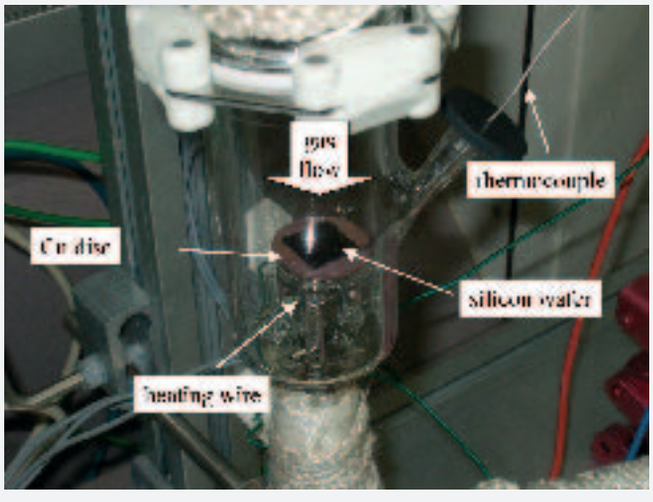


Figure 2. Coating of Si-wafer by MOCVD with 18 as precursor.

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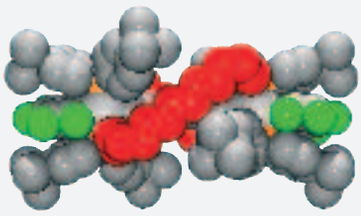
Prof. Dr. John Gladysz

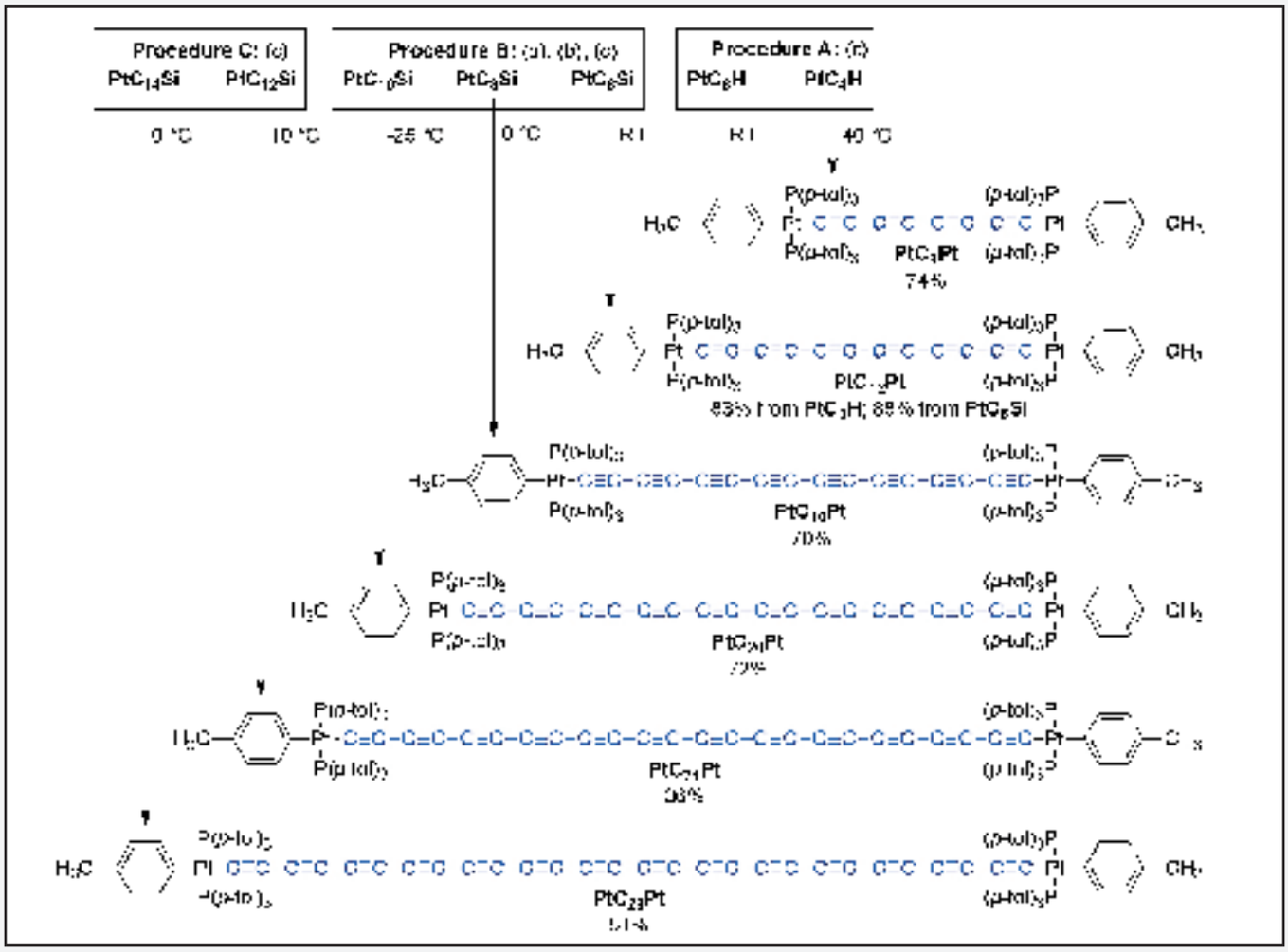
Frontiers in Organometallic Redox-Chemistry



The Gladysz group has garnered many honors in the field of organometallic chemistry. Interests further extend into catalysis, organic synthesis, enantioselective reactions, stereochemistry, mechanism, and materials chemistry.

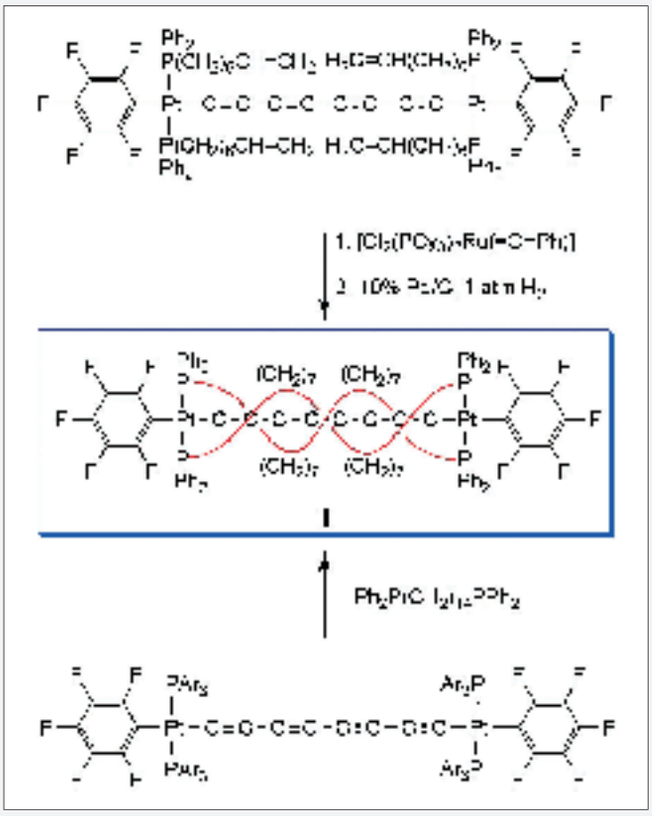
Die Arbeitsgruppe Gladysz hat viele Ehrungen auf dem Gebiet der organometallischen Chemie gesammelt. Weitere Forschungsinteressen gehen in Richtung Katalyse, organische Synthese, enantioselektive Reaktionen, Stereochemie, Mechanismen und Materialchemie.

Research in the Gladysz group has traditionally been centered around organometallic chemistry, and from this core area branches into catalysis, organic synthesis, enantioselective reactions, stereochemistry, mechanism, and materials chemistry. Currently, about half of the group is involved with catalysis projects, divided 50:50 between structurally novel enantioselective catalysts and highly fluorinated recoverable catalyst systems. The other half designs organometallic building blocks for the synthesis of molecular wires, compasses, and gyroscopes.



Scheme 1. Synthesis of Diplatinum Polyynediyl Complexes with Even Numbers of C≡C Bonds: (a) wet n-Bu_4N^+ F^-/Acetone; (b) $ClSiMe_3$; (c) cat. CuCl/TMEDA, O_2, Acetone.

One active area involves complexes in which wire-like sp-carbon chains span two transition metals. There is the obvious question of how long a polyalkyne or $(C{\equiv}C)_n$ bridge can be synthesized. As shown in Scheme 1, PtC_xPt complexes with as many as twenty-eight carbons are easily isolated – shattering the record for polyynes previously held by carbon or silicon endgroups.[1] Because of the metal termini, all such species are redox-active. This in turns raises the possibility of a variety of charge-transfer phenomena involving the metal termini. In order to help stabilize certain charged redox states, we have sought to „insulate“ the sp-carbon chains. The two approaches in Scheme 2 yield novel double-helical diplatinum complexes of the type I, in which sp^3-carbon chains coil around the sp carbon chain.[2] Such compounds are now being tested as „molecular wires“. Figure 1 illustrates the impressive degree of steric protection.



Scheme 2. Syntheses of Double-Helical Diplatinum Complexes

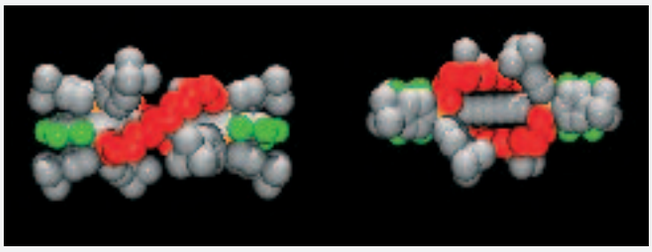


Figure 1. Space Filling Representation of a Typical Double-Helical Diplatinum Complex

In Scheme 2, it was a pleasant surprise that alkene metathesis could be applied within a metal coordination sphere. This led to the consideration of other possible uses. For example, gyroscopes have numerous technological applications, but until our work no molecules that mimic the symmetry, connectivity, and rotational abilities of common toy gyroscopes were known. In a synthetic tour-de-force, a three-fold alkene metathesis reaction was used as shown in Scheme 3 to access families of complexes with the structures III and IV.[3] Views of the crystal structure of III are supplied in Figure 2.

Scheme 3. Syntheses of gyroscope-like molecules.

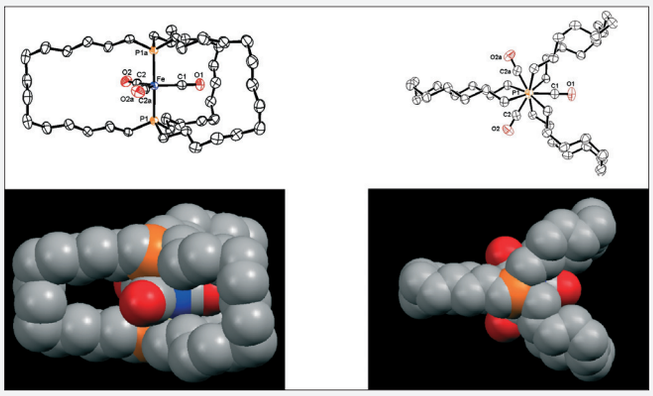
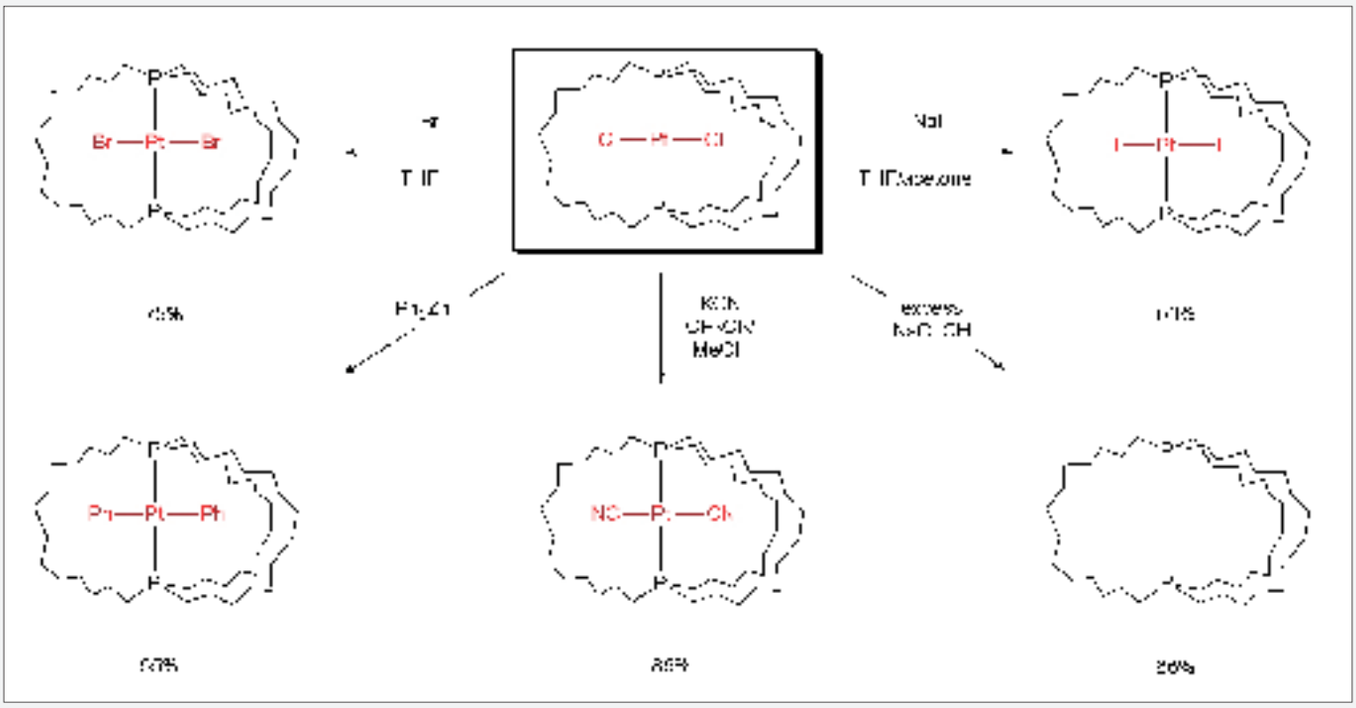


Figure 2. ORTEP (top) and space-filling (bottom) representations of the crystal structure of III (n = 6).

NMR measurements show that the $Fe(CO)_2(NO)$ moiety in IV rotates within the methylene cage at an effective rate of 1000000 rpm at room temperature. This work has been extended to other metals and rotating groups, as well as much larger cage sizes. Some recent results with a similarly-synthesized platinum gyroscope are illustrated in Scheme 4. In collaborations with physicists, possible nanotechnological applications are being probed.

In enantioselective catalysis, ferrocene-containing chiral ligands play a major role. We have sought to incorporate a wider range of „spectator“ metal fragments that feature unique architectural and electronic properties into donor ligands. Typical examples of ligands and/or their complexes are shown in Figure 3.[4] These have provided exceptionally effective rhodium and palladium catalysts for enantioselective hydrogenations, hydrosilylations, and related processes. Furthermore, the rhenium-containing phosphine VII has recently been shown to be an effective „organocatalyst“ for various transformations, two of which are depicted in Scheme 5.



Scheme 4. Reactions of a Platinum-Containing Gyroscope-like Molecule

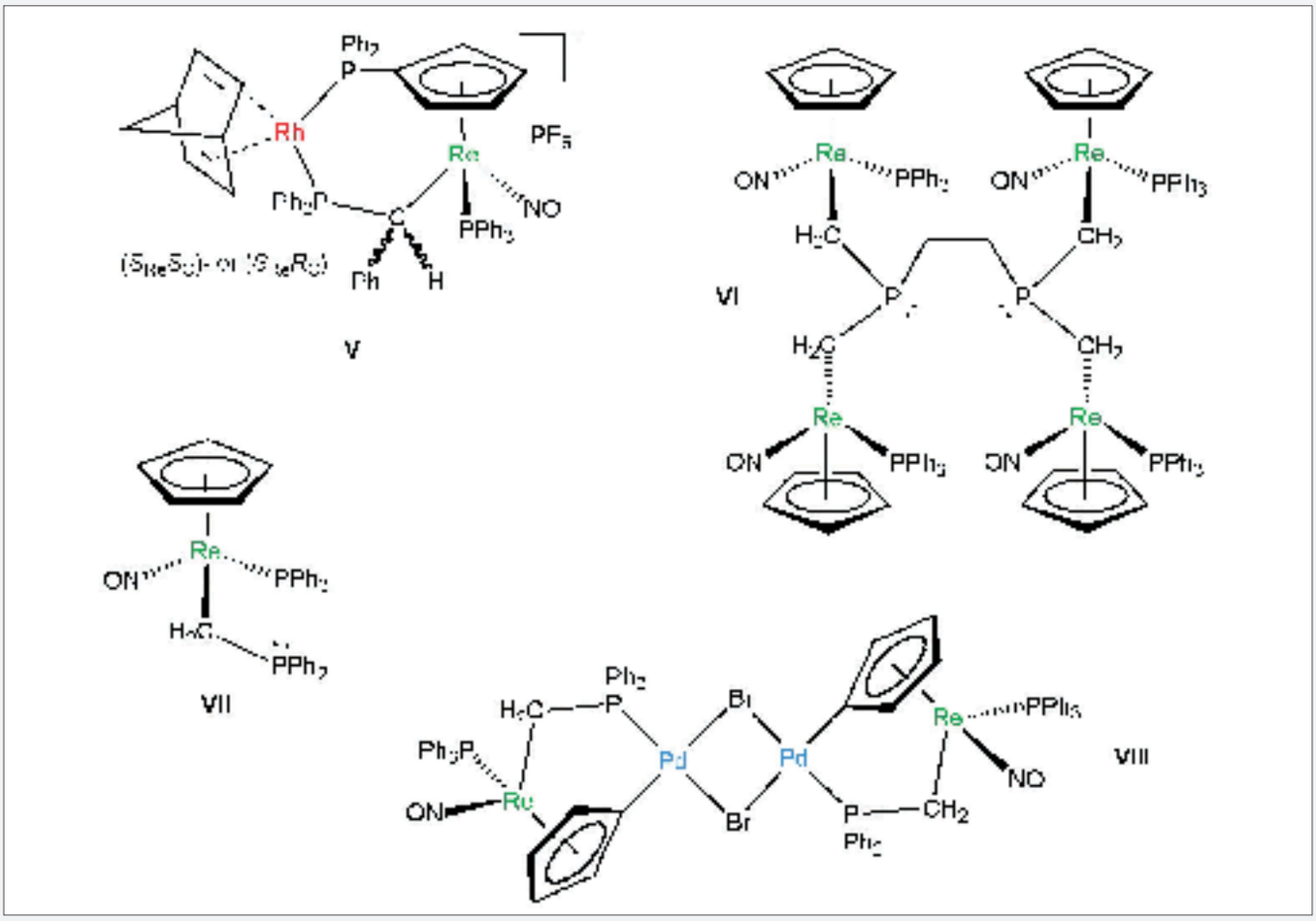
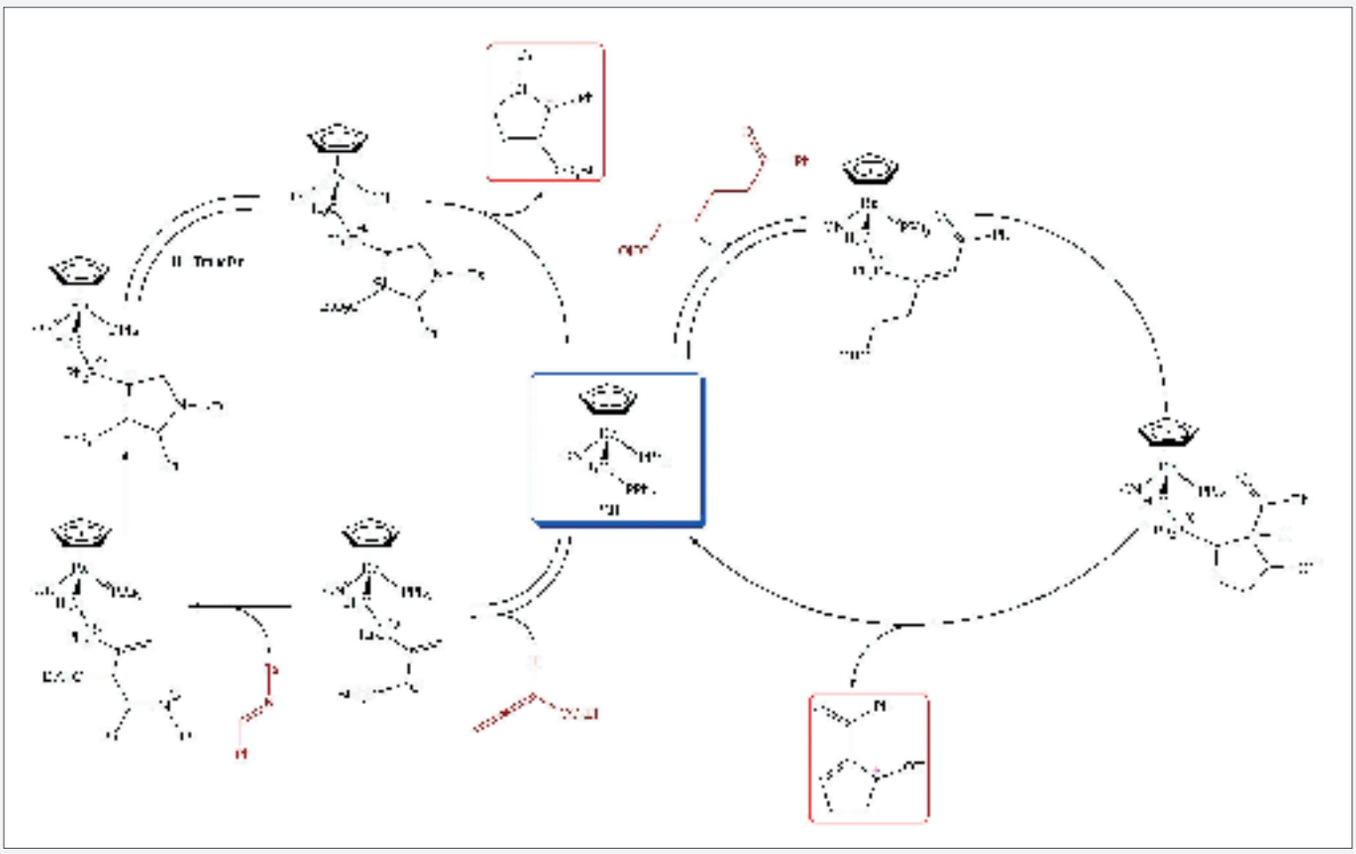
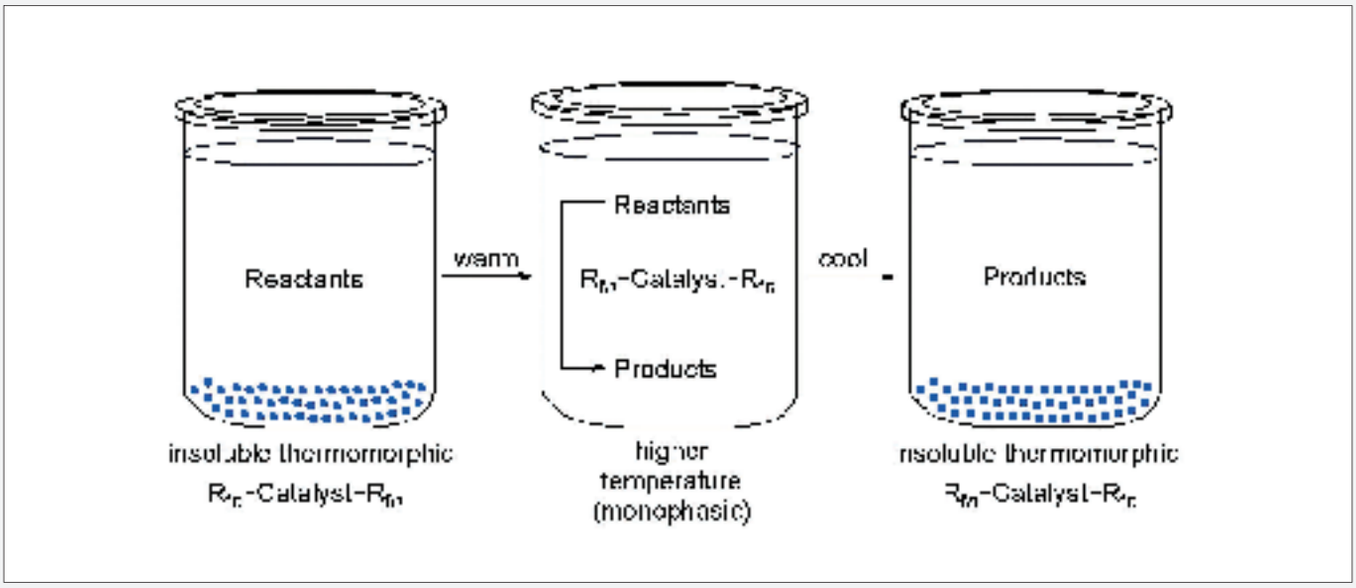


Figure 3. Ligands that contain a chiral rhenium fragment, and/or complexes there of.

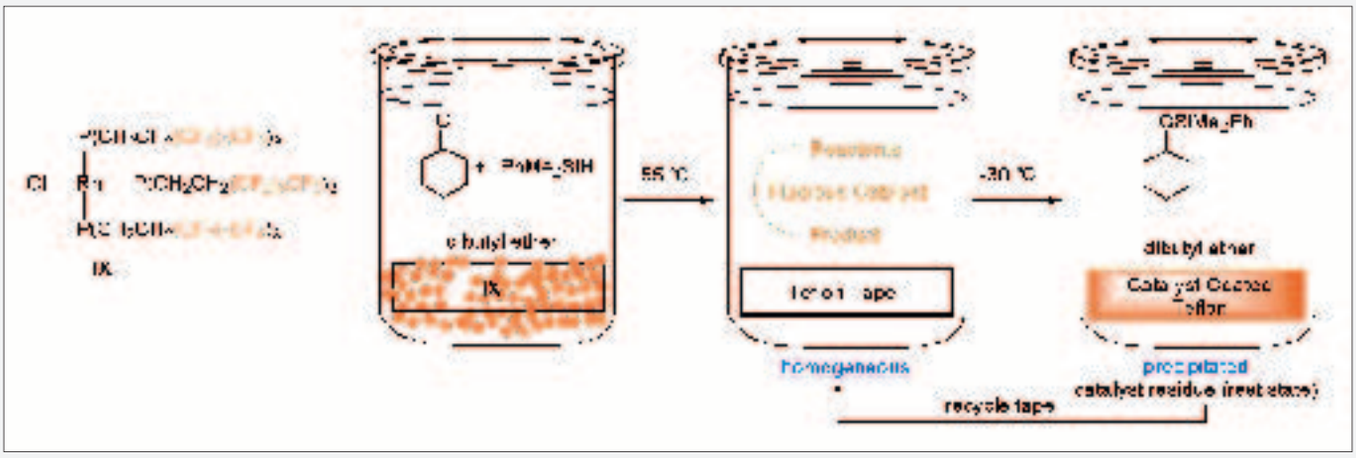


Scheme 5. Enantioselective Catalysis using Chiral, Rhenium-Containing Phosphines

Another area of current interest involves „fluorous“ chemistry. When sufficient numbers of „ponytails“ $(CH_2)_mR_{fn}$ ($R_{fn} = (CF_2)_{n-1}CF_3$) are added to catalysts or reagents, they acquire exceptional affinities for perfluoroalkanes and other fluorous phases. Furthermore, they also commonly exhibit highly temperature-dependent solubilities in organic solvents. As shown in Scheme 6, reactions can often be conducted under homogeneous conditions at elevated temperatures, and the catalyst recovered by a liquid/solid phase separation at lower temperature.



Scheme 6. Recovery of Fluorous Catalysts via Solid/Liquid Phase Separation.



Scheme 7. Recycling of a Thermomorphic Fluorous Rhodium Hydrosilylation Catalyst using Teflon® Tape.

For laboratory-scale reactions involving efficient catalysts, it is often only necessary to recover a few milligrams of material. To facilitate such separations, fluorous supports have been investigated. Of these, the most interesting proves to be common laboratory Teflon tape. In fact, the catalyst can even be precoated on the tape, allowing delivery to be controlled by length. As shown in Scheme 7, a rhodium complex containing fluorous phosphines (IX) desorbs at 55 °C in dibutyl ether, catalyzes the hydrosilylation of ketones, and reprecipitates onto the tape upon cooling.[5]

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Prof. Dr. Johann Gasteiger

Chemoinformatics in Organic Chemistry and Drug Design

The research group of Prof. Gasteiger has been instrumental in the last 30 years to establish the field of chemoinformatics in Germany (1,2). It has developed a variety of methods for the computer representation and manipulation of chemical structures and reactions. This laid the basis for the prediction of physical, chemical, or biological properties of chemical compounds by inductive learning methods. Applications have been developed in such diverse areas as drug design, structure elucidation, synthesis design, the analysis of biochemical pathways and the prediction of metabolism. Many of the methods have been laid down in widely used computer programs.

Die Forschungsgruppe von Prof. Gasteiger hat in den letzten 30 Jahren wesentlich zur Etablierung des Gebietes der Chemoinformatik in Deutschland beigetragen (1, 2). Es wurde eine Reihe von Methoden zur Computerverarbeitung chemischer Strukturen und Reaktionen entwickelt. Auf dieser Grundlage konnten dann physikalische, chemische und biologische Eigenschaften chemischer Verbindungen mit Hilfe induktiver Lernverfahren vorhergesagt werden. Anwendungen wurden für so verschiedene Bereiche wie Wirkstoffforschung, Strukturaufklärung, Syntheseplanung, Analyse biochemischer Reaktionspfade und Vorhersage des Metabolismus entwickelt. Viele der Methoden wurden in breit genutzten Computerprogrammen stabilisiert.

Structure Representation

A hierarchy of methods has been developed for the computer representation of chemical structures, from the constitution through 3D structures to molecular surfaces. Thus, the 3D structure generator CORINA generates a 3D molecular model from only information on the constitution of a molecule (Figure 1). CORINA has more than 120 installations worldwide.

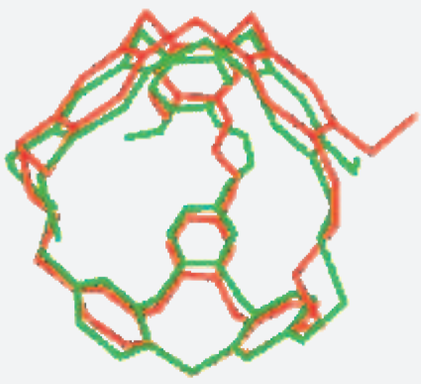

Figure 1. Comparison of a CORINA generated model with the corresponding X-ray structure.

Conformational flexibility is handled by the program ROTATE. Empirical methods for the rapid calculation of physicochemical effects in organic molecules such as charge distribution or inductive, resonance, or polarizability effects have been developed in order to treat large sets of molecules with millions of structures such as those handled in combinatorial chemistry or high-throughput screening. These physicochemical effects have been used for a more detailed structure representation (3).

The methods developed in the group also laid the foundation for the building of databases on chemical information such as the Beilstein database and the ChemInform reaction database of FIZ CHEMIE.

Property Prediction

Much work was directed to learning from chemical information, for establishing correlations between the chemical structure of a compound and its property, be it a physical, chemical, or biological property. Such relationships were established by inductive learning methods such as pattern recognition methods or artificial neural networks (4).

Spectra Simulation

Based on the structure representation methods that incorporated physicochemical effects, neural networks also allowed the prediction of spectra such as infrared, or ^{1}H NMR spectra (http://www2.chemie.uni-erlangen.de/services/telespec and http://www2.chemie.uni-erlangen.de/services/spinus).

Drug Design

Heavy emphasis was put onto developing chemoinformatics methods to be used in drug design such as for lead discovery, lead optimization, and the prediction of pharmacological properties.

The superimposition of several ligands binding to a receptor protein allows one to define the essential features needed for a compound to bind to that receptor and can thus be used for finding new lead structures (Figure 2).

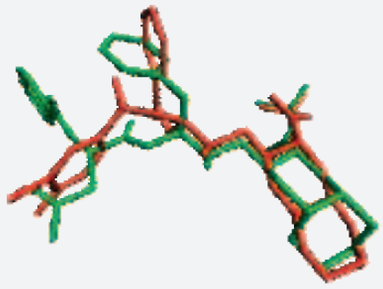

Figure 2 Superimposition of two HIV protease inhibitors

Figure 3. The development of a synthesis plan with the WODCA system

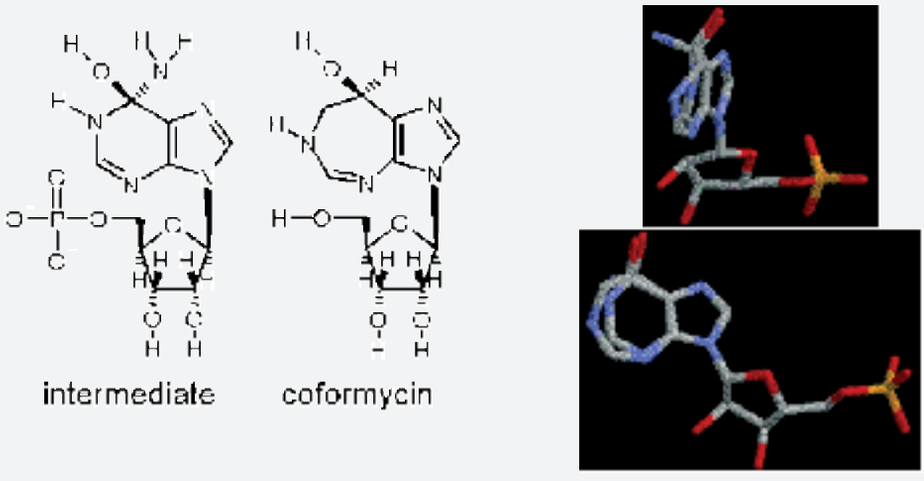

Figure 4. Superimposition of the intermediate of the reaction catalyzed by AMP deaminase (EC 3.5.4.6) with the inhibitor coformycin

Synthesis Design

The synthesis design system WODCA offers a variety of tools that allow the chemist to more efficiently plan the synthesis of organic compounds.

The user can disconnect a target molecule at strategic bonds to obtain molecules that can serve as precursors for the synthesis of the target structure. Similarity searches allow the user to find appropriate starting materials for these precursors. The retroreaction obtained in the disconnection approach can be verified by searches in a reaction database connected to the WODCA system. A graphical user interface allows the chemist to intuitively interact with the system (Figure 3).

Biochemical Pathways and Metabolism

Recent work is concerned with the analysis of biochemical reaction sequences. The Biochemical Pathways poster (Figure 3) has been converted into a structure and reaction database that can be searched according to a variety of criteria providing deeper insights into biochemical pathways (http://www2.chemie.uni-erlangen.de/services/biopath) (5).

The BioPath database can serve as a basis for furthering our understanding of enzyme catalyzed reactions. Intermediates of biochemical reactions extracted from this database can serve as models for finding inhibitors of these reactions (Figure 4).

Other work is concerned with the prediction of the metabolism of drugs by the different cytochrome P450 enzymes.

Acknowledgements

Much of our work was generously supported by the BMBF, DFG, VCI and several pharmaceutical companies. More details on our research can be found at http://www2.chemie.uni-erlangen.de. Some of our systems are further developed and marketed by Molecular Networks GmbH, a spin-off of the University Erlangen-Nuremberg (http://www.mol-net.de).

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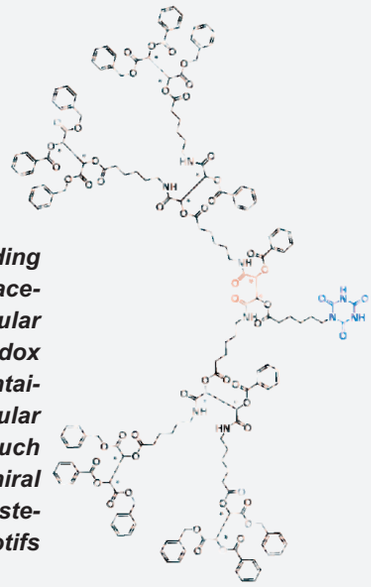
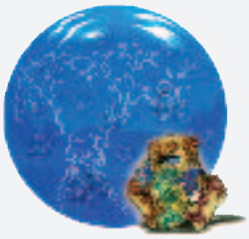
Prof. Dr. Andreas Hirsch

Development of New Molecular and Supramolecular Architectures



Our research is devoted to the design of new materials composed of various molecular building blocks such as fullerenes, carbon nanotubes, porphyrines, dendrimers, calixarenes and acetylene compounds. These functional units are linked by covalent bonds or via supramolecular organization. The aim is to generate structures, which, for example, represent models for redox proteins, enable a directed photo-induced electron- or energy transfer, can form micellar containers for the encapsulation of guest molecules, are useful for applications in the field of molecular electronics and serve as new redox active drugs. The basis for the successful realization of such complex architectures is a) the development of new synthesis concepts, for example, for chiral and amphiphilic building blocks as well as for derivatives of carbon rich molecules, b) the systematic investigation of the self-assembly of achiral and chiral supramolecular organization motifs and c) the calculation of molecular properties with quantum mechanical methods.



Wir beschäftigen uns mit der Konzeption von neuen Materialien, die wir aus der Kombination verschiedener molekularer Bausteine wie Fullerene, Kohlenstoffnanoröhren, Porphyrine, Dendrimere, Calixarene und Acetylenverbindungen aufbauen. Diese Funktionseinheiten werden gezielt durch kovalente Bindungen oder supramolekulare Organisation miteinander verknüpft. Dabei sind Zielstrukturen von Interesse, die zum Beispiel Modelle für Redoxenzyme darstellen, einen gerichteten photoinduzierten Elektronen- oder Energietransfer ermöglichen, neue mizellare Container für die Aufnahme von Gastmolekülen bilden können, für den Einsatz in der molekularen Elektronik geeignet sind oder als neue redoxaktive Wirkstoffe verwendet werden können. Das Fundament für die erfolgreiche Realisierung solch komplexer Architekturen bilden a) die Entwicklung neuer Synthesemethoden zum Beispiel für chirale und amphiphile Funktionseinheiten sowie für derivatisierte kohlenstoffreiche Moleküle, b) die systematische Erforschung des Selbstaufbaus achiraler und chiraler supramolekularer Überstrukturen, sowie c) die Berechnung von Moleküleigenschaften mit quantenmechanischen Methoden.

Fullerenes (Figure 1) and carbon nanotubes (Figure 2) represent new allotropes of carbon. They exhibit a variety of unprecedented properties. For example, the fullerene C_{60} is a good electron acceptor, it is able to host guest atoms in its interior and exhibits outstanding radical scavenging properties as well as conducting and magnetic properties after reduction.[1,2] Carbon nanotubes are either metallic or semiconducting depending on their structure and at the same time they exhibit an extreme mechanical robustness. Consequently, these new carbon allotropes are attractive building blocks for molecular electronics, composite materials, medicinal imaging and redox active drugs. In order to develop such applications it is very important to systematically investigate the chemical functionalization of fullerenes and carbon nanotubes.

Our group played a leading role in the development of fullerene chemistry from the very beginning. We have studied systematically the principles of fullerene reactivity and have presented a variety of methods that enable the regioselective functionalization of C_{60}.[3,4] These achievements allowed us to introduce the fullerenes as versatile building blocks for organic chemistry and for their use as highly functional archi-

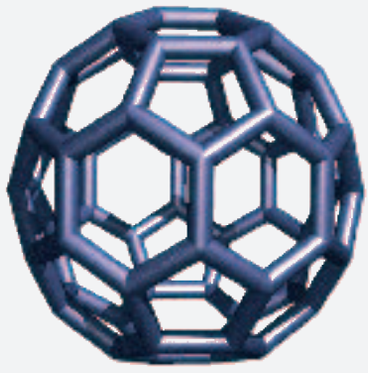


Figure 1: Fullerene C_{60}: Structure and Toluene Solution

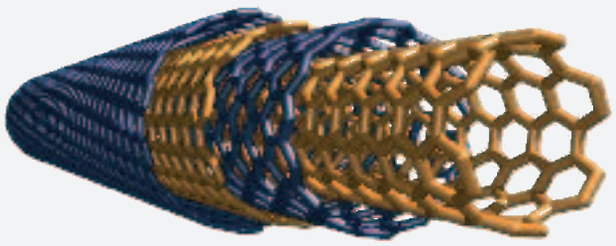


Figure 2: Carbon Nanotubes

tectures and new materials. In specifically designed fullerene-porphyrin-diads such as the system *trans-2*-CoTPP-C_{60} (Figure 3) photo-induced electron transfer between the porphyrin and the fullerene can occur.[5] In analogy to the primary events of photosynthesis or solar cell technology charge separated states are generated whose life times can be controlled by the specific structural variations of the architectures.[6] In the single crystal of *trans-2*-CoTPP-C_{60} coordination polymers are formed where the fullerens serves as an axial ligand for the CoTTP-unit both intra- amd intermolecularly.

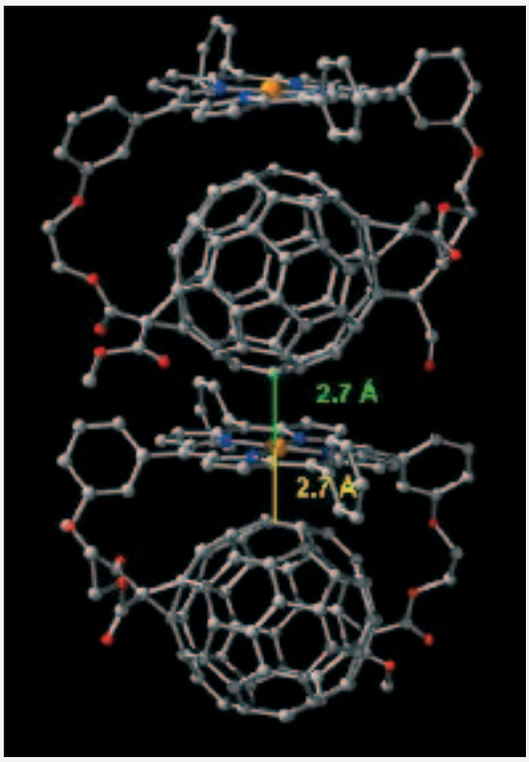


Figure 3: Fullerene-Porphyrin-Diad trans-2-CoTPP-C_{60}: Structure und Stacking Arrangement in the Crystal

Further attractive structure motifs that were made accessible by tailor designed addition chemistry are hexakisadducts of C_{60} involving an octahedral addition pattern. In analogy to octahedrally coordinated metal complexes a large variety of architectures with interesting combinations of properties can be made available.[7,8,9,10] Examples are superamphiphiles which form pH-switchable liposomes (buckysomes) in water, model systems for heme proteins and chiral dendrizymes (Figure 4), exhibiting a C_3-symmetrical, inherently chiral addition pattern.

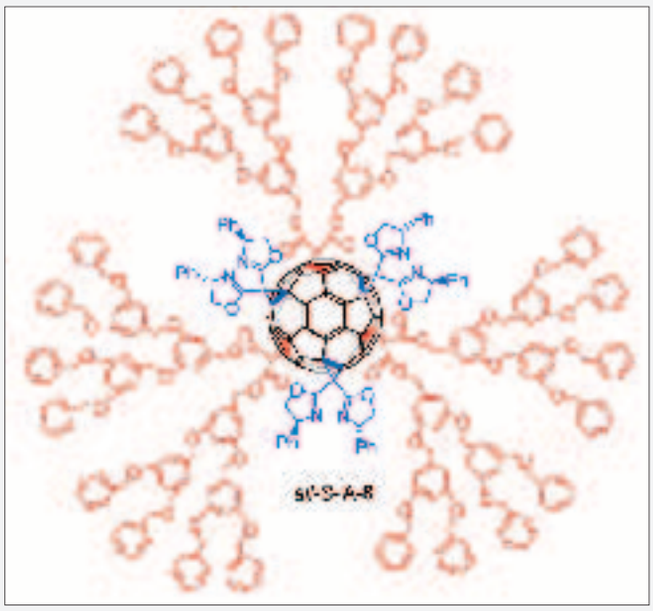


Figure 4: Chiral Fullerene based Dendrizyme

We have synthesized the cluster modified heterofullerene $C_{59}N$ by substitution of one C-atom of the fullerene core against nitrogen. This heterofullerene exists at the dimer $(C_{59}N)_2$.[11] Heterolysis and subsequent oxidation leads to the intermediate cation $C_{59}N^+$,[12] which serves as precursor for the highly regioselective synthesis of a large variety of derivatives $RC_{59}N$.[12] One example is the pyrene derivative shown in figure 5, which allows for the directed transduction of energy from the pyrene- to the fullerene moiety.

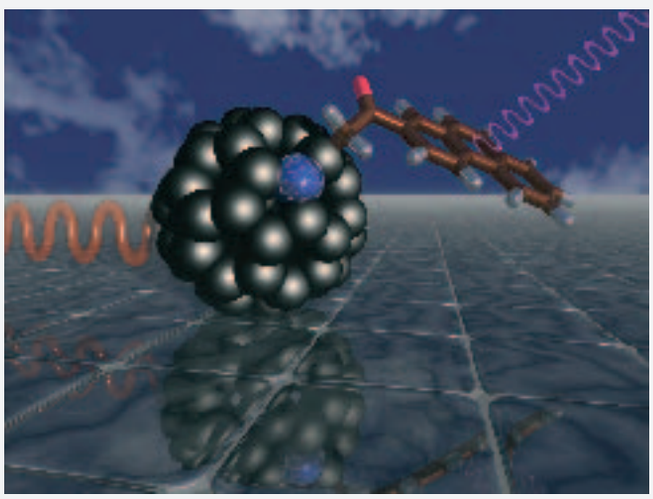


Figure 5: Energy Transduction in a Heterofullerene-Pyrene-Diad

For the establishment of a preparative chemistry of carbon nanotubes we have developed a couple of functionalization methods.[13,14] Next to the functionalization of already existing defects we have explored the addition of very reactive groups such as radicals, carbenes, nitrenes und carbanions to the side walls of the tubes. This allows us to generate soluble nanotubes derivatives (figure 6) and to provide the basis for the development of new materials, which, for example, are characterized by remarkable mechanical properties.

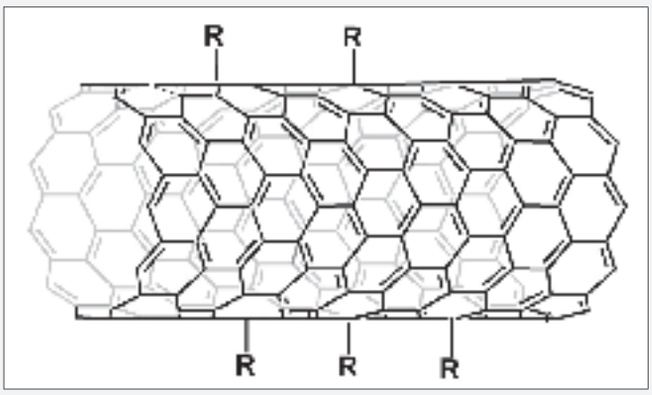


Figure 6: Sidewall Functionalized Carbon Nanotube

Another so far still hypothetical form of carbon is carbyne, which formally consists of infinite chains of sp-C-atoms. In order to predict the physical and chemical properties of this allotrope we have synthesized a series of model systems. Among these the dicyanooligoynes (Figure 7) that we have isolated for the first time exhibit the closed similarities with carbyne.[15] The stability of such oligoynes was improved by the introduction of bulky end-groups such as dendrimers. Analyis of the physical and spectroscopic data of such oligoynes leads to the prediction that carbyne is a colored, extreme unstable insulator whose C-atoms exhibit ^{13}C NMR-chemical shifts at 63 ppm.

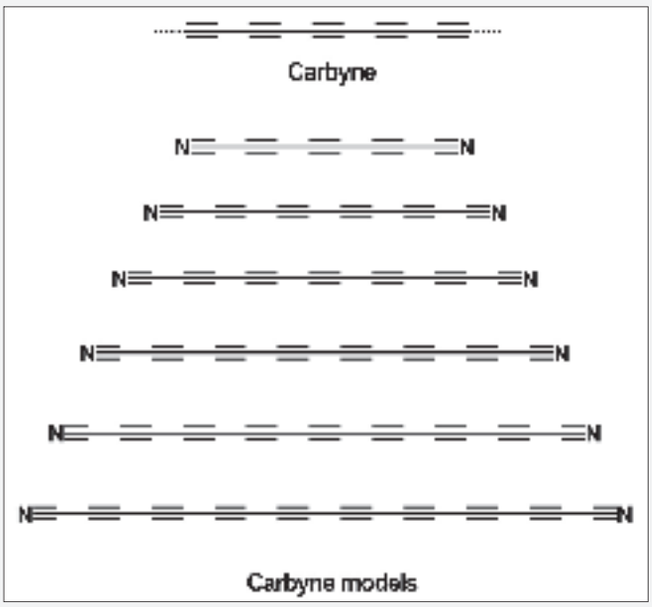


Figure 7: Hypothetical Carbon Allotrope Carbyne and Dicyanooligoynes as Model Systems

We have discovered the principle of spherical aromaticity of organic and inorganic cluster molecules. The aromatic character of such clusters depends of the occupation of the molecular orbitals with valence electrons. We have found the $2(N+1)^2$-rule for spherical aromaticity which represents the analogue of the 4N+2-Hückel-rule for cyclic systems.[16,17]

In order to simulate globular proteins we are investigating the synthesis and the supramolecular organization of dendrimers.[18] We have introduced a new type of chiral dendrimers consisting of amino acid- and tartaric acid building blocks. We have assembled these depsipeptide units with other building blocks to superstructures in a variety of ways and realized, for example, the metal induced folding of dendrimers and the self-assembly of chiral dendrimers. We were able to determine chirality transfer and pronounced cooperativity asociated by the stepwise complexation of depsipeptide cyanurates

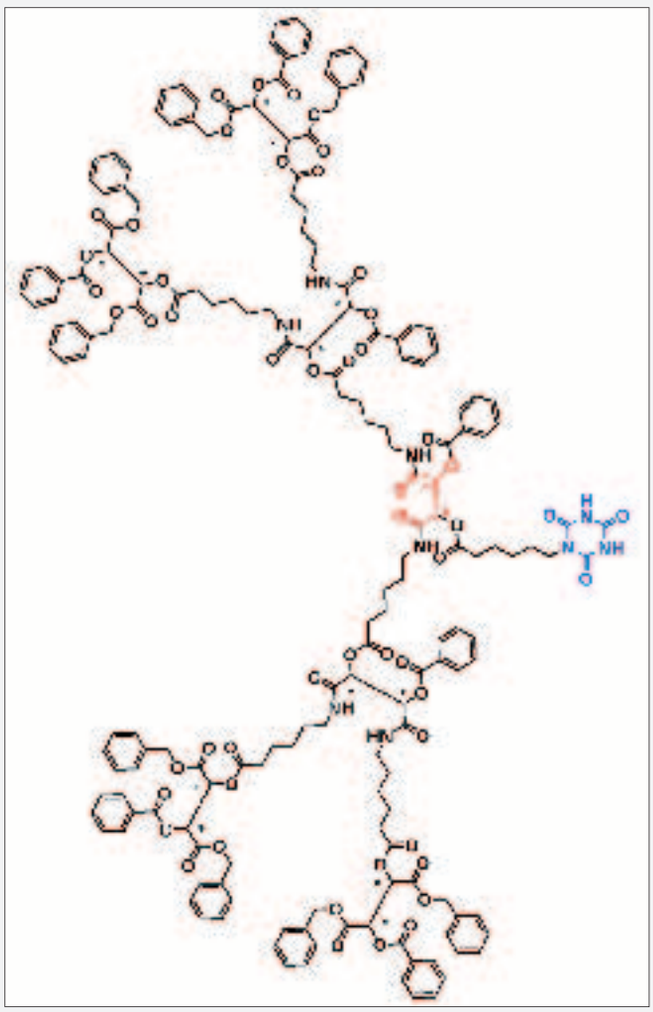


Figure 8: A Depsipeptide Dendron for the Supramolecular Assembly of Chiral Dendrimers

(Figure 8) to Hamilton receptor building blocks. Combination of specific cores, branching units and end-caps, held together by complementary H-bonding motifs allowed for the first completely supramolecular assembly of dendrimers.[19]

By synthesizing new amphiphiles with a rigid T-shape structure we succeeded in realizing the first stable and structurally persistent micelles (Figure 9).[9,20] For this purpose we have used multifunctional core units such as calixarenes and fullerenes to which in a defined way hydrophilic dendrons and hydrophobic alkyl chains were connected. The stable micelles formed out of these amphiphiles were characterized with molecular resolution by cryo transmission electron microscopy. The aggregation behaviour can be controlled by the pH-value. Because these micelles can host apolar guest molecules and can be further be functionalized in the outer hydrophilic part, they represent interesting candidates for drug delivery vehicles.

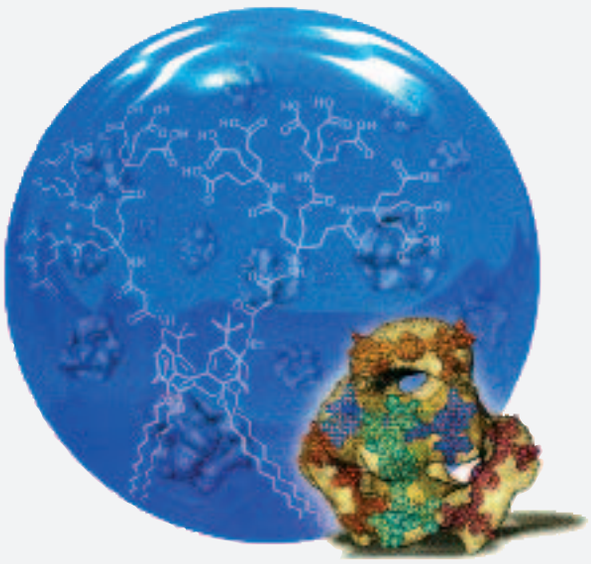


Figure 9: Amphiphilic Calixarenes and their Association to Structurally Defined Micelles in Water

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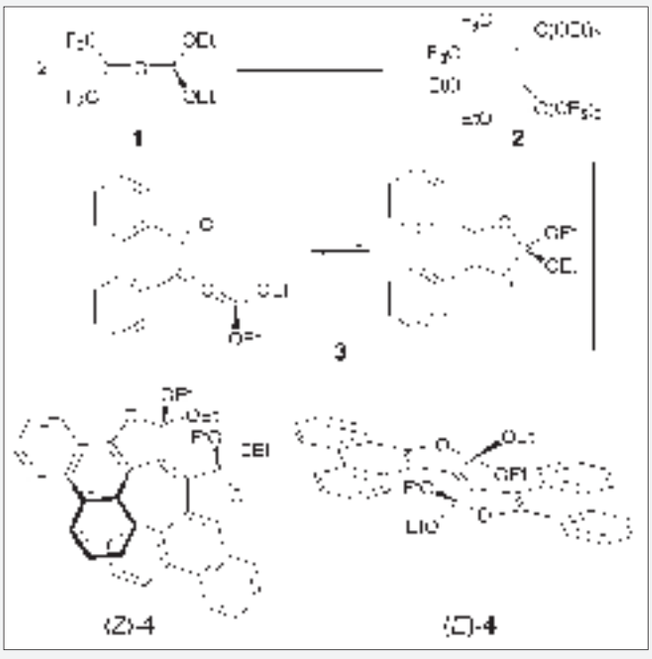
Prof. Dr. Rolf W. Saalfrank

From Allenes to Oligonuclear Complexes

A well-balanced integration of carefully planned strategies, combined with a straightforward evaluation of developing new points of view, has spontaneously uncovered a variety of topics, through which runs a common thread, and which are discussed below.

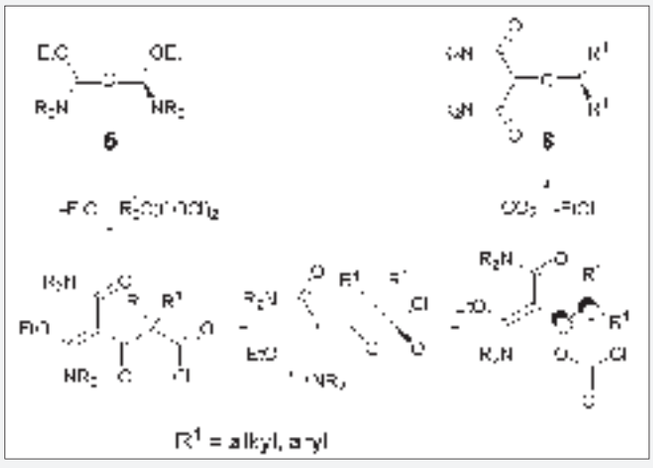
Die ausgewogene Abstimmung sorgfältig geplanter Strategien in Kombination mit einer unmittelbar anschließenden Auswertung sich neu entwickelnder Perspektiven ließ, spontan eine Reihe von Themen sichtbar werden, durch die sich ein roter Faden zieht, und die im Folgenden diskutiert werden.

Recognizing the similarities in different areas of chemistry allows the prediction of potential results in related fields. For instance, during our investigations on carbenes, we became interested in push-pull substituted allenes. Due to the ambiphilicity (carbene character) of their central carbon atom, they readily dimerize. Examples for this are the dimerization of 1,1-bis(trifluormethyl)-3,3-bis(diethoxy)allene **1** to give 1,2-bis(methylene)cyclobutane **2** or the dimerization of allene **3** to give the olefins (*Z*)-**4** and (*E*)-**4** (Scheme 1).[1]



Scheme 1. Dimerization of 1 and 3.

Stimulated by our investigations on push-pull substituted allene **1**, we focused on tetradonor-substituted allenes, and as a result, we employed tetraethoxyallene as a synthetic equivalent of the fictitious malonic ester 1,1/1,3- dianion synthon. This concept led to the synthesis of heterocumulenes and, even more importantly, starting from 1,3-bis(dialkylamino)-1,3-diethoxyallenes **5** to the synthesis of allene-1,1-dicarboxanilides **6** via *transallenation* (Scheme 2).[1]

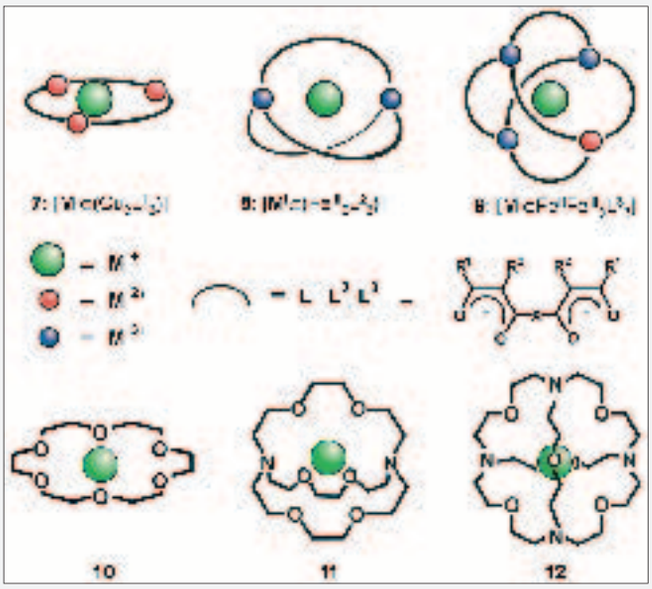


Scheme 2. Mechanism of the transallenation.

The allenecarboxanilides **6** isomerize via intramolecular Diels-Alder reaction or intermolecular Domino cyclization to give heterocycles. In addition, starting from propargyl alcohols, via [2.3]/[3.3]-sigmatropic rearrangement, we developed a new method for the synthesis of 1,1-functionalized allenes. Butatrienes are accessible via *cumuhomologation*.[1]

Most of the supramolecular systems which have been generally known in the past, trace back to serendipitous discoveries. However, more recently a concept to rationally design oligonuclear metal complexes was developed.
According to a procedure developed in our laboratories, the metalla-topomers **7**-**9** of the well known coronates **10** and cryptates **11** and **12** were prepared in one-pot reactions in gram scale (Scheme 3).[2-4] In comparison with the conventional *N*-linked bi- and tricyclic supramolecular structures **11** and **12**, the new complexes **8** and **9** feature that in their case metal ions function as bridgehead atoms. In contrast to their mere organic counterparts **10**-**12**, according to the extra metal ions,

the complexes **7-9** exhibit additional spectroscopic, electronic, magnetic and catalytic properties.



Scheme 3. Comparison of metalla-topomers 7-9 with classical supramolecular systems 10-12.

The template mediated reaction of diethyl ketipinate (H_2L^1) and copper(II) acetate in the presence of calcium nitrate afforded after crystallization from tetrahydrofuran/diethylether green crystals of complex $[Ca\subset(Cu_3(L^1)_3(NO_3)_2]\cdot THF\cdot H_2O$ (**13**). In **13**, the copper ions in the ring are linked by bis-bidentate ketipinate dianions $(L^1)^{2-}$, creating a square planar arrangement of oxygen donors around each copper(II) center. Additional coordination of water, tetrahydrofuran and nitrate ions, respectively, results in a square pyramidal environment at all copper ions. The charge of the calcium ion in the center of the metalla-cryptand is compensated by two axially coordinated nitrate ions (Fig. 1, left).

Whereas, the encapsulation of the small calcium ion leads to the host-guest system **13** with 1:1 stoichiometry, by double deprotonation of bis-tert.-butyl ketipinate (H_2L^2) with 2N potassium hydroxide followed by reaction of the dianion $(L^2)^{2-}$ with copper(II) chloride dihydrate, the metalla-crown sandwich complex $\{K\subset[Cu_3(L^2)_3]_2OMe\}\cdot 7HOMe$ (**14**) with 2:1 stoichiometry is formed. The molecular structure reveals **14** being composed of two neutral trimetalla-crown-6-building blocks, rotated by 60° against each others, sandwiching a potassium ion (Fig. 1, right).[2]

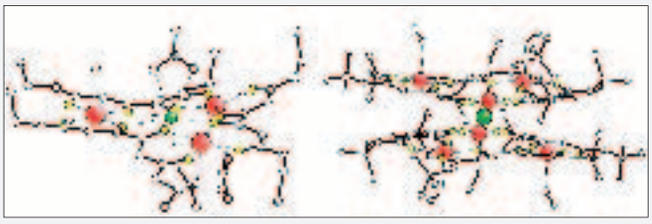


Figure 1. Left: Metalla-coronate 13. Right: Cation of sandwich 14^+. Counterion MeO^- omitted for clarity.

Deprotonation of 1,1'-(2,6-pyridylene)bis-1,3-(4-dimethyl)pentandione (H_2L^3) with potassium hydride in THF, followed by addition of iron(III) chloride and work up with aqueous potassium hexafluorophosphate accomplishes bicyclic metalla-cryptate $\{K\subset[Fe_2(L^3)_3]\}(PF_6)$ (**15**) (Fig. 2).[3]

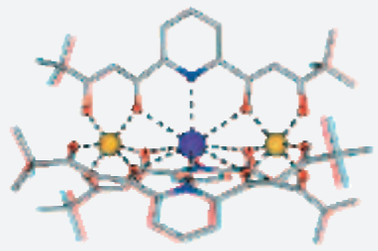
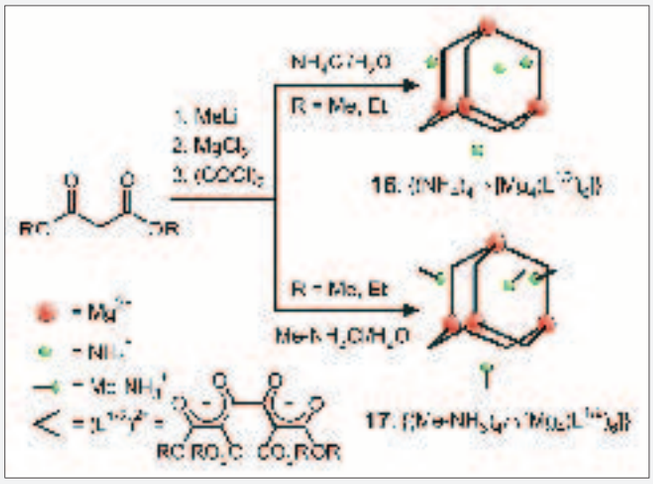


Figure 2. Stereo view of the cation of metalla-cryptate 15. Counterion $(PF_6)^-$ omitted for clarity.

In the case of **15**, three doubly deprotonated ligands $(L^3)^{2-}$ together with two iron(III) ions build up the neutral cryptand, which, due to the extra electron density derived from the pyridyl spacer, is capable to host a cation in the center. Counterion is a hexafluorophosphate anion.

We have previously reported the gram-scale one-pot synthesis of tetrahemispheraplexes **16** and **17** in high yields by deprotonation of dialkyl malonates with methyllithium, subsequent addition of magnesium chloride and oxalyl chloride followed by work-up with NH_4Cl, Me-NH_3Cl, or MOH (M = K, Cs) (Scheme 4).[4]



Scheme 4. Synthesis of the tetrahemispheraplexes 16 and 17.

Similar complexes are also accessible with Mn^{2+}, Co^{2+}, and Ni^{2+}. In the case of iron(III) we were able to generate all-iron(III) complex $\{H_2O\subset[Fe^{III}_4(L^2)_6]\}$ **18** with endohedral encapsulation of water and four acetonitrile solvent molecules in the pockets of the tetrahedron faces. Minor changes of the reaction conditions led to mixed-valent species like $\{M\subset[Fe^{II}Fe^{III}_3(L^2)_6]\}$ **19** with endohedral encapsulation of a K^+- or Cs^+-ion for charge compensation (Fig. 3).[4]

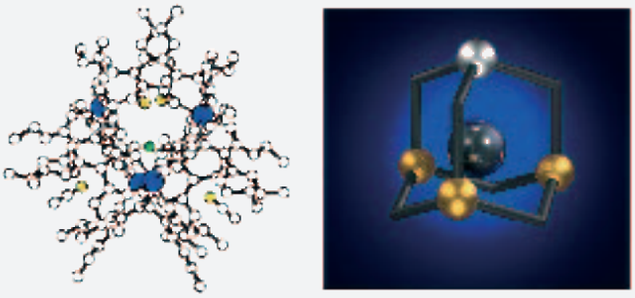


Figure 3. Left: Structure of complex 18. Right: Cartoon of complex 19.

In an attempt to generalize the methodology for the construction of three-dimensional complexes with $[M_4L_6]$ stoichiometry, as realized for **18** and **19**, the threefold symmetric tris-bidentate ligands afforded the synthesis of clusters of general stoichiometry $[M_4L_4]$.
The construction of a tetrahedral scaffold with $[M_4L_6]$ stoichiometry like **18** and **19** results from the linkage of the four metal ions by six bis-bidentate chelating ligands along the edges. On the other hand, complexes with $[M_4L_4]$ stoichiometry as **20** are accessible with threefold symmetric tris-bidentate ligands. In this case the ligands link three metal ions each across the tetrahedral faces (Fig. 4).[5]

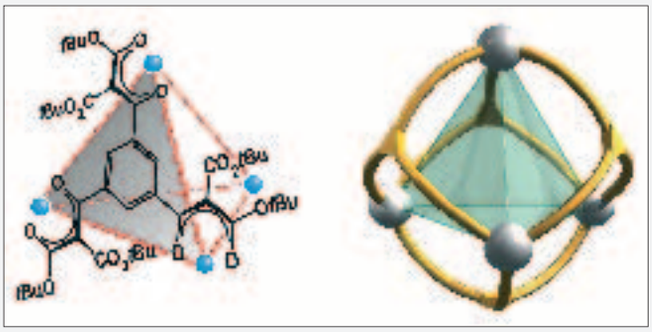
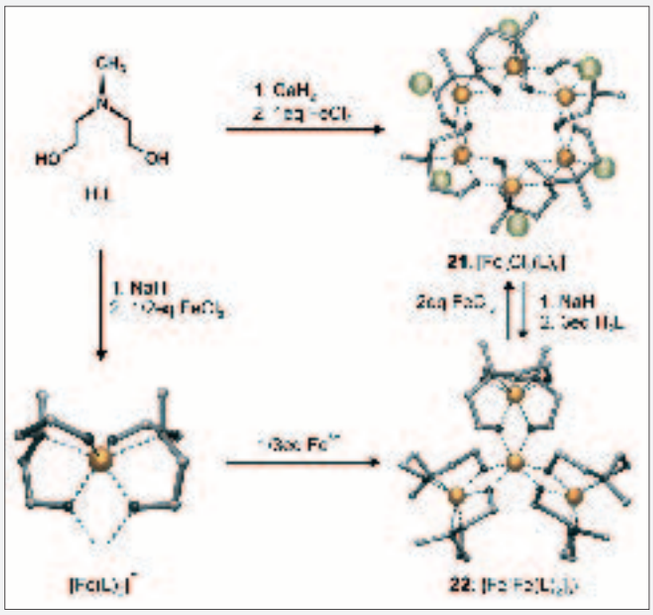


Figure 4. Cartoon presentations of 20.

In earlier work, we were interested in the template mediated synthesis of six- and eight-membered metalla-coronates $[M\subset\{Fe_n[N(CH_2CH_2O)_3]_n\}]^+$ (M = Na, Cs; n = 6, 8), so called *ferric wheels,* on the basis of triethanolamine. Detailed studies on these systems initiated the design of many different six-membered iron-coronands like **21** on the basis of *N*-substituted diethanolamines. Mechanistic studies on the formation of the *ferric wheel* **21** revealed, that the *ferric star* **22** is a precursor. (Scheme 5).[6]

Besides for the synthesis of many other metalla-coronands, this method was also used for the convergent synthesis of metalla-dendrimers alike **23** (Fig. 5).

As demonstrated for the diamagnetic indium wheel **24** by variable temperature ^{1}H NMR spectroscopy (VT ^{1}H NMR), these



Scheme 5. Synthesis of ferric wheels and ferric stars. Exemplarily demonstrated for N-methyldiethanolamine.

systems are not rigid, but rather dynamic, given the fact, the ligands are sufficiently flexible (Fig. 6).[7]
Principally, all *ferric wheels* are isostructural, however, they differ fundamentally with respect to their crystal packing. Depending on the nature of their sidearms, the ferric wheels create various substructures. Some create ball shaped discrete molecules, others pile in parallel in cylindrical columns or give rise to compartementation through pronounced van der Waals interaction with incorporated guest molecules. Even three-dimensional scaffolds are realized by strong π-π interaction as demonstrated for **25** (Fig. 7).[8]

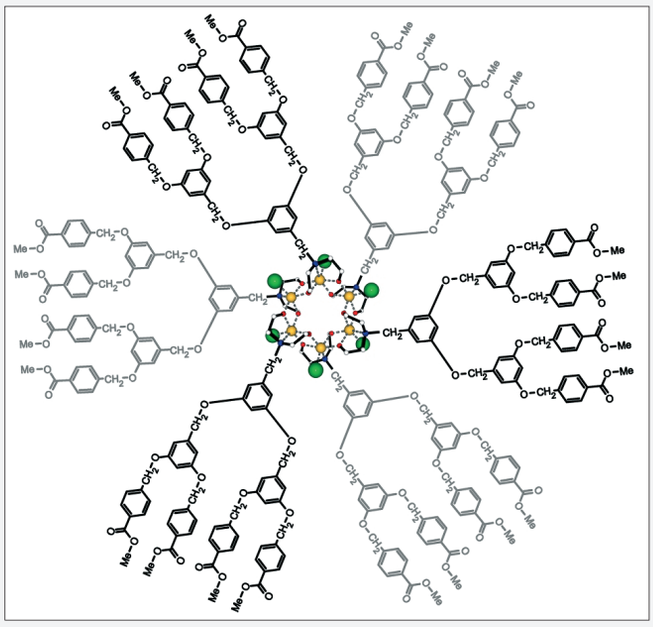


Figure 5. Metalla-dendrimer 23.

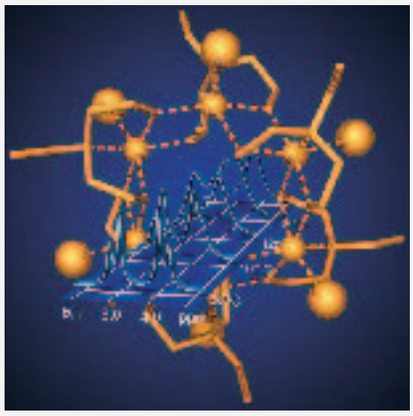


Figure 6. Schematic presentation of indium wheel 24, together with a detail of its VT ^{1}H NMR spectrum.

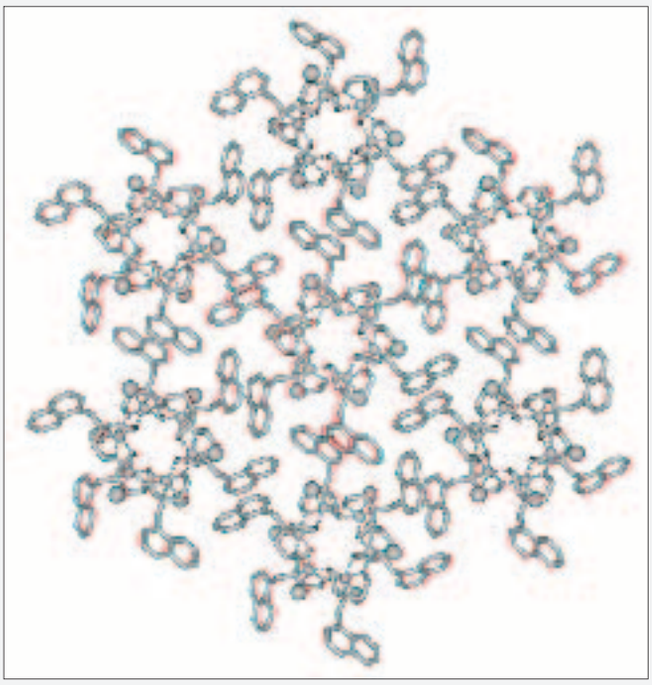


Figure 7. Stereo view of 3D-network of 25.

As exemplarily shown for **26**, it is possible to determine the exact location of the Mn- and Fe ions in the metal-centered, six-membered, mixed-valent, heterometallic wheel by the combination of FAB-mass spectroscopy, X-ray diffraction, and cyclic voltammetric techniques (Fig. 8).[9]

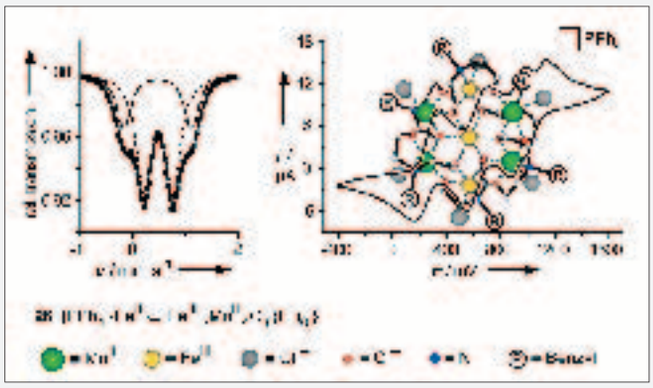


Figure 8. Schematic presentation of complex 26 together with its Mössbauer spectrum and cyclic voltammogram.

The *ferric star* $\{Fe[Fe(L)_2]_3\}$ **22** is a single molecule magnet (SMM) and shows hysteresis on magnetization and the *ferric wheel* $[Na\subset\{Fe_6[N(CH_2CH_2O)_3]_6\}]^+$ **27** reveals cooling by adiabatic increase of magnetization (in cooperation with Prof. Dr. P. Müller, Institute of Physics, Erlangen) (Fig. 9).[10]

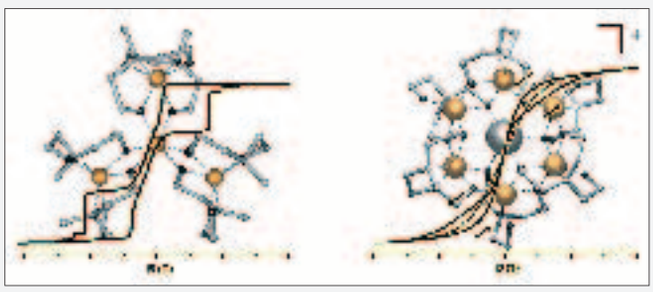


Figure 9. Schematic presentation of the magnetic properties of ferric star 22 and ferric wheel 27.

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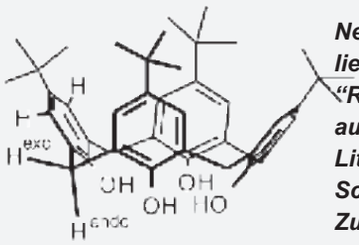
Prof. Dr. Walter Bauer

NMR Studies on Organolithiums and Development of New NOE Methods

New NMR methods based on the nuclear Overhauser effect (NOE) give detailed insight into the solution structures of organolithiums and related compounds. "Rotating frame" methods circumvent the "zero crossing" problem of the NOE.
The application on a claimed endo complex between tert-butylamine and a calixarene revealed a literature error: an exo complex is formed instead. By using an NOE pulse sequence based on "excitation sculpting", the structure of a chiral organolithium compound was correlated with its stereoselectivity.



Neue, auf dem nuklearen Overhauser Effekt (NOE) basierende NMR-Methoden erlauben detaillierte Einsichten in die Lösungsstruktur von Lithiumorganylen und verwandten Verbindungen. "Rotating frame"-Methoden sind frei vom "Nulldurchgangsproblem" des NOE. Die Anwendung auf einen bekannten endo-Komplex zwischen tert-Butylamin und einem Calixaren deckte einen Literaturirrtum auf: es liegt ein exo-Komplex vor. Mittels einer Pulssequenz, die auf "Excitation Sculpting" beruht, konnte die Struktur einer chiralen Organolithiumverbindung aufgeklärt und in Zusammenhang mit der Stereoselktivität gebracht werden.

The nuclear Overhauser effect (NOE) exploits spatial relationships of nuclei due to cross relaxation. Both homonuclear (e.g., ^{1}H,^{1}H- NOESY) and heteronuclear (e.g., ^{1}H,^{31}P-HOESY) variants may be applied. Inherently, the NOE is related to the inverse 6th power of the internuclear distances. Thus, the NOE offers a powerful tool for structural analysis of, e.g., proteins or organolithiums.
In recent years, NOE methods based on pulsed field gradients and on gradient echoes ("excitation sculpting") have become popular (DPFGSE-NOE) [1]. However, the well-known problem of „NOE zero-crossing" for $\omega\tau_c$ = 1.12 still persists for DPFGSE-NOE. We have recently described the application of the rotating frame analogue, DPFGSE-ROE for such cases [2]. The corresponding pulse sequences are shown in Fig. 1. By using DPFGSE-ROE, all direct NOEs are positive, irrespective of the molecular correlation time.

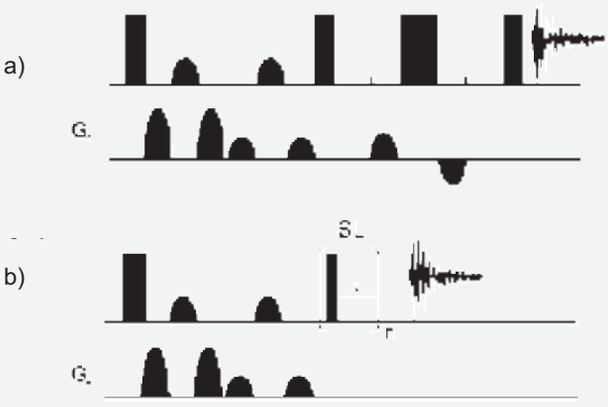


Fig. 1 Pulse sequence of a) DPFGSE-NOE and b) DPFGSE-ROE. SL denotes the (pulse-delay)$_n$ spin lock period, Gz denotes half-sinusoidal pulsed field gradients

A paper by Gutsche et al [3] dating back to 1987 reported the formation of an endo-calix complex between tert-butylamine and p-allylcalix[4]arene. These findings were based on the occurrence of appropriate cross peaks in a two-dimensional NOESY spectrum. We repeated these measurements by using a mixture of tert-butylamine and p-tert-butylcalix[4]arene and by the application of the DPFGSE-NOE method. The relevant spectra are depicted in Fig. 2.

As can be clearly seen from the NOE spectra in Fig. 2, there is *no* spatial relationship between the protons of the amine and the protons of the calixarene. Hence, *no* endo-calix complex is formed. Rather, in agreement with theoretical calculations, an exo-calix complex is present [4]. The erroneous conclusions by Gutsche must be based on artifacts which were introduced into the claimed NOESY spectrum by a cosmetic symmetrization process.

Enantioselective syntheses are of major interest in modern organic chemistry. By using a valine-derived lithiated 3-methylthiomethyl-1,3-oxazolidine-2-one derivative, Seebach et al were able to obtain chiral 1,2-diols starting from achiral aldehydes with high enantiomeric excess (ee). The synthetic route is outlined in Fig. 3.

In order to understand the reaction mechanism it was of crucial importance to study the lithiated intermediate and to an-

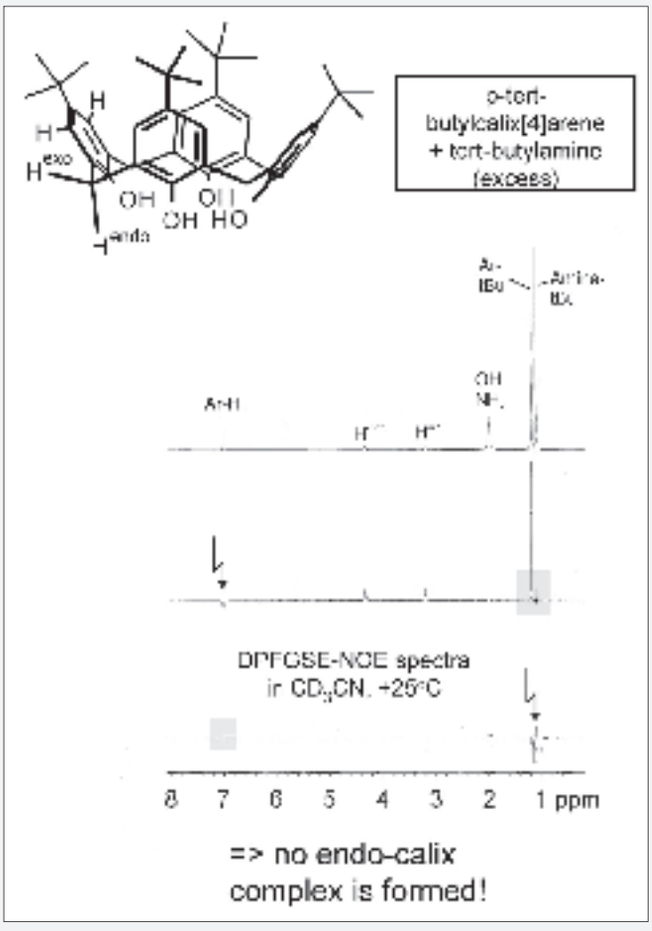


Fig. 2 NOE experiments on a mixture of tert-butylcalix[4]arene and tert-butylamine (excess). Top: normal ^{1}H-spectrum. Middle and bottom: DPFGSE-NOE spectra under irradiation at the indicated positions. Missing signals within the grey fields indicate remote entities and are not compatible with a claimed endo-calix complex.

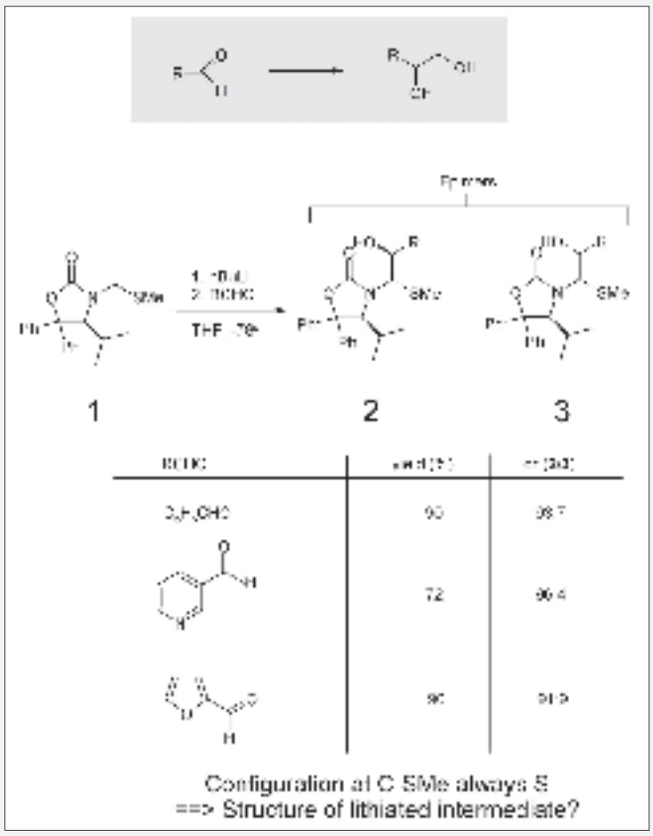


Fig. 3 Enantioselective syntheses by using a valine-derived lithiated 3-methylthiomethyl-1,3-oxazolidine-2-one

swer the question whether the pro-R or the pro-S proton at the CH_2-SMe group is abstracted by n-butyllithium (n-BuLi). An NMR study based on the DPFGSE-ROE method yielded the spectra shown in Fig. 4 [6].

As can be deduced from the NOE spectrum in Fig. 4, there is close proximity between the CH(Li) proton and the valine isopropyl group. Hence, the diastereomer of the organolithium species indicated by a thick arrow must be present. This, in turn, indicates that the pro-S proton of the educt has been abstracted by n-BuLi. Furthermore, the subsequent quench reaction with the electrophile (aldehyde) proceeds with *retention* of the configuration at the lithiated carbon atom. Under the measurement conditions of Fig. 4, the rotating frame variant of the NOE turned out to be mandatory. The medium-sized organolithium compound has a slow molecular correlation time at -50 °C which leads to negative NOEs when DPFGSE-NOE or conventional difference NOE is applied. Due to spin diffusion phenomena, artificial signals will be obtained in these cases.

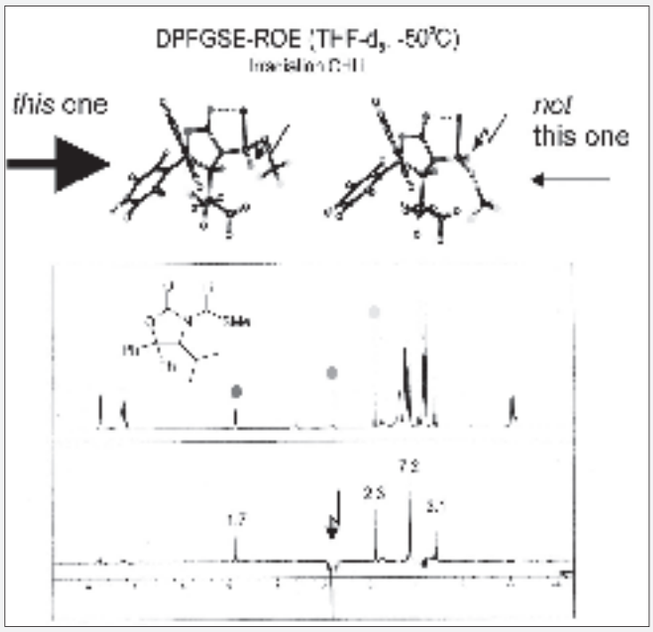


Fig. 4 NOE spectra of the lithiated intermediate of the reaction outlined in Fig. 3. Top: normal ^{1}H-spectrum. Bottom: DPFGSE-ROE spectrum with irradiation at the indicated position. Numbers are percentage numbers of the obtained NOEs. Clearly, the pro-S proton has been abstracted by n-BuLi.

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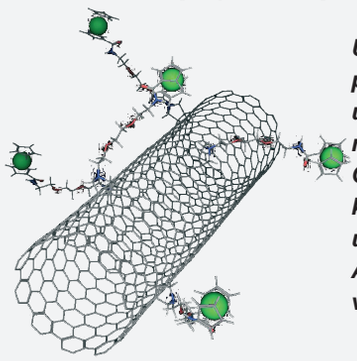
Prof. Dr. Dirk M. Guldi

Spectroscopy and design of nanometer scale structures for photoinduced electron transfer processes

This outline summarizes our current research activities, namely, the application of an arsenal of spectroscopic and microscopic techniques to a variety of molecular systems designed specifically to explore the nature of the chemical, physical and photophysical properties of new molecular architectures. In particular, we explore new preparative strategies towards supramolecular hybrids, quantum dots, quantum rods and nanoparticles. Our experimental tools span from ultrafast spectroscopy (absorption and fluorescence) and vibrational spectroscopy (Raman and IR) to electrochemistry and microscopy (Raman, TEM and AFM). Such conception is extremely valuable for the realization of solar energy conversion, photovoltaics, and catalytic reactivity, specifically to novel chemical and light driven systems.



Unsere aktuellen Forschungsaktivitäten umfassen die Anwendung einer Vielzahl spektroskopischer und mikroskopischer Techniken zur Charakterisierung von chemischen, physikalischen und photophysikalischen Eigenschaften von neuen, molekularen Architekturen. Wir verfolgen neue präperative Strategien hinsichtlich von supramolekularen Hybridsystemen, Quantendots, Quantenrods und Nanopartikeln. Unsere experimentellen Arbeitstechniken reichen von der Ultrakurzzeitspektroskopie (Absorption und Fluoreszenz) über Schwingungsspektroskopie (Raman und IR) und Elektrochemie bis hin zur Mikroskopie (Raman, TEM und AFM). Als extrem wertvoller Anwendungsbezug in der Praxis dienen molecular-licht gesteuerten Systeme der Realisierung von Sonnenenergieumwandlung, Photovoltaik und katalytischen Vorgängen.

The bacterial photosynthetic reaction center provides meaningful incentives for the optimization of charge separation processes in artificial model systems – *nanometer scale structures*. Common to all these systems is a relay of short-range energy / electron transfer reactions, evolving among chlorophyll and quinone moieties. Among many key parameters that govern electron transfer reactions the reorganization energy imposes probably the most far reaching impact. The reorganization energy (λ) is the energy required to structurally reorganize the donor, acceptor and their solvation spheres upon electron transfer. For example, the primary electron transfer processes of photosynthesis are characterized by an extremely small reorganization energy (0.2 eV), attained by the transmembrane protein environment. This aspect is central for achieving the ultrafast charge separation and retarding the energy wasting charge recombination, which is highly exergonic ($-\Delta G_{CR}$ = 1.2 eV). Efficient light conversion into electric current, which are inspired by nature, is one of the most ambitious research objectives of our times.

Nanometer scale structures – fullerenes and carbon nanotubes (CNT) – are the focus of considerable interest because they can be used to test fundamental ideas about the roles of dimensionality and confinement in materials of greatly reduced size. These classes of materials have extended, delocalized π-electron systems, which, in combination with photoexcited electron donors, renders them useful for managing charge transfer within novel, ultra high efficient photoelectrochemical cells for water splitting and reduction of CO_2 to fuels. This, in turn, defines one of the directions that we are considering in our research, namely, the potential of using carbon nanostructures in the context of photovoltaics, which aims at the conversion of solar energy into electricity.

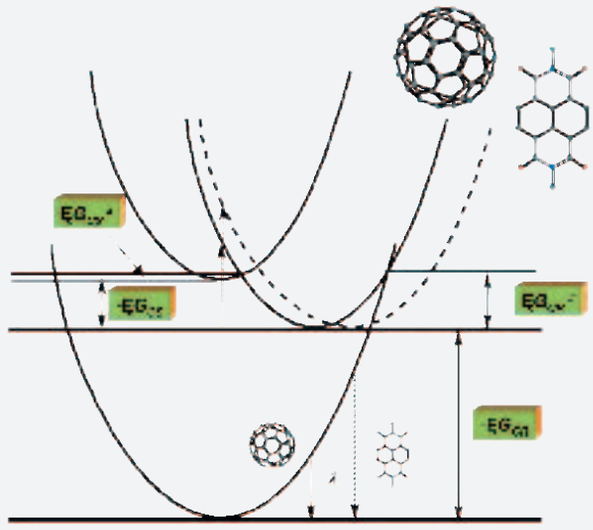


Figure 1: Profile for the free energy surfaces for electron transfer in electron donor-acceptor ensembles based on spherical C_{60} (solid line) and planar naphthalenediimide (dashed line).

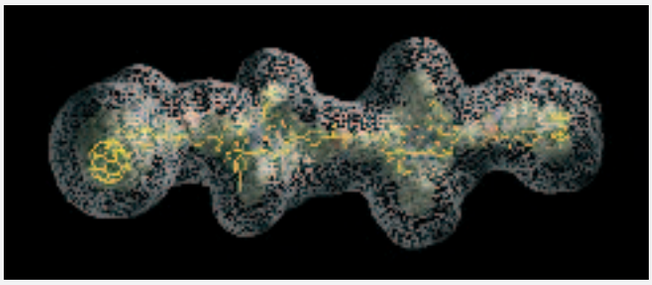


Figure 2: Molecular *linear array* as a leading example of a covalent approach (i.e., nanoconjugates) towards the integration of C_{60} as electron acceptor – together with ferrocene, zinc tetraarylporphyrin (ZnP) and free base tetraarylporphyrin (H_2P) as light harvesting electron donors – into *electron-donor-acceptor* ensembles. Cascade of multistep electron transfer events evolving from the singlet excited state of ^{1}*H_2P. In the final charge separated state, which has a lifetime of 0.38 s and is formed with a quantum yield of 0.24, 54 % (~1.1 eV) of the initial excited state energy is stored.

Our largely interdisciplinary strategy focuses on well-defined molecular architectures: We start with building blocks (i.e., at an atomic and / or molecular scale) that give access to *a priori* design of multifunctional molecular materials and their integration into 2- or 3-dimensional solid *electron-donor-acceptor* ensembles. In our group, we have pursued two general strategies: i) covalent functionalization, and ii) noncovalent functionalization. Eventually, the two approaches may lead to similar results, but they differ in the degree of involvement of the carbon skeleton in the formation of covalent bonds. A broad range of spectroscopic (i.e., time-resolved and steady-state measurements with spectrophotometric detection covering a time range from femtoseconds to minutes) and microscopic techniques (i.e., scanning probe microscopy, electron microscopy,) are routinely employed to address issues that correspond to the optimization and fine tuning of dynamics and / or efficiencies of charge separation and charge recombination processes.

One cast of active *nanometer scale structures* that we employ are fullerenes. Since the initial discovery of fullerenes chemists and physicists worldwide have studied solid state properties ranging from nanostructured devices to endohedral fullerene chemistry. The 3-dimensional, spherical structure of fullerenes, which are made of alternating hexagons (i.e., electron rich) and pentagons (i.e., electron deficient) with diameters starting at 7.8 Å for C_{60}, evoked a lively interest to relate their properties to conventional 2-dimensional π-systems – Figure 1. Their extraordinary electron acceptor properties – predicted theoretically and confirmed experimentally – have resulted in noteworthy advances in the areas of light induced electron transfer chemistry and solar energy conversion. It is mainly the small reorganization energy, which fullerenes exhibit in electron transfer reactions and which is much smaller than in 2-dimensional π-systems, that is accountable for a noteworthy breakthrough. In particular, ultrafast charge separation together with very slow charge recombination features lead to unprecedented long-lived radical ion pair states formed in high quantum yields.

Original and well-established synthetic methodologies, applied to fullerenes, have produced a wide variety of novel architectures (i.e., linear arrays, rotaxanes, catenanes, etc. – see Figures 2 and 3), in which the unique electrochemical and photophysical features of C_{60} have largely been preserved. A recent breakthrough in our work includes a 24% efficient charge-separation within molecular tetrads. The lifetime of the spatially separated (~49 Å) radical pair, which is the product of a sequence of energy and electron transfer reactions, reaches well beyond milliseconds (0.38 s). Such an extended charge separation had not previously been accomplished in any other artificial photosynthetic reaction center.

The second cast of *nanometer scale structures* is CNT. Of the wide range of nanostructures available, CNT, in general, and single wall carbon nanotubes (SWNT), in particular, stand out as unique materials. In fact, CNT have emerged as a new class of materials with exceptionally high tensile strength, and the highest thermal conductivity known. Whereas different approaches towards the design of *electron-donor-acceptor* ensembles have provided interesting and promising results, the use of CNT could lead to important breakthroughs.

SWNT are quasi 1-dimensional structures consisting of hexagon networks of carbon atoms that are rolled up to create seamless cylinders, along a chiral vector. While their diameters are typically in the range of nanometers, individually CNT reach lengths of up to 4 cm leading to high aspect ratios. However, several obstacles need to be properly addressed

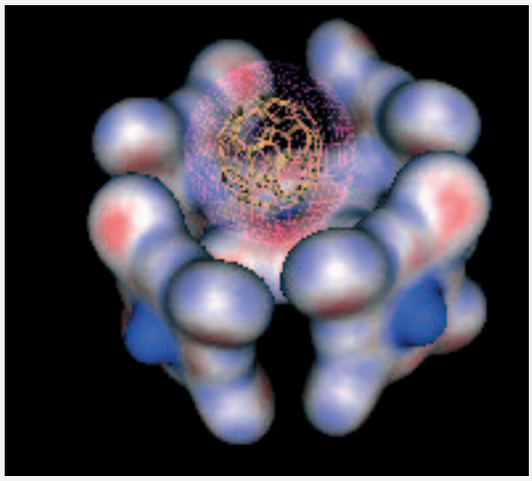


Figure 3: C_{60} in the box as a leading example of a non-covalent approach (i.e., nanohybrids) towards the integration of C_{60} as electron acceptor – together with ruthenium tetraarylporphyrins (RuP) and zinc tetrapyridylporphyrin (ZnP) as light harvesting electron donors – into *electron-donor-acceptor* ensembles.

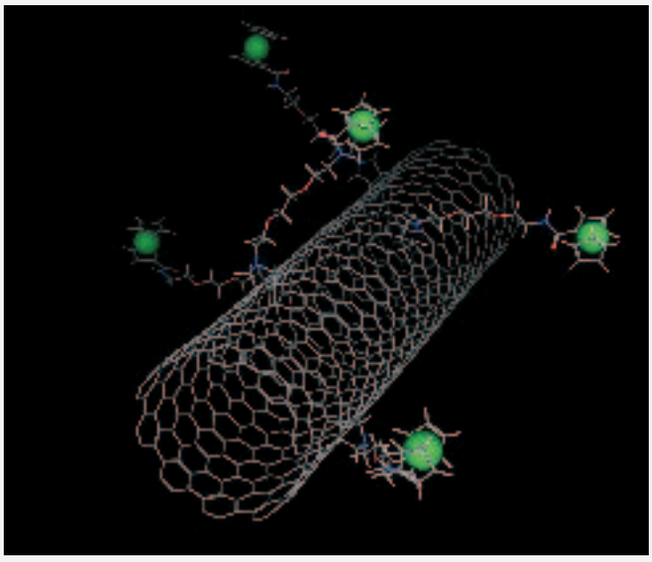


Figure 4: Leading example of a covalent approach (i.e., nanoconjugate) towards the integration of SWNT as electron acceptor – together with ferrocene electron donor – into *electron-donor-acceptor* ensembles.

before integrating CNT into functional nanohybrids and testing them in practical applications. Controlled modification of their surface with multifunctional groups, such as chromophores, electron donors, biomolecules, etc. – see Figures 4 and 5 – is required to fully realize their potential in nanotechnology. CNT have the further advantage of their shear size. Upon receiving the charge, the transport – under nearly ideal conditions along the axis of the nanometer long carbon structure – can contribute to a reduced probability of back-transfer to the (photoexcited) donor.

On the other hand, multiple concentric graphene cylinders – multi wall carbon nanotubes (MWNT) – exhibit metallic or semiconducting properties, which depend solely on their outer most shell. On account of the large number of concentric cylindrical graphitic tubes present in MWNT they are considered even more suitable in *electron-donor-acceptor* ensembles than SWNT. It is notable that in line with this purely structural assumption appreciable differences were seen as far as the stabilization of charge separation is concerned. To transfer, however, their outstanding properties from the nanoscale to the macroscale the chemical and physical modification of the SWNT and MWNT surface are essential steps.

Porphyrinoid and especially metalloporphyrinoid systems – with their rich and extensive absorptions throughout the visible region of the solar spectrum – hold particularly great promise as integrative building blocks with increased absorptive cross sections. Over the course of recent years they emanate as light harvesting building blocks in the construction of molecular architectures. Their high electronic excitation energy, typically exceeding 2.0 eV, powers a strongly exergonic electron transfer and intercedes hereby the conversion between light and chemical / electrical energy. Another important feature of porphyrins is their highly delocalized π-electron systems. Such delocalization results – upon an uptake or release of electrons – in minimal structural change upon electron transfer. Rich redox properties render porphyrins and porphyrin analogous as essential components in important biological electron transport systems including photosynthesis and respiration.

All the mentioned *nanometer scale structures* – fullerenes and CNT – are natural electron acceptors. Proof of this concept is obtained mathematically even by qualitative molecular orbital theory. The argument starts from isolated C_2 fragments that are brought together starting from infinite distance. Each fragment has a π and a π* orbital. As they are brought together to form, for example, a CNT, the two degenerate sets of π and π* orbitals mix prevalently between themselves and spread in energy. The low-lying end of the π* orbitals is very stable and readily accept electrons. Therefore, combining *nanometer scale structures* – see leading examples in Figures 2-5 – with electron donor groups signifies an innovative concept to solar energy harvesting systems, which leads to conversion into practical electricity.

Some of these *nanometer scale structures* have been successfully utilized to convert photolytically generated radical ion pairs into electrical or chemical energy by constructing integrated artificial photosynthetic assemblies – on modified indium-tin-oxide electrodes (Figure 6). While other systems may presently show higher efficiency, the approach offers high flexibility with the formation of long-lived charge separated species under a wide variety of conditions and can be considered complementary to the techniques already existing. We believe that the initial results are so promising that further research in this field to obtain practical conversion of light energy into electricity is not only justified but desirable.

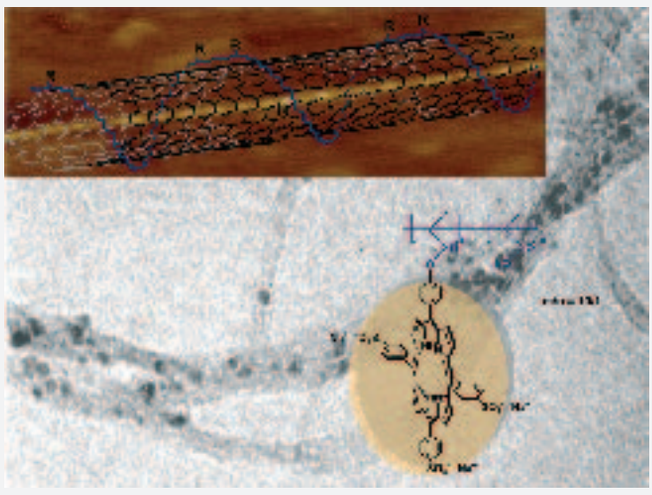


Figure 5: Leading example of a non-covalent approach (i.e., nanohybrids) towards the integration of SWNT as electron acceptor – together with free base tetraarylporphyrin (H_2P) as light harvesting electron donor – into *electron-donor-acceptor* ensembles.

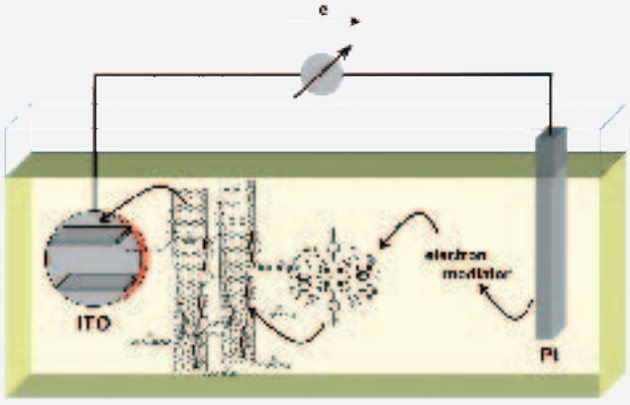


Figure 6: Schematic illustration of photocurrent generation in ITO-electrodes covered with a single SWNT • pyrene^{+} • ZnP^{8-} stack – red indicates baselayer of polyelectrolyte deposited initially onto ITO.

One of the major challenges that still lie ahead is to regulate the forces, which will ultimately dictate size and shape in relation to function of the resulting *nanometer scale structures*. Can molecular tailoring of fullerenes and CNT contribute to the induction of new assemblies? To address such issues, we have probed in recent years novel *electron-donor-acceptor* ensembles, in which *nanometer scale structures* constitute the acceptor moiety and biomimetic organization principles – *hydrogen bonding, complementary electrostatics, π-π stacking and metal coordination* – and, thereby, ensuring the hierarchical integration of multiple components into well-ordered arrays. These spontaneous organization principles permit engineering of novel functional *electron-donor-acceptor* (nano)conjugates and (nano)hybrids and, simultaneously, achieve predetermined architectures of controlled sizes and outer-shell structures, with high directionality and selectivity.

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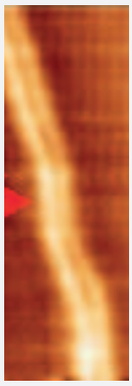
Prof. Dr. Carola Kryschi

Optical spectroscopy studies of interactions between biological macromolecules and chromophores

The first research project (I) is targeted to the elucidation of the dynamic interactions between carminic acid and DNA in aqueous buffer solution at pH=7 (BPES), whereas the focus of the second research project (II) is directed to the application of fluorescence spectroscopy to the study of the transport properties of P-glycoprotein in Caco-2 cells. I. The excitation relaxation dynamics of carminic acid-DNA complexes are examined using femtosecond resolved transient absorption spectroscopy and fluorescence upconversion. The evaluation of the transient absorption spectroscopic data of carminic-acid in BPES yields four lifetimes for the excited state (S_1): 8 ps, 15 ps, 33 ps and 46 ps. The four S_1 lifetimes are ascribed to the coexistence of the normal and tautomer form of carminic acid in its non dissociated state (i.e. CAH and CAHT) and in its deprotonated state (i.e. CA^- and CA^-T), respectively. The two lifetimes of CA^- T and CAHT, 33 ps and 46 ps, are confirmed by fluorescence up-conversion spectroscopy. The formation of intercalation complexes between carminic acid and DNA is associated with a prolongation of the two lifetimes which is explained by the rigid environment of the base pairs stacking. II. For the pharmacokinetic study of P-glycoprotein the fluorescence dye rhodamine-123 is used as substrate. While the apical-to-basolateral transport of the dye occurs through pores of the Caco-2 cell membrane, P-glycoprotein mediates the basolateral-to-apical transport.



In ersten Forschungsprojekt (I) werden die Wechselwirkungsprozesse zwischen Carminsäure und DNA in Pufferlösungen bei pH=7 (BPES) untersucht, während im zweiten Forschungsprojekt (II) Rhodamin-Farbstoffe als fluoreszierende Sonden für die Charakterisierung der Transporteigenschaften von P-Glykoprotein in Caco-2-Zellen eingesetzt werden. I. Die interkalative Bindung von Carminsäure an DNA wird mit stationärer optischer Spektroskopie und Rastertunnelmikroskopie nachgewiesen, während die Relaxationsdynamiken von Photo-angeregten Carminsäure-DNA-Assoziaten mit fs transienter Absorptionsspektroskopie und Fluoreszenz-Aufwärtskonversion untersucht werden. In BPES dissoziiert Carminsäure (CAH) zu ca. 50% zum Anion (CA^-), und beide Zustände koexistieren mit ihrer tautomeren Form (CAHT und CA^-T). Die Interkalation des Carminsäure-Chromophors zwischen den DNA-Basenpaaren behindert nicht nur den doppelten Protonentransfer im angeregten Zustand (ESIPT), sondern führt auch zur Verlängerung der Fluoreszenzlebensdauern der Tautomeren. II. Für die pharmakokinetischen Untersuchungen von P-Glykoprotein wird der Fluoreszenzfarbstoff Rhodamin-123 eingesetzt. Der Transport des Farbstoffes von apikal nach basolateral erfolgt durch Zellmembranporen, während P-Glykoprotein den basolateral-nach-apikalen Transport vermittelt.

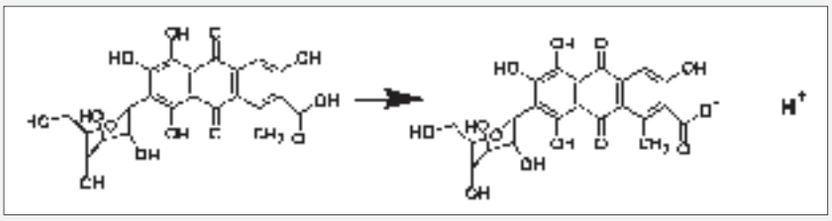
Optical spectroscopy study of carminic acid-DNA interactions

Antitumor anthracyclines have been extensively studied for decades in an effort to optimize their therapeutic function for the treatment of various human cancers. These compounds are believed to develop their cytotoxic effect by penetrating into the tumor cell nucleus and interacting there with DNA via intercalation between the CG base pairs. The formation of intercalation complexes may inhibit the DNA replication and RNA transcription. Irradiation with light enhances the cytotoxicity of anthracyclines by several orders of magnitudes. Despite extensive research activities on the examination of photo-activated anthracycline-DNA complexes, to this date their excited-state relaxation dynamics as well as the structural mechanism at the molecular level are more hypothetically discussed than really understood. In particular, tautomerization reactions of hydroxylanthra-quinone-DNA complexes are completely ignored.

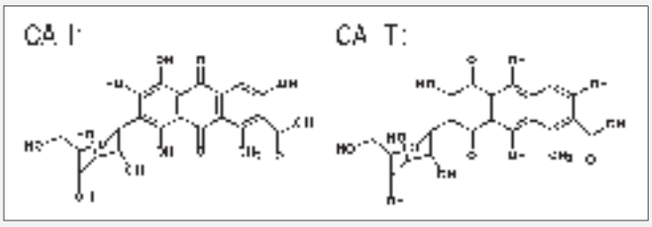
Our research efforts are focused to carminic acid, since this natural dye constitutes the essential structural features of the anthracyclines. The main impetus for us is to understand the complex mechanism and dynamics of the excited-state relaxation of carminic acid in the presence of DNA.

Carminic acid as a carboxylic acid dissociates in water at pH=7 to equal concentrations of non dissociated carminic acid (CAH) and of its deprotonated form (CA^-) [1].

These keto-enol pair structures enable a double proton transfer and therewith suggest the coexistence of the normal form (CAH) and the tautomer CAHT.



Scheme 1: Dissociation of carminic acid.



Scheme 2: Normal (CAH) and tautomer form (CAHT).

Photo-exciting carminic acid in BPES at 340 nm generates two fluorescence emissions, peaking at 15100 cm^{-1} (orange emission) and at 22700 cm^{-1} (blue emission) (*see* Fig.1, dashed line). The observation of dual fluorescence indicates to an excited state intramolecular proton transfer (ESIPT). The blue emission is ascribed to the normal form, whereas the tautomer exhibits the orange emission. While for carminic acid the ratio of orange fluorescence intensity to blue fluorescence intensity is 2:1, in the presence of DNA the ratio is altered to 0.8:1 (Fig.1, solid line). The increase of the blue fluorescence intensity at the expense of the orange fluorescence intensity manifests the structural stabilization of carminic acid when intercalated in the DNA base pair stacks.

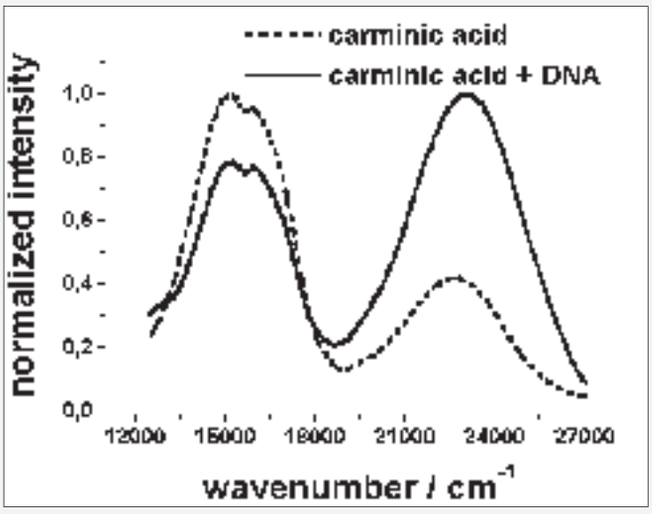


Fig.1 Fluorescence spectra of carminic acid and carminic acid-DNA complexes in aqueous solution at pH=7.

Another evidence for the formation of carminic acid-DNA complexes is obtained from scanning tunnelling microscopy imaging of HOPG substrates covered by evaporation of carminic acid-DNA solutions (see Fig.2). The red arrows mark carminic acid molecules attached at the DNA double strand.

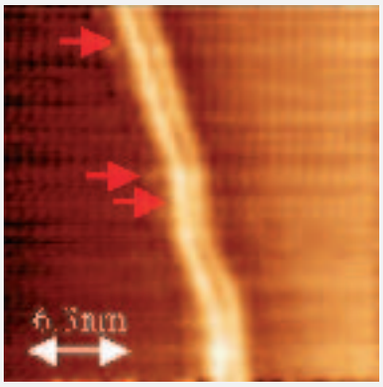


Fig.2 STM image of Carminic-acid-DNA complexes on HOPG.

The excited-state decay dynamics of carminic acid in BPES are investigated utilizing fs transient absorption spectroscopy and fluorescence upconversion. Fig.3 represents the time evolution of the transient absorption spectra between 0 and 100 ps depicted in a 3D-plot.

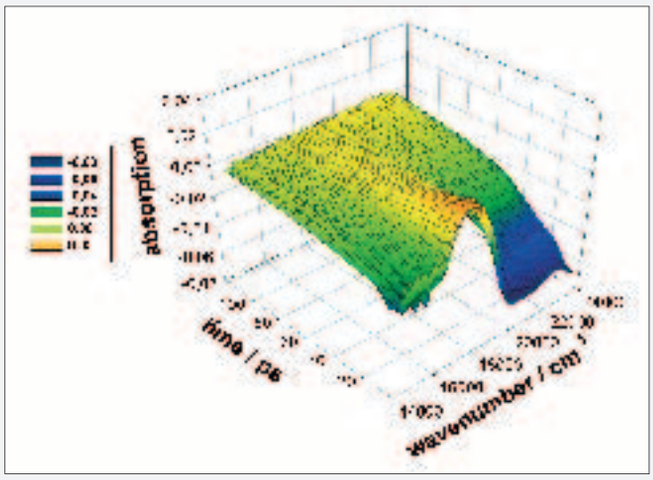


Fig.3 3-D plot transient absorption spectra vs. delay time.

The time evolution of the involved spectral components is analyzed by decomposition of each into 8 Gaussian functions. The temporal behavior of each amplitude, as a measure for the relative absorption of the respective spectral component, is described by a monoexponential function. The exponential fits yield four different excited-state lifetimes for the 8 spectral components: 15 ps, 20 ps, 33 ps and 46 ps, which are assigned to the four species of carminic acid (CAH, CAHT, CA^-, CA^- T). The fluorescence up-conversion experiments conducted on carminic acid in aqueous solution lead to two lifetimes of tautomers CA^- T and CAHT (*i.e.* 33 ps and 47 ps). Since the rise time of fluorescence up-conversion transients corresponds to the instrumental response time constant of 270 fs, only ultrafast ESIPT with a proton-transfer time constant smaller than 100 fs may be involved in the excitation of the tautomers. In the presence of DNA the observed lifetimes increase from 33 ps to 48 ps for CA^- T and from 47 ps to 61 ps for CAH T3. Their prolongation in the presence of DNA is ta-

ken as an additional evidence for the formation of intercalation complexes between DNA and carminic acid [1].

II. Fluorescence spectroscopy study on the transport properties of P-glycoprotein

P-glycoprotein (P-gp) is an ATP-dependent multidrug transporter belonging to the ATP-binding cassette super-family. Its ability to transport an enormous variety of lipophilic compounds causes multi-drug resistance in cancer chemotherapy upon treatments with anticancer drugs (*e.g.* actinomycin, daunomycin). Another class of compounds transported by P-gp is the rhodamine dyes. P-gp is expressed in the Human colon carcinoma Caco-2 cells on their apical surface. Hence Caco-2 cells are used as an in-vitro cell model for drug transport studies.

The global goal of our fluorescence spectroscopy study of P-gp mediated transport of rhodamine-dye substrates is to obtain quantitative data for the efficiency of the binding of different inhibitors to P-gp. The prior condition is to culture Caco-2 cell monolayers with a reproducible expression level of P-gp. Similarly essential is the reliable determination of the net transport of rhodamine dye substrates from separately measuring the fluorescence intensity of the dye solution at the apical side and at the basolateral side of Caco-2 cells. Therefore Caco-2 cells were grown as polarised monolayers on permeable supports (*i.e.* polycarbonate Transwell filter) and are incubated with a 1 µM rhodamine-123 solution. *Fig.4* shows a confocal fluorescence microscopy image of a Caco-2 cell monolayer stained with rhodamine-123.

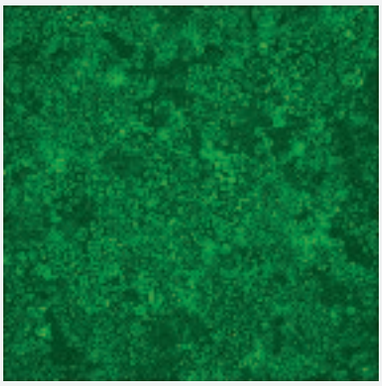


Fig.4 Confocal fluorescene microscopy image of a Caco-2 cell monolayer stained with rhodamine-123 (5·5 mm²).

The green fluorescence emission of rhodamine-123 is excited at 490 nm and detected between 505 and 530 nm. The dye is intestinally absorbed by the cells, and the secretion by P-gp takes also place. Vectorial transcellular transport is studied using polarised Caco-2 cell monolayers confluently grown on polycarbonate filters which are inserted in a diffusion cells. Basolateral-to-apical transport dynamics are monitored after adding a 1 µM solution of rhodamine-123 into the basolateral compartment, whereas for the apical-to basolateral direction the apical compartment solution initially contains 1 µM of the dye. Each hour after adding the substrate samples of 20 µl are taken from the initially dye-free compartment, and their dye concentration is determined by measuring the fluorescence spectrum of the sample. Fig.5 shows the increases of the fluorescence intensity with rising time which are directly proportional to the apical-to-basolateral and basolateral-to-apical transport dynamics, respective-ly. The net transport of P-gp for rhodamine-123 resulting from the ratio of the respective fluorescence intensities (basolateral-to-apical:apical-to-basolateral) represents a direct measure for the P-gp activity (see Fig.6).

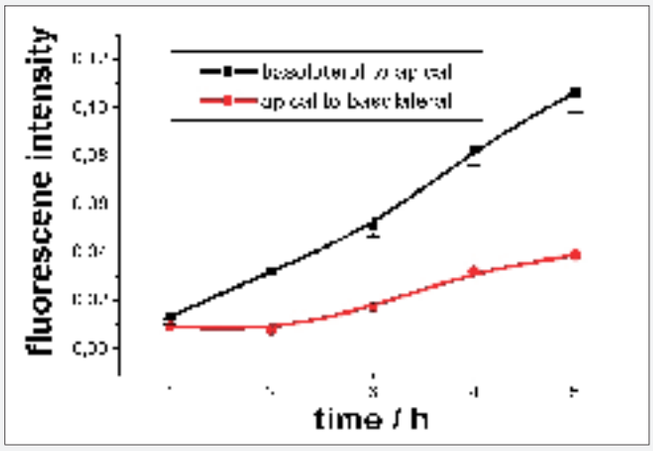


Fig.5 Fluorescence intensity vs. time plots for the basolateral-to-apical and apical-to-basolateral transport of rhodamine-123.

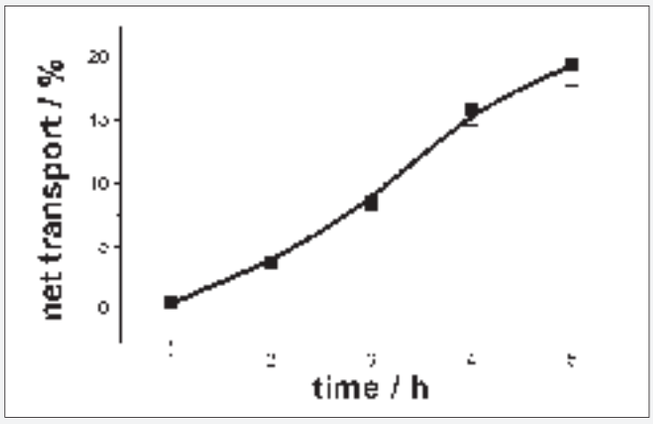


Fig.6 Net transport of P-gp mediated rhodamine-123 efflux.

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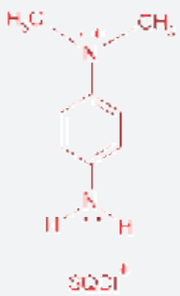
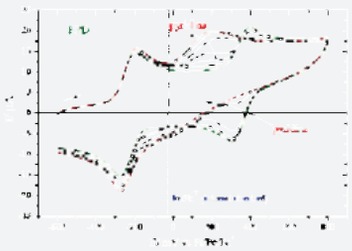
Prof. Dr. Ulrich Nickel

Electrochemical Reduction of Aromatic Azo Compounds and the Chemical and Electrochemical Oxidation of the Resulting Amines.

The degradation of aromatic azo compounds is an important task in environmental chemistry. A procedure has been developed to convert these chemically and biologically very stable substances by means of electrochemical reduction to amines, which subsequently are destroyed with ease by common methods of environmental technology. The mechanisms and the kinetics of the oxidation of these aromatic amines by inorganic compounds are of interest also for theoretical considerations. Particularly p-phenylenediamines can be regarded as model systems for the study of electron transfer reactions, which are coupled to proton transfer reactions. Therefore, studies of this kind have been carried out both in homogeneous solution and at the surface of electrodes. The problem of proton transfer in non aqueous solution has been resolved by the addition of a tiny amount of pyridine. This procedure offers a new interesting field for the study of the coupled transfer of electrons and protons.





Der Abbau aromatischer Azoverbindungen besitzt große Bedeutung in der Umweltchemie. Im Arbeitskreis wurde ein Verfahren entwickelt, um diese chemisch und biologisch resistenten Verbindungen durch elektrochemische Reduktion in die Amine zu überführen, die dann in einfacher Weise mit den üblichen Verfahren der Umwelttechnologie zerstört werden können. Der Mechanismus und die Kinetik der Oxidation dieser aromatischen Amine durch anorganische Substanzen ist auch unter theoretischen Gesichtspunkten sehr interessant. Vor allem p-Phenylendiamine können als Modellsysteme für die Untersuchung von Elektronenübertragungsreaktionen angesehen werden, die von einer Protonenübertragung begleitet sind. Aus diesem Grund wurden derartige Untersuchungen sowohl in homogener Lösung wie auch an der Oberfläche von Elektroden durchgeführt. Das Problem der Übertragung von Protonen in nicht wässriger Lösung wurde durch die Zugabe sehr geringer Mengen an Pyridin gelöst. Dieses Verfahren eröffnet ein neues interessantes Gebiet der Untersuchung gekoppelter Elektronen- und Protonenübertragungsreaktionen.

Electrochemical reduction of azo-compounds in special electrochemical cells

To reduce aromatic azo compounds several electrochemical cells have been developed. Usually, carbon felt cathodes were chosen, due to the high over potential of the hydrogen formation and the efficient reaction in a three-dimensional electrode set-up.

The course of the reduction of azo compounds like sunsetyellow can be followed by recording time resolved UV-vis spectra. Several isosbestic points confirm the lack of side reactions, because of the special configuration of the anode (i.e., a platinated titanium wire) in the center of the cell. Thus, the anodic oxidation of the formed amines can be avoided. The amines are removed from the reaction solution by either adsorption at, for example, suitable resins or by oxidation in subsequent chemical and / or electrochemical processes to the corresponding quinoidic compounds.

Fig. 1 exhibits the influence of i) the electrode material and ii) current on the rate of the reduction. Evidently, carbon felt cathodes (a) and (a´) are much more efficient than solid cathodes (b) and (c). The platinum anode wire (a), on the other hand, performs better than a large area anode (a´), and (c). Moreover, as curve c shows, the reduction is also achieved with alternating currents.

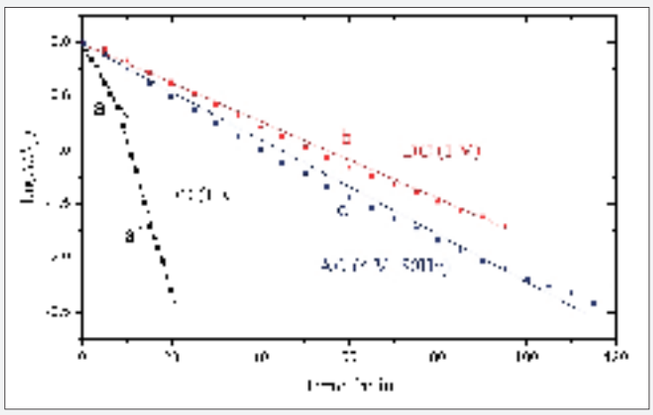


Fig. 1 Influence of the electrode material and kind of current on the rate of reduction of sunsetyellow recorded at 530 nm.

An example for further improvement of the electrochemical reduction shows Fig. 2.

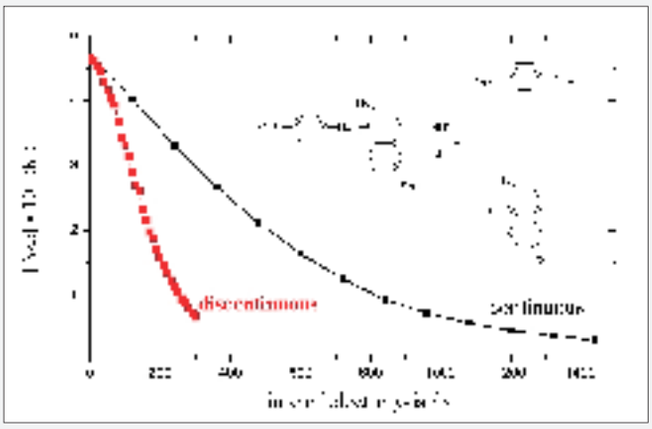


Fig. 2 Comparison of the continous and discontinuous reduction of Sunsetyellow.

The advantage of a three-dimensional carbon felt can be used when allowing sufficient time for the azo-compound to diffuse from the bulk of the solution to the electrode. Therefore, the reduction was carried out discontinuously, that is, interrupting the current in one minute intervals for 10 s.

This method is shall be applied in operating a cascade of electrochemical cells, which have been installed to clean the waste water of a company (see Fig. 3).

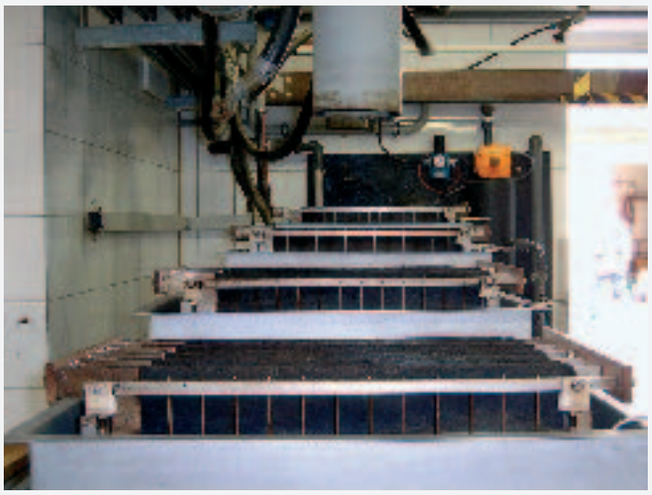
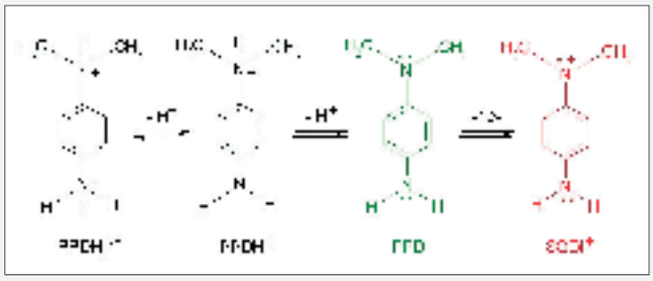


Fig. 3 Four electrochemical cells of a cascade with continuous flow.

Chemical oxidation of N-substituted p-phenylenediamines with peroxodisulphate

Oxidation of p-phenylenediamines (PPD) has been carried out with many oxidizing compounds. In general, no direct relationship has been established between the reaction rates and the standard redox potentials of the redox couple. Weak chemical oxidants – like iodine and hexacyanoferrate(III) – oxidize very fast The course of these reactions requires stopped-flow techniques. In contrast, strong oxidizing Iron(III)$_{aq}$ or peroxodisulphate react very slowly. Key to the reaction is an autocatalytic increase of the reaction. Hereby, equilibrium conditions between the reduced form of PPD and the completely oxidized QDI form to regenerate SQDI is rapidly established.
Most often, only the unprotonated p-phenylenediamine is oxidized. At pH < 6 the concentration of this form is, however, very low.



The p-semiquinonediimine (SQDI) is stable in the 2 < pH < 9 range. Due to its prominent absorbance, especially in the visible region, the course of the reactions is followed with ease.

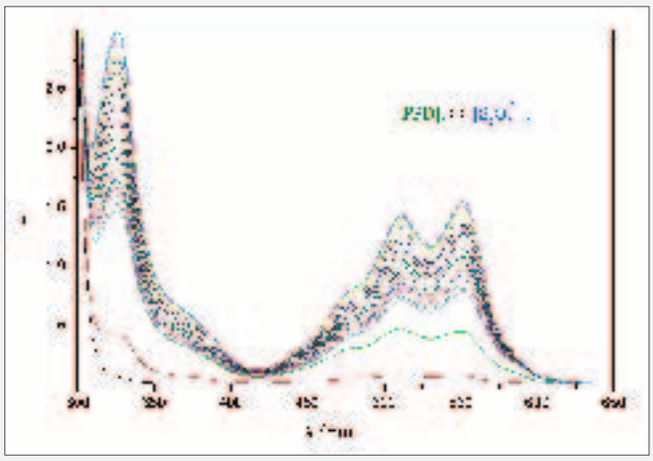
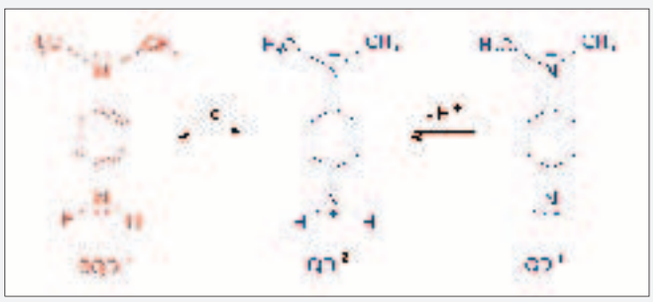
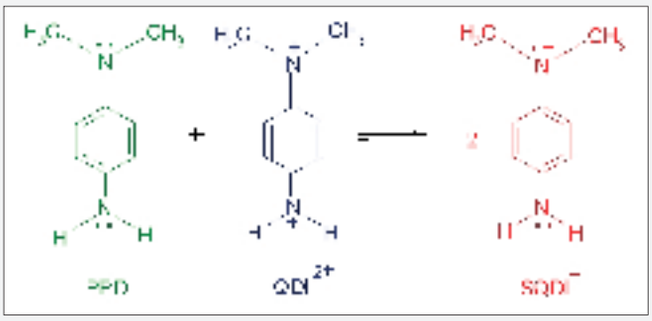


Fig. 4 Time resolved spectra of the formation of SQDI by oxidation of 1 mM N,N-diethyl-p-phenylenediamine with 0.1 mM peroxodisulphate at pH≈ 4,0; d= 10 mm; T= 25°C.

SQDI is oxidized to the corresponding uncoloured quinonediimine (QDI), which in aqueous solution looses a proton.



The synproportionation between PPD and QDI affords high concentrations of the corresponding ion radicals:



The oxidation of PPD by peroxodisulfate ($S_2O_8^{2-}$) in aqueous solution follows a complex mechanism. Implicit is a radical chain reaction, linked to an autocatalytic reaction as well as to several consecutive and parallel reactions. As soon as trace amounts of SQDI are present, peroxodisulfate oxidizes nearly exclusively this organic radical to the corresponding QDI. The sulfate radical ($SO_4^{\cdot-}$), which is formed by the 1-electron reduction of $S_2O_8^{2-}$, preferably oxidizes PPD. The rate of this radical chain reaction increases autocatalytically, because of the fast synproportionation between QDI and PPD. This synproportionation regenerates up to two molecules SQDI for each molecule SQDI oxidized by $S_2O_8^{2-}$ (and $SO_4^{\cdot-}$). Eventually, the contribution of the radical chain reaction drops down. During the autocatalytic increase of SQDI concentrations two consecutive reactions are considered

$$PPD \rightarrow SQDI \rightarrow QDI$$

$$S_2O_8^{2-} \rightarrow SO_4^{\cdot-} \rightarrow SO_4^{2-}$$

as they are linked to four parallel reactions

$$PPD + S_2O_8^{2-} \rightarrow SQDI$$

$$SQDI + S_2O_8^{2-} \rightarrow QDI$$

$$PPD + SO_4^{\cdot-} \rightarrow SQDI$$

$$SQDI + SO_4^{\cdot-} \rightarrow QDI$$

Overall, the synproportionation functions as the pump of the reaction. Rate determining is hereby the SQDI oxidation by peroxodisulfate. Despite such complex mechanism the rate constants for the oxidation i) of N,N-dimethyl-p-phenylenediamine and ii) of the corresponding semiquinonedimine by $S_2O_8^{2}$ (i.e., k_1 and k_2) was determined. A procedure was used that is based on a plot of the formation rate of SQDI, measured as change in absorbance, against the corresponding absorbance. At 25 C, pH = 5.4 and ionic strength 0.025 M, the pH-dependent rate constant has the value 1,8 (± 0.2) $M^{-1}s^{-1}$, whereas the pH-independent rate constant k_2 is 95 (± 4) $M^{-1}s^{-1}$.

This very complex reaction mechanism is demonstrated by the results displayed in Fig. 5. Notably, all these different curves are obtained by mixing only two reactants in aqueous solution varying nothing more than the initial concentration.

Excess of PPD

▪ variation of $[PPD]_o$ (**a**):
The course of the reaction is independent of [PPD], the reaction is zero order in PPD.

▪ variation of $[S_2O_8^{2-}]_o$ (**b**):
The reaction depends strongly on $[S_2O_8^{2-}]$, the reaction is 2nd order in $S_2O_8^{2-}$.

Stoechiometric excess of $S_2O_8^{2-}$:

▪ variation of $[PPD]_o$ (**c**):
The half time (given by the maximum absorbance) is almost independent of [PPD]. The reaction is 1st order in PPD

▪ variation of $[S_2O_8^{2-}]_o$ (**d**):
The half time depends on $[S_2O_8^{2-}]_o$. The reaction is 1st order in $S_2O_8^{2-}$.

A serious problem is, however, that the sulphate radical attacks nearly all compounds that are present in the solution – also the buffer substances. Our next goal is to detect the influence of this radical on the course of the reaction. Furthermore, we intend to reveal the influence of additives like ascorbic acid, hydroxylamine, hydrazine and sulphite, which are often used as antioxidants.

Electrochemical Oxidation of N-substituted p-phenylenediamines

Electrochemical oxidations of p-phenylenediamines are usually accompanied by proton transfer. Thus, this class of compounds is well suited for testing coupled proton und electron transfer reactions, especially in non aqueous media. As an electrochemical inert substance, which can accept and / or release protons, we have chosen pyridine.

The redox behaviour of N,N-dimethyl-p-phenylenediamine and N,N-dimethyl-p-phenylenediamine·2HCl (PPD·2HCl) in acetonitrile was studied by means of cyclic voltammetry – both in the absence and in the presence of proton accepting pyridine. The oxidation occurs in two separate steps yielding first $SQDI^+$ and then subsequently QDI^{2+} or $QDI^+(H^+)$. In the case of N,N-dimethyl-p-phenylenediamine the 1st oxidation step is fully reversible, while the 2nd oxidation step is slightly quasi-reversible. At 10 °C the formal redox potentials of the $PPD/SQDI^+$ and $SQDI^+/QDI^{2+}$ redox couples are - 0,200 ± 0,005 V and 0,380 ± 0,010 V (versus Fc/Fc^+), respectively. The synproportionation constant $K_{syn} = [SQDI^+]^2/[PPD][QDI^{2+}]$ is $2.1 \cdot 10^{10}$.

Fig. 6 illustrates that the addition of pyridine to the reaction mixture leads to a shift of the 2nd anodic wave to less positive potentials. This shift is primarily due to proton transfer from QDI^{2+} to pyridine to form QDI^+, which overall renders the

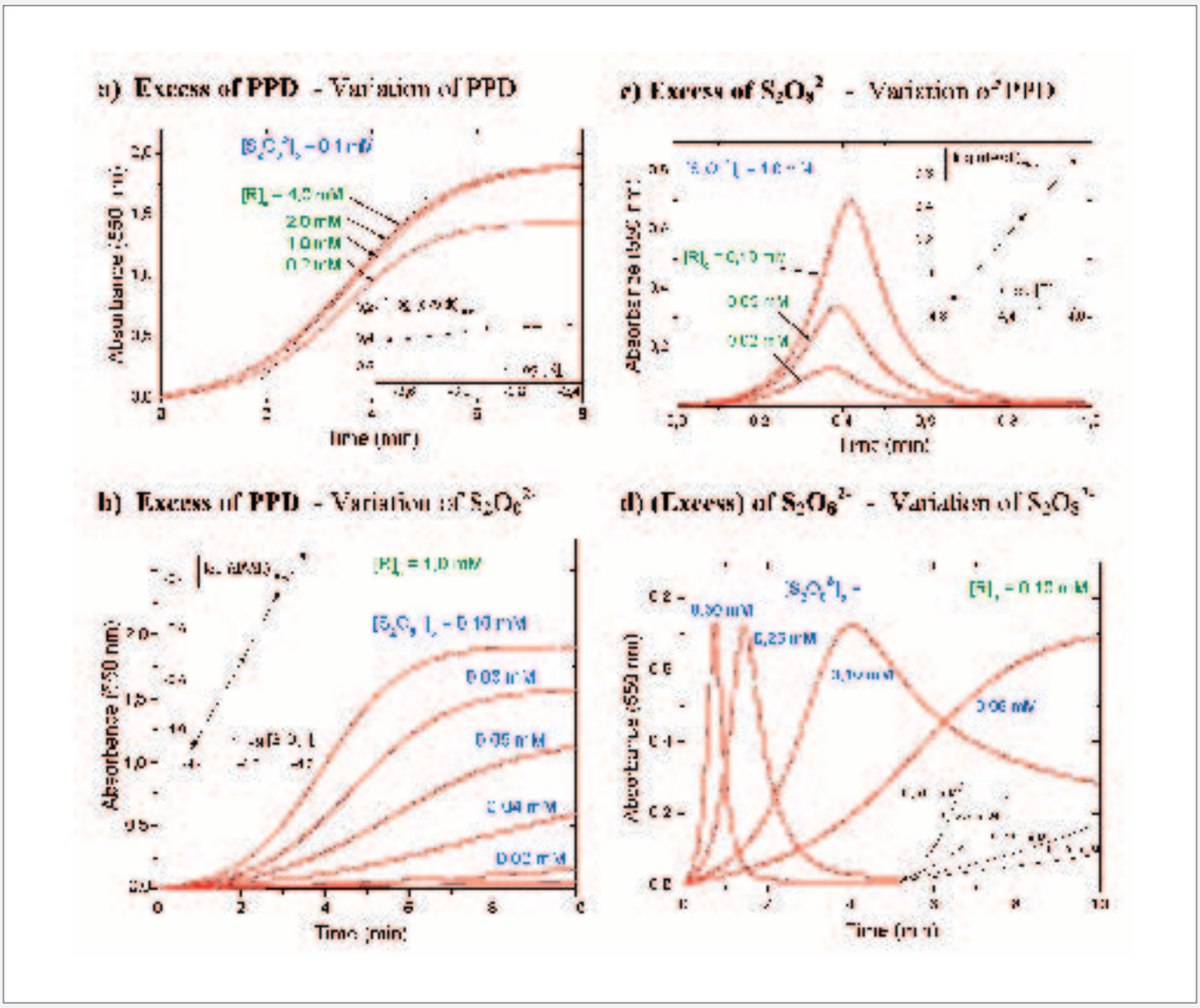


Fig. 5 Influence of the ratio of the initial concentration of N,N-dimethyl-p-phenylenediamine and peroxodisulphate on the formation rate of SQDI, recorded at pH≈ 4,0; d= 10 mm; T= 25°C

oxidation easier. The corresponding cathodic peak, on the other hand, disappears as the reduction of QDI^+ necessitates a proton. The formal oxidation potential of the redox couple $SQDI^+/QDI^+(H^+)$ is 0,190 ± 0,010 V and, therefore, the syn-proportionation constant amounts to $K'_{syn} = 1{,}7 \cdot 10^6$.

N,N-dimethyl-p-phenylenediamine ·2HCl lacks completely the 1st anodic peak (see Fig. 7). The position of the anodic peak is given by the direct oxidation of $PPDH^+$ to $QDI^{2+}(H^+)$ and is similar to that of the $SQDI^+/QDI^{2+}$ redox couple. Upon adding pyridine the 2nd anodic peak shifts notably to less positive potentials and redox processes attributable to the $PPD/SQDI^+$ redox couple are seen. As pyridine influences the potential of the Ag pseudo-reference electrode a reference electrode based on the ferrocene-ferrocenium redox couple was used.

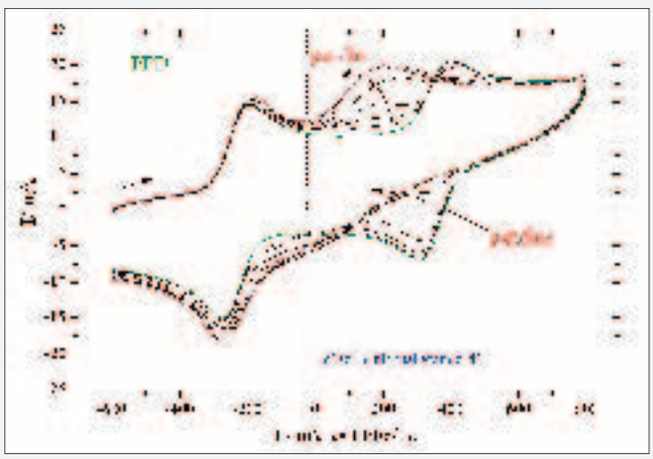


Fig. 6 Influence of pyridine on the cyclic voltammograms of N,N-dimethyl-p-phenylenediamine in acetonitrile.

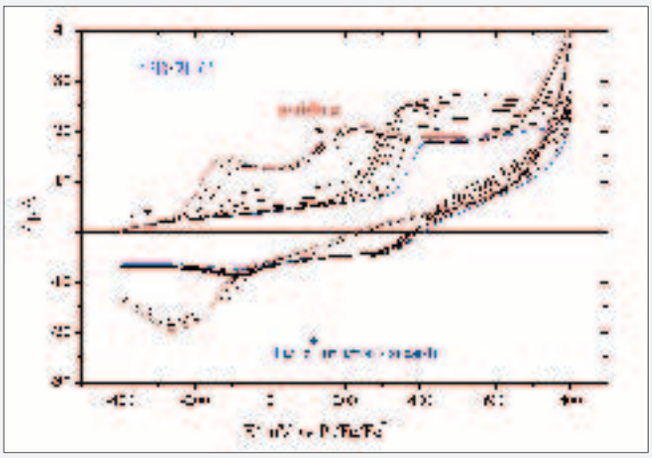


Fig. 7 Influence of pyridine on the cyclic voltammograms of the HCl salt of N,N-dimethyl-p-phenylenediamine in acetonitrile.

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Prof. Dr. Hans-Peter Steinrück

New materials and surface reactions

Surfaces are the skin of any condensed material. They dominate its interaction with the environment and play a decisive role in numerous natural and technological processes, ranging from heterogeneous catalysis and nanotechnology to modern material science. The activities of the Steinrück group focus on these areas with the main research interests in (1) the development of new materials with novel electronic and chemical properties, (2) the detailed investigation of elementary steps of surface reactions, and (3) the development and construction of advanced scientific apparatus. For these investigations, a large variety of experimental methods is applied, including synchrotron radiation-based techniques.

Oberflächen sind die natürliche Begrenzung jedes Festkörpers und jeder Flüssigkeit. Sie bestimmen die Wechselwirkung mit der jeweiligen Umgebung und spielen damit naturgemäß eine Schlüsselrolle für eine Vielzahl natürlicher und technologischer Prozesse, von der heterogenen Katalyse über die Nanotechnologie bis hin zur modernen Materialwissenschaft. Die Aktivitäten der Arbeitsgruppe Steinrück liegen auf diesem Gebiet. Im Vordergrund stehen (1) neue Materialien mit neuartigen elektronischen und chemischen Eigenschaften, (2) die detaillierte Untersuchung der Elementarschritte von Oberflächenreaktionen und (3) die Entwicklung und der Aufbau neuer wissenschaftlicher Messapparaturen. Dazu werden eine Vielzahl experimenteller Methoden eingesetzt, einschließlich der Nutzung von Synchrotronstrahlung.

Surfaces as templates for molecular architectures

Single crystal surfaces in ultrahigh vacuum are perfect templates for the adsorption of molecular aggregates in a well-defined, clean, and solvent-free environment. Metalloporphyrins are of particular interest as they are building blocks for nanosized structures and play a key role in many natural and technological processes. There, they often control the decisive steps in reactions that involve the reversible attachment of a molecular ligand to the central metal ion. Their chemical and electronic properties can be widely modified by variation of the metal center and additional ligands, making them promising candidates for tailored catalytic processes and for the integration in electronic circuits. In addition, adsorbed metallo-porphyrins are excellent model systems to study the interaction of a (complexated) metal ion with a surface in a well defined distance. The strength of this interaction can be tuned by spacer substituents on the periphery of the porphyrin unit.

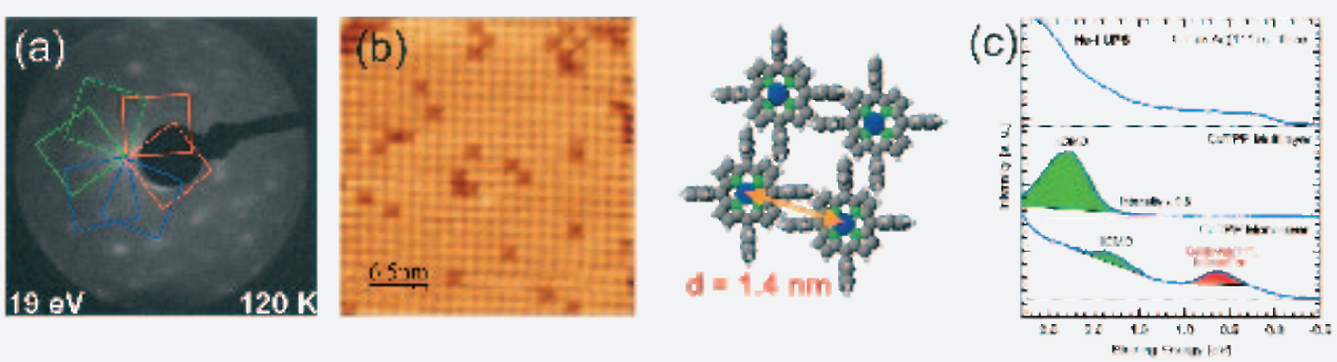

Fig. 1: Adsorption of Co(II)-tetraphenylporphyrin on a Ag(111) single crystal surface: (a) Low energy electron diffraction pattern of a well ordered monolayer; (b) corresponding scanning tunneling microscopy image of one of six nonequivalent domains, along with a schematic illustration of the lateral arrangement in the unit cell. (c) UV photoelectron spectroscopy data showing the valence region of the monolayer.

Tailoring the electronic and chemical properties of solid surfaces [1-4]

The ultimate goal when developing new materials is to be able to tune their properties in a well defined way over a wide parameter range, depending on the desired application. The systems investigated in our lab range from ultrathin metal and oxide layers on metals and oxides, to silicides, metal/molecule sandwich layers and organic layers on metals. To tailor the properties, we systematically search for possibilities to modify growth modes, alloy formation or chemical state in a well defined way, i.e., by choosing the appropriate temperature, deposition rate, or other parameters such as interface composition or coadsorbed molecules. The key for understanding the chemical properties of these systems is the knowledge of their electronic and geometric structures. The studies on the electronic properties focus on the valence region of the substrate and/or the adsorbate layers, which show, depending on the individual system, one-, two- or three-dimensional behavior. Concerning

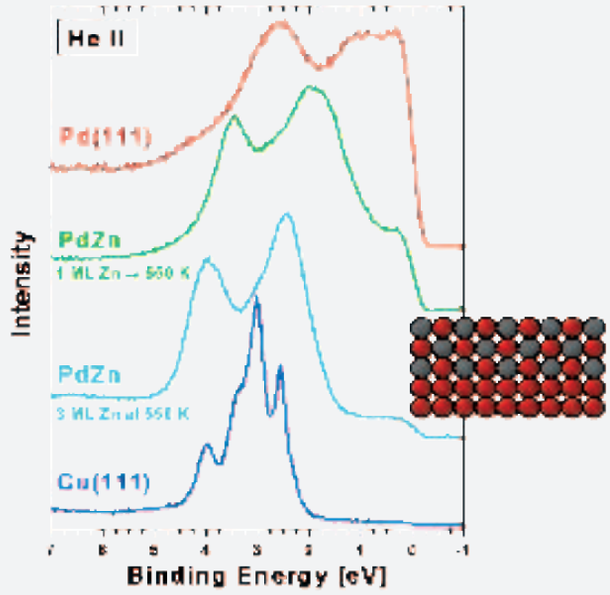

Fig. 2: UV photoelectron spectra of Pd(111), Cu(111) and two ordered alloys [4]. The alloys have been prepared by deposition of Zn onto Pd(111) at the denoted temperature. When increasing the amount of deposited Pd, the electronic structure of the Pd alloy can be changed to a structure similar to that of Cu(111), with the density of states very low at E_F (E_B=0) and highest between 2 and 4 eV. This explains the very similar performance of Cu and PdZn when used as catalysts for methanol steam reforming, a very important reaction to produce hydrogen for fuel cells.

the geometrical properties, we determine the structure of the surface as well as adsorption sites, orientation and bond distances of adsorbates. Based on that information, we are then able to modify the chemical properties, especially the strength of the adsorbate/substrate bond and the reactivity of the surface, by the appropriate combination of different materials.

New insights in surface reactions by advanced photoelectron spectroscopy [5-8]

The prerequisite for the detailed understanding of heterogeneous catalysis is the identification of the relevant elementary steps using advanced experimental methods. We investigate the kinetics and dynamics of the various processes involved in surface reactions (adsorption, intermediate formation, reaction, desorption) for selected model systems and study in particular their dependence on chemical nature, composition and structure of the surface, temperature, coverage, presence of coadsorbates, pressure or impingement rate and the translational and internal energy of the particles. For these studies, we have - among other instruments – recently built up two new unique photoelectron spectrometers. One is combined with a supersonic molecular beam and is designed for in situ X-ray photoelectron spectroscopy utilizing synchrotron radiation; it allows highly resolved measurements with a data collection time of down to 1 sec per spectrum. The other instrument is a lab apparatus developed to study surface reactions in the so-called “pressure gap”, i.e., up to pressures of 1 mbar and thereby connects Surface Science in ultra-high vacuum and real catalysis at ambient pressures and high temperatures.

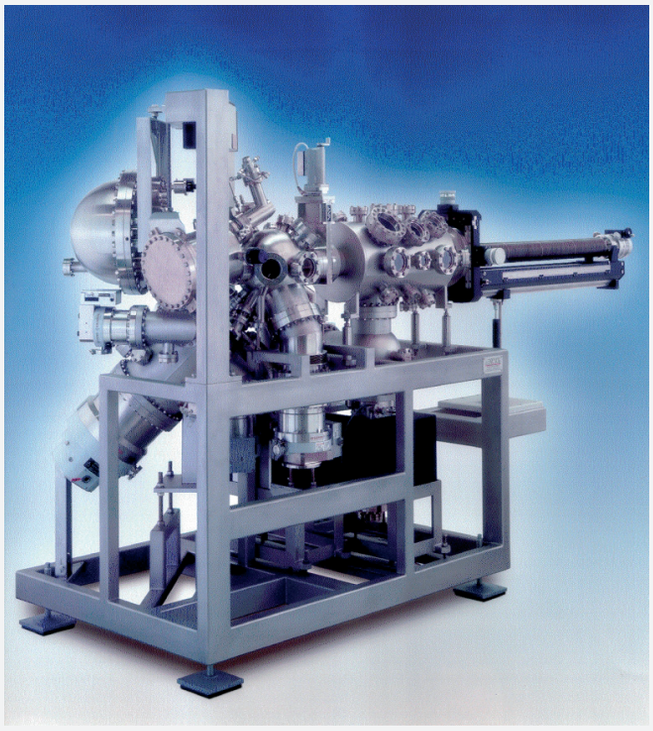

Fig. 3: Photo of a transportable UHV apparatus that combines high-resolution X-ray photoelectron spectroscopy (HR-XPS) and supersonic molecular beam. It is used for in situ studies of chemical reactions during adsorption and/or while heating the sample; the measurements are performed at synchrotron radiation facilities, e.g., BESSY II in Berlin [5]. Due to the high photon flux, full XP spectra can be measured within 1 second.

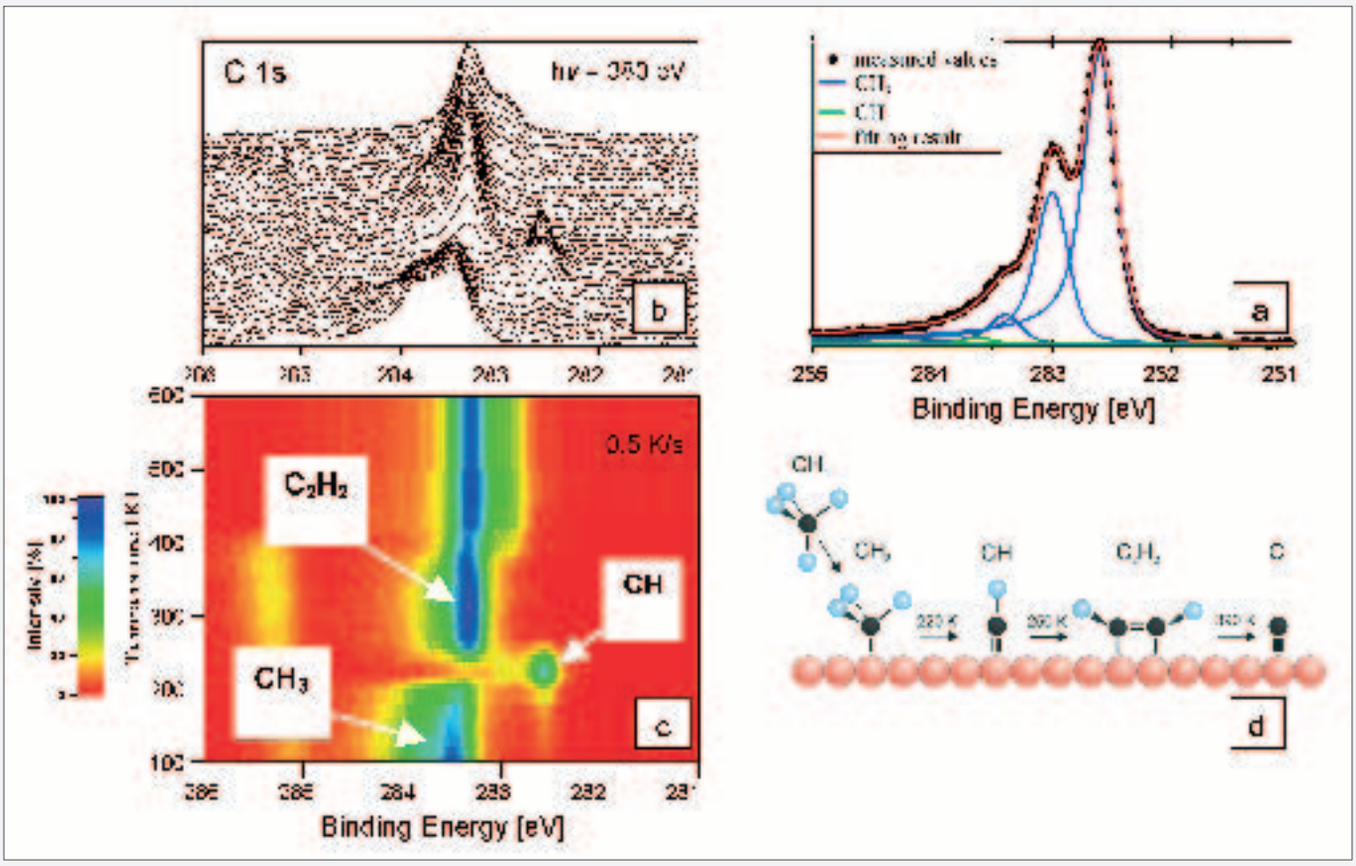

Fig. 4: Adsorbed methyl (CH_3) is the result of dissociative adsorption of methane (CH_4) on Ni(111) at 120 K. This activated process is facilitated in UHV by dosing the methane with a supersonic molecular beam, with kinetic energies > 0.25 eV. Highly-resolved XP spectra of adsorbed methyl recorded using synchrotron radiation at BESSY II show a well resolved fine structure (a), due to vibrational excitations of the ionic final state. Using time-resolved XPS during continuous heating of the adsorbed methyl layer with a heating rate of 0.5 K/s, a temperature-programmed XPS series of C 1s spectra, as shown in (b) is obtained. Encoding the intensity using a colour scale, the thermal reaction can be visualized in (c). Each adsorbed species is represented by a characteristic C 1s binding energy. Following a dehydrogenation step from CH_3 to CH around 220 K, a C-C coupling reaction to acetylene (C_2H_2) can be observed, before total dehydrogenation takes place above 400 K; this reaction pathway is schematically illustrated in (d). The time per C 1s spectrum is 8 s; spectra were recorded every 10 K.

By studying the appropriate core levels, we can distinguish different adsorbates, intermediates, and reaction products in situ during the adsorption process or their thermal evolution, while applying a temperature ramp. Furthermore, even different adsorption sites of the same molecules can be identified. Vibrational excitations during the photoemission process are resolved and can be further used to differentiate between adsorbed species. The investigated molecules range from carbon monoxide, nitric oxide, carbon dioxide, water, alkanes, alkenes, alkines to benzene, cyclohexane, and simple alcohols and aldehydes. Very recently, we have also started to investigate the surfaces of ionic liquids under UHV conditions.

Tailoring lateral nanostructures for catalysis

Recently, we started to extend our investigations on layer systems (which represent vertical nanostructures) to well-defined lateral nanostructures and laterally nanostructured surfaces. The investigated length scales range from the subnanometer region (i.e. atomic resolution) up to structured areas of some mm. Central topics are the preparation of nanostructures on surfaces and the investigation of the related chemical properties; special attention is paid to new preparation routes and new nanoscopic materials relevant for heterogeneous catalysis. For this purpose, we have installed a new state-of-the-art,

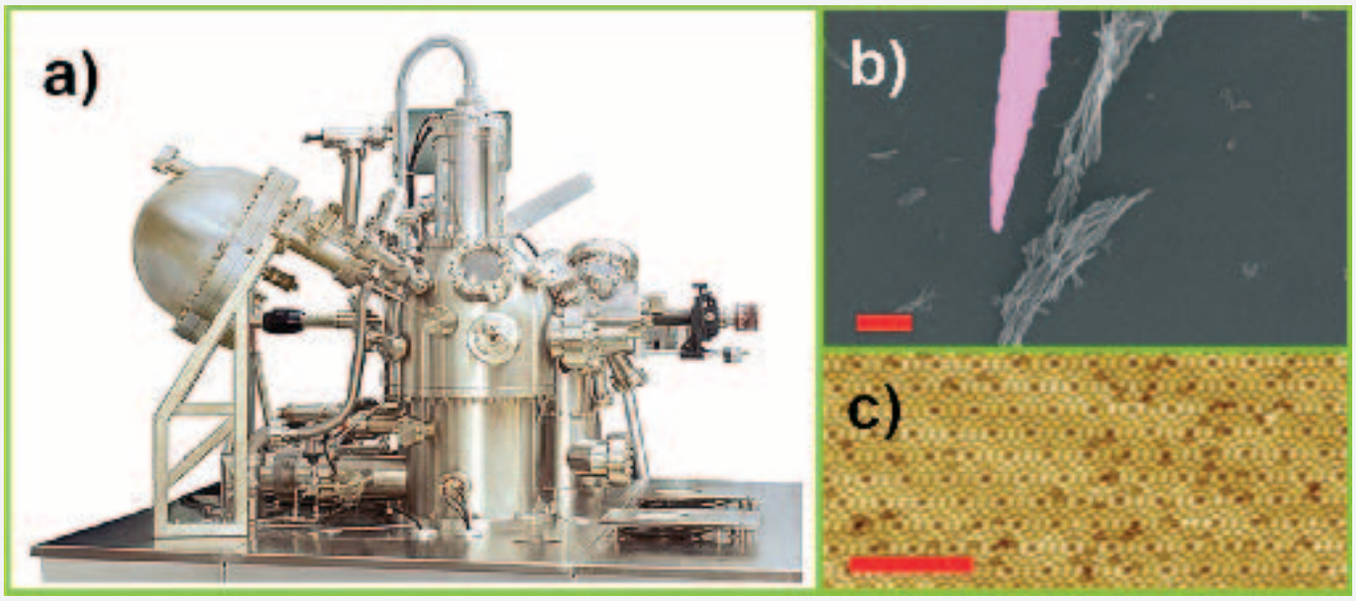

Fig. 5: a) Photo of UHV chamber with combined SEM, STM, and hemispherical electron energy analyzer (left).
b) SEM image showing bundles of Titanium dioxide nanotubes on Si(111) and the STM tip (marked purple) placed over the region of interest. The scale bar represents 500 nm.
c) STM image of Si(111)-7x7 surface with atomic resolution. The scale bar represents 10 nm.

combined scanning electron (SEM) and scanning tunneling microscope (STM), which enables us to study the same spot on the surface with both methods. An additional hemispherical electron analyser (EA) in combination with the electron column of the SEM allows us to acquire the local elemental composition of a sample by means of Auger electron spectroscopy (AES). By tuning to a specific energy and scanning the electron beam (scanning Auger microscopy), one obtains elemental maps of the surface.

Our approach to fabricate lateral nanostructures is to exploit the very fine electron beam of the SEM to locally crack certain precursor molecules on the surface. A deposit (electron beam induced deposition, EBID) builds up (non-volatile part) and possibly fractions of the dissociated precursor molecule desorb from the surface (volatile part). In the ideal case, e.g., metal containing precursor molecules that are dosed as a gas into the chamber will produce an EBID deposit that consists of pure metal. An important goal is to learn more about the fundamental aspects of this type of nanostructuring process and how to optimize and control the chemical composition of the EBID deposit. These are interesting topics, also from the technological viewpoint, since the EBID process is on the borderline of industrially relevant techniques, namely conventional electron beam lithography and chemical vapour deposition (CVD).

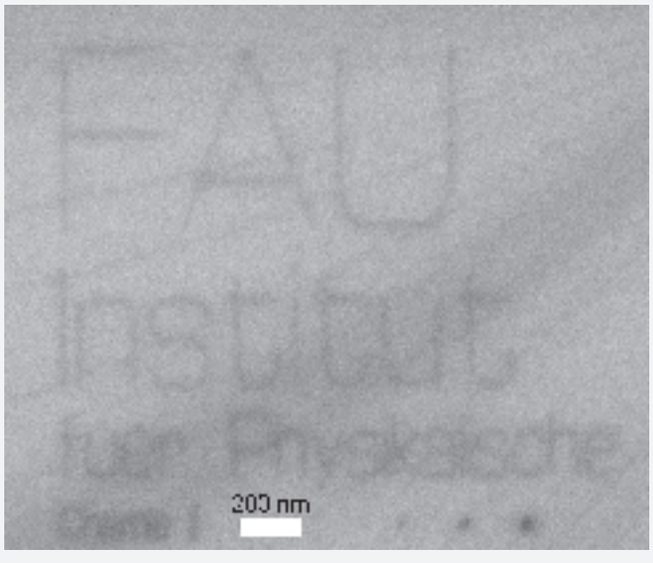

Fig. 6: SEM image of structures generated by a lithographic EBID process on Si(111). Ethylene was dosed as the precursor molecule for the carbonaceous deposits (dark letters). For some letters (e.g. the F) the line widths are clearly smaller than 20 nm.

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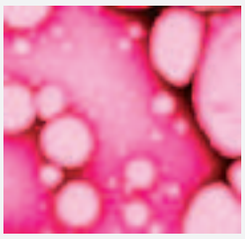
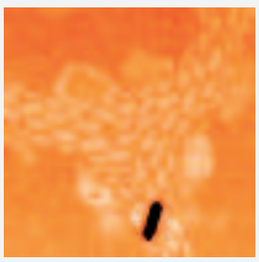
Prof. Dr. Rainer Fink

Molecule spectroscopy, organic thin films and microspectroscopy

Large organic molecules have become promising materials in molecule based electronics (field effect transistors, light-emitting devices) due to the possibility to tailor their electronic and optical properties. However, the properties of the electronic devices largely depend on the structural properties of the organic film. In case of sufficiently large interactions at the interface between the organic molecules and the underlying substrate (usually metal single crystals) the geometric properties of the film can be controlled. We concentrate on the electronic and structural properties of the metal-organic hybrid systems using high-brilliance synchrotron radiation. In order to monitor lateral inhomogeneities on a lateral length scale below 30 nm, we are developing high-resolution microspectroscopes utilizing the superior spectral contrast in the near-edge x-ray absorption spectra of organic molecules. Further interests concern magnetic studies, ferrofluids and microscopic studies of biological objects.





Große organische Moleküle werden in zunehmendem Maße für elektronische Anwendungen eingesetzt. Deren Eigenschaften hängen stark von der Struktur der kondensierten Molekülschichten ab. Unsere Arbeiten konzentrieren sich auf Metall-Organik-Hybridsysteme, der Untersuchung der geometrischen und elektronischen Struktur und den einhergehenden Grenzflächeneigenschaften. Dazu wird u. a. hochbrillante Synchrotronstrahlung eingesetzt. Aus der Röntgenabsorptionsfeinstruktur (NEXAFS) und Photoemission (XPS) kann auf intra- und intermolekulare Wechselwirkungen oder auf die Bindung der Moleküle an der Grenzfläche zum Substrat geschlossen werden. Zwei in Aufbau befindliche Mikrospektroskope erlauben volumen- und oberflächenempfindliche spektroskopische Untersuchungen mit einer Ortsauflösungen unter 30 nm. Das Anwendungspotenzial erstreckt sich auf magnetische Untersuchungen, Flüssigkeiten oder biologische Objekte.

Electronic structure of large organic molecules

Detailed investigations of the electronic properties of large organic molecules have become a major issue in fundamental research. The sophisticated experimental techniques and theoretical concepts available nowadays allow a comprehensive understanding of the molecular properties and *intramolecular* effects. Major sources of information are the various electron spectroscopic techniques which can also be utilized to investigate the intermolecular interactions in the solid state and the molecular bonding to a different material, e.g. a substrate. The near-edge x-ray absorption fine structure (NEXAFS) spectroscopy is extremely well suited to organic substances [1-4]. NEXAFS supplies interesting information on the reorganization of the electronic system upon core hole creation, which leads to the selective excitation of vibronic modes due to local changes in the molecular orbital system. Our investigations refer to a variety of model substances (e.g. TCNQ based acceptor molecules) for the application in molecular electronics. In particular NEXAFS investigations at ultimate photon energy resolution (resolving power > 10.000) offers the possibility to evaluate structure-property relationships of intermolecular interactions in interface-modified organic films.

Fig.1 shows high-resolution C K-edge NEXAFS data of TCNQ prepared as ultrathin film on a Ag(111) substrate. The observed fine structure refers to both, electronic excitations and the coupling of electronic excitations to vibronic modes. In the lower part of Fig. 1 the calculated resonances from a free TCNQ molecule are plotted. The different colours refer to the chemically different carbon atoms within the TCNQ molecule. Interestingly we find only few vibronic modes which efficiently couple to the core-excited electrons for most molecular substances under investigation. From the linear NEXAFS dichroism it is found that most molecules are oriented coplanar with the metal substrate due to the strong π-interaction.

Another interesting class of substances are magnetic supramolecules prepared in the group of Prof. Saalfrank. In these so-called “molecular magnets” the magnetic moments of the paramagnetic ions (e.g. Fe, Co, Mn) couple ferromagnetically at sufficiently low temperatures. Thus, interesting phenomena like spin tunneling can be explored. Fig. 2 shows the NEXAFS spectra at the Mn L-edge for two different circular polarizations and the resulting x-ray magnetic circular dichriosm (XMCD) spectrum of a supramolecular aggregate consisting of 7 Mn ions in two different valence states. The temperature of about 10 K is not low enough to observe the ferromagnetic coupling.

The dichroic signal is due to the Zeeman splitting for the "isolated" paramagnetic Mn ions.

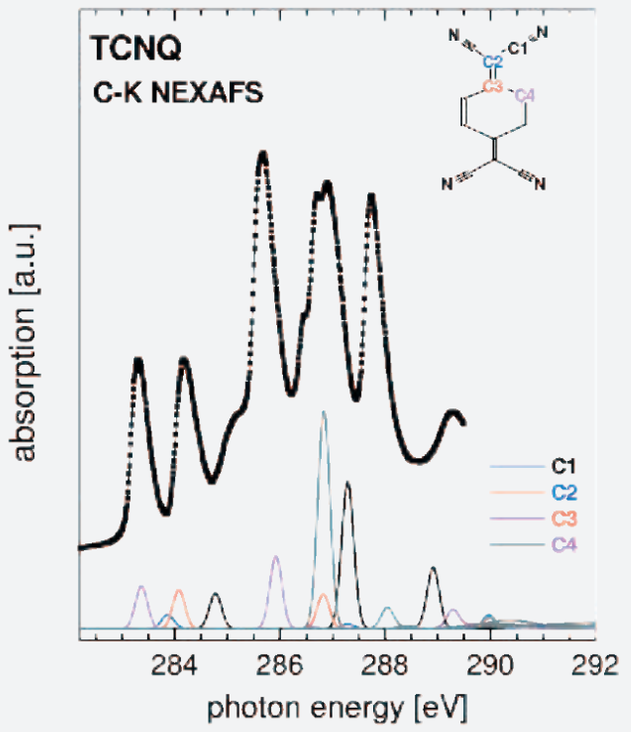


Fig. 1: High-resolution C K-edge NEXAFS spectrum from an ultrathin TCQU film adsorbed on Ag(111) in comparison with ab-initio Hartree-Fock calculations for an isolated molecule.

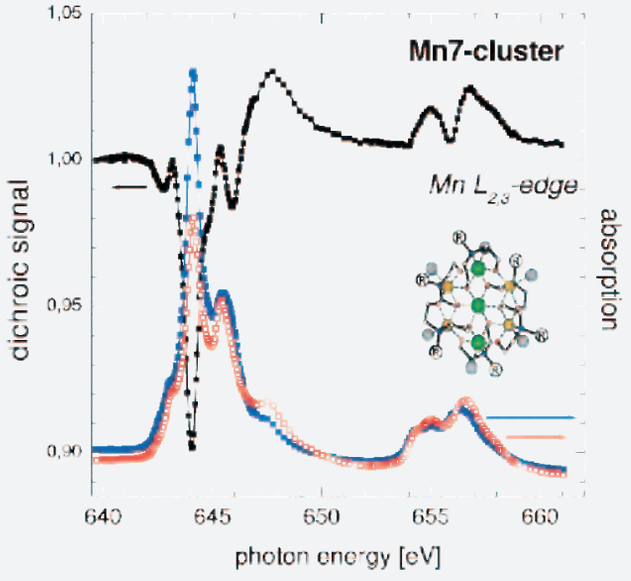
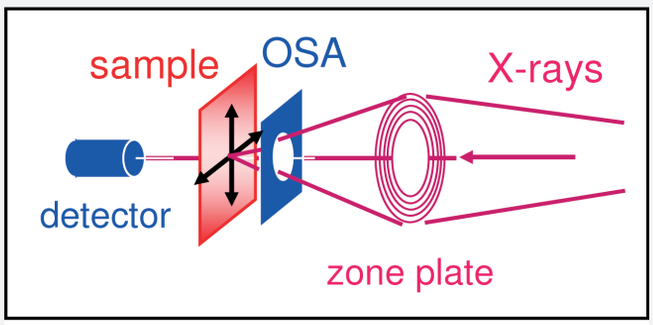


Fig. 2: Mn L2,3-edge NEXAFS spectra of supramolecules containing 7 Mn ions for circularly polarized light (blue, red) and corresponding XMCD spectrum (black). Spectra were collected at 10 K and a magnetic field of ±3 Tesla.

Microspectroscopy

Focusing soft x-rays down to about 25 nanometers allows one to investigate the electronic and chemical properties on the respective length scales. Scanning transmission x-ray microscopy (STXM) uses a Fresnel zone plate as optical elements in this type of microspectroscopes (instrument scheme see Fig 3, top). The photon-energy dependent transmitted x-ray intensity through a raster-scanned sample (thin solid or liquid films, thickness 100 nm to 1 µm) yields local spectroscopic information. On the bottom of Fig. 3 a 2D STXM image from a thin TNCQ film recorded at 298 eV is shown from which preferential orientation of TCNQ microcrystals is concluded. Within a larger consortium we presently install a STXM called PolLux at the Swiss Light Source (Villigen/Switzerland). This instrument, which is a modified version of the setup at the ALS [5] will enable us to investigate thin organic films with respect to lateral chemical inhomogeneities also in-situ during wet chemical processing. Such studies may be important for, e. g., sensor applications.



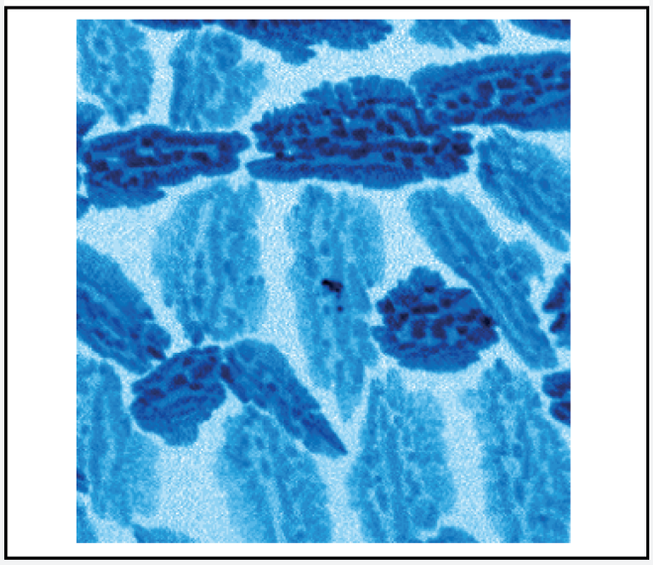


Fig. 3: Top: Schematic sketch of a scanning transmission x-ray Microspectroscopic using zone plate optics. The order-sorting aperture (OSA) selects the first-order diffracted x-rays focused onto the sample which is raster-scanned to produce a 2D image. Bottom: 2D image (60 x 60 µm²) of a TCNQ film (nominal thickness: 100 nm) adsorbed on a Si_3N_4 membrane. From the different colours for horizontal and vertical crystallites preferential growth of the microcrystals is concluded.

Another more surface-sensitive microspectroscopic approach is given through photoemission electron microscopy (PEEM). Besides conventional PEEM using an Hg arc lamp as excitation source in the home laboratory, the SMART spectromicroscope (installed at BESSY, Berlin) uses soft x-rays [6]. Using a special magnetic beam splitter together with an electron mirror the chromatic and spherical aberrations of the objective lens are corrected independently thus aiming at an ultimate resolution of 2 nm at full spectroscopic capabilities. Illumination with (coherent) electrons furthermore allows high-resolution electron microscopy. At present this instrument is under commissioning and partly used for the observation of the in-situ growth of organic thin films for molecular beam epitaxy.

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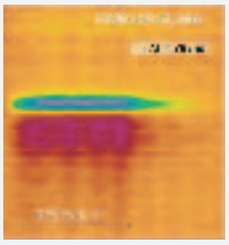
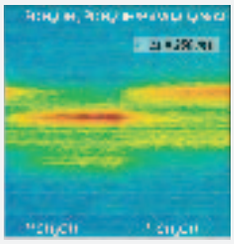
Prof. Dr. Jörg Libuda

Kinetics and Dynamics at Nanostructured Surfaces

Chemical reactions and physical processes at complex surfaces play a pivotal role in many areas of today's technology. Still, our understanding of the related physical and chemical phenomena is poor at the microscopic level and is basically limited to very few and simplistic surface reactions. In contrast, most real surface processes take place in enormously complex environments, both from a chemical and from a structural point of view. In order overcome this gap between fundamental surface science and applied research, we develop complex nanostructured model surfaces, e.g. in the field of heterogeneous catalysis. The dynamics and kinetics of chemical reactions on these models is probed using molecular beams, reactor methods and time-resolved spectroscopy from ultrahigh vacuum conditions up to atmospheric pressure. Our aim is to develop microscopically well-founded kinetic models and mechanisms which are relevant for surface and interface related applications.





Chemische Reaktionen und physikalische Prozesse an komplexen Oberflächen spielen eine Schlüsselrolle in vielen aktuellen Technologiebereichen. Ungeachtet dessen ist unser Verständnis der zugrunde liegenden Vorgänge auf mikroskopischer Ebene jedoch sehr begrenzt und beschränkt sich im Wesentlichen auf wenige und sehr einfache Oberflächenreaktionen. Hingegen laufen reale Oberflächenreaktionen im Allgemeinen in strukturell und chemisch sehr komplexen Umgebungen ab. Um diesen Gegensatz zwischen grundlegenden Untersuchungen in den Oberflächenwissenschaften und der angewandten Forschung zu überwinden, entwickeln wir Modellsysteme für komplexe, nanostrukturierte Oberflächen, z.B. im Bereich der heterogenen Katalyse. Die Dynamik und Kinetik chemischer Reaktionen an diesen Modellen untersuchen wir mittels von Molekularstrahlen, Reaktormethoden und zeitaufgelöster Oberflächenspektroskopie von Ultrahochvakuumbedingungen bis hin zu Atmosphärendruck. Ziel ist die Entwicklung mikroskopisch fundierter kinetischer Modelle und Mechanismen, die für anwendungsorientierte Fragestellungen relevant sind.

Heterogeneous catalysis, environmental and energy technology, materials science and nanotechnology: these are only few examples of central areas of 21st century technology, in which surface and interface reactions play a key role. Surprisingly, the mechanisms and kinetics of the related chemical processes is, in most cases, only poorly understood at the molecular level. Naturally, this lack of knowledge often limits rational improvement and development in the corresponding fields.

The reasons for the limited insight into 'real life' surface and interface processes become obvious if we have a closer look at the chemical systems and environments in which these reactions occur. As an example we focus on the field of heterogeneous catalysis, which is of highest economical and environmental relevance (most products in chemical industry are synthesized via heterogeneously catalyzed steps). Typical catalysts are highly complex materials such as e.g. multi-component mixtures of oxides or combined oxide-metal systems. The chemical and structural complexity of these materials is crucial: Often, the catalytic properties are found to depend sensitively on structural parameters such as particle size or shape or chemical parameters such as the properties of the support or promotor materials. In catalyst development, these dependencies provide the possibility of empirically optimizing structural and chemical properties in order to maximize selectivity and activity with respect to the desired reaction pathway. From a fundamental research point of view, however, the resulting systems are inherently difficult to characterize at the microscopic level. This problem is often referred to as the "complexity" or "materials gap" between surface science and catalysis.

A fundamental understanding of reaction kinetics on heterogeneous catalysts requires a direct link between the microscopic structure on the one side and the reaction kinetics on the other. Towards this aim we follow a strategy, which combines a model approach with detailed and quantitative kinetic experiments and in-situ spectroscopy (see Fig. 1).

Here, the principal advantage of model systems is that the complex structural or chemical features of catalyst surfaces can be simulated under well-controlled conditions. These model surfaces are typically prepared using surface science techniques under ultrahigh-vacuum conditions, thus avoiding contaminations and providing a maximum of structural and

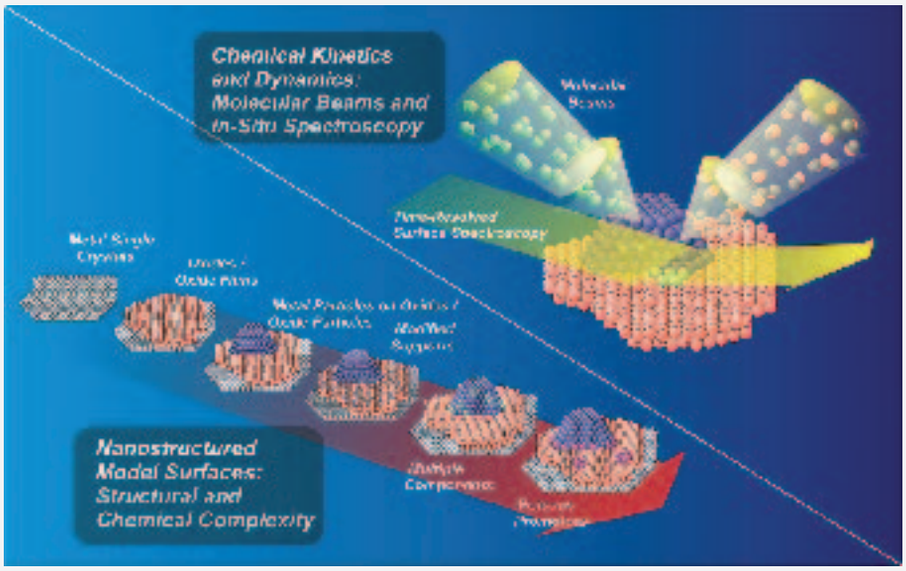


Fig. 1: (left) Development of complex model surfaces in heterogeneous molecular beams, (right) molecular beam / spectroscopy approach to surface kinetics and dynamics.

chemical control. In a hierarchical fashion, nanostructured model surfaces of increasing complexity can be designed, simultaneously avoiding the vast complexity of the real system. In a second step kinetic measurements are performed, combining molecular beam methods, reactor methods, and time resolved surface vibrational spectroscopy. In this way, connections between structural features of the surface on the one side and their role in the reaction kinetics on the other can be identified (see e.g. [1-4] for a more detailed discussion of the approach).

A particularly important class of heterogeneous catalysts are so called supported catalysts, which are based on nanometer-sized active particles finely dispersed on support materials (in most cases oxides). It is found that their catalytic properties often sensitively depend on the size and structure of the active particles, on the support as well as on the presence of poisons and promotors. These structural and chemical properties are often optimized in an empirical fashion. From a fundamental point of view many different ideas have been put forward, which may contribute to the specific activities of these systems. For example one may imagine that the electronic structure of small catalytically active metal particles may differ from the bulk material, thus modifying the adsorption and reaction behaviour (electronic effects). An alternative explanation would involve the presence of specific active sites on the particles, such as particle edges, corners or the metal/oxide interface (geometric effects). In addition, it is often suggested that also the support may play a role (support effects), either by directly taking part in the reaction, via modification of the active particles (metal-support interaction) or by surface diffusion between the support and the active component (spillover and capture zone). Moreover there are specific kinetic effects at the nanometer scale, which do not involve modified adsorption and reaction properties, such as the coupling of different active sites via surface diffusion (communication effects) or coverage fluctuations.[6] Finally, small particles are often found to change easily their structure and chemical state under the influence of reactants (restructuring, structural fluctuations, oxidation).

In spite of the large number of ideas, however, there are only very few examples, in which these phenomena have been clearly connected with the kinetics of heterogeneously catalyzed reactions at the microscopic level. It is the aim of the group, to identify and investigate such mechanistic and kinetic phenomena on complex nanostructured surfaces. In a second step, based on the experimental data, suitable concepts are developed, which allow us to describe and microkinetically model these phenomena. Finally these models may be transferred back to applied research and may help to understand, simulate and improve real surface-related processes and reactions.

A brief example is depicted in Fig. 2. Here, we investigate the dissociation and reduction of NO on a Pd/Al_2O_3 model catalyst (see Fig. 2, top). The reaction is of relevance in the field of automotive exhaust catalysis. Investigations were performed by using multiple molecular beams and time-resolved IR reflection absorption spectroscopy.[1, 5] (see Fig. 2, bottom, the figure shows a schematic representation of a new combined molecular beam / surface IR spectroscopy system at the Friedrich-Alexander-University). NO and CO are supplied via two individual molecular beam sources and the surface species are monitored as a function of time employing IR reflection absorption spectroscopy. Simultaneously, the reaction rates are recorded in gas phase using quadrupole mass spectrometry. Two IR absorption bands are found, which correspond to NO adsorbed at different sites on the Pd nanoparticles, i.e. NO adsorbed at regular (111) facets (band at lower wavenumbers) and NO adsorbed at defects, particles edges and (100) sites (band at higher wavenumbers). Upon reaction, atomic nitrogen and oxygen successively block the adsorption sites on the particles. It can be seen, however, that the atomic species preferentially block the defect sites and (100) facets, which are most active for NO dissociation, but not the regular (111) facets. As a result, the distribution of atomic intermediates over the different active sites critically controls the catalytic activity of the nanoparticles. A differentiation between atomic oxygen and nitrogen is possible by instantaneous oxygen removal using intense CO pulses (Fig. 2, arrows). In this manner, the combination of multi molecular beam experiments and time-resolved IR spectroscopy allows us to monitor the distribution of reaction intermediates over the active sites of a catalyst nanoparticle under reaction conditions.[5]

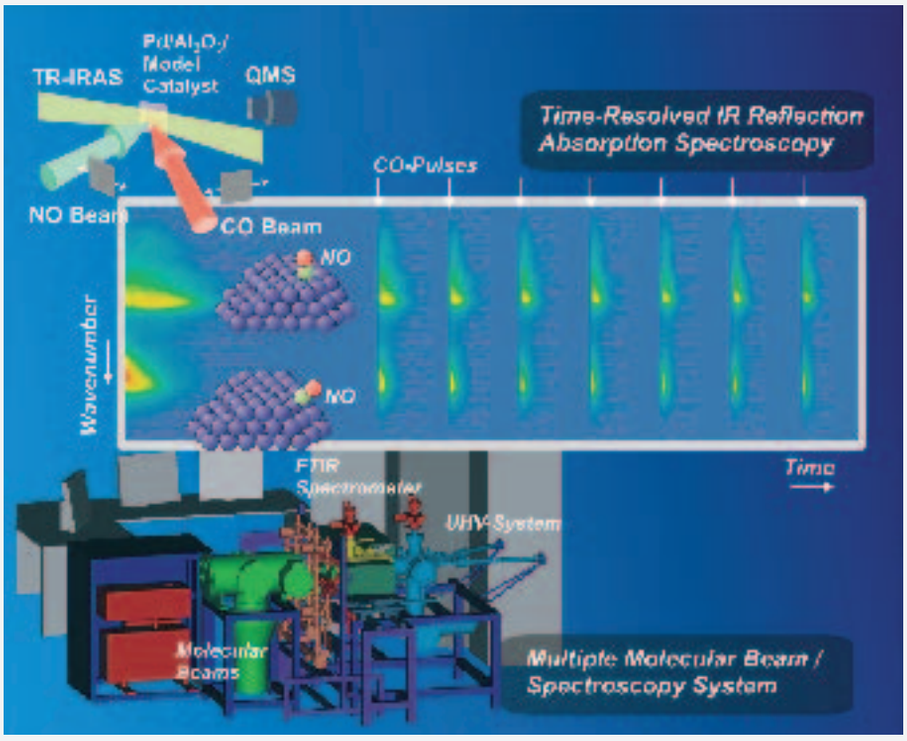


Fig. 2: (top) Kinetic study on the dissociation and reduction of NO on Pd nanoparticles supported on Al_2O_3: The distribution of atomic oxygen and nitrogen over the Pd particles of approximately 5 nm size is monitored using time-resolved IR reflection absorption spectroscopy and molecular beams of NO and CO. It is shown that the atomic adsorbates preferentially block defect sites, which are most active for NO reduction, from [1, 5]. (bottom) New combined multi molecular beam / reactor / spectroscopy system for kinetic and dynamic studies at surfaces.

Similar experiments have been performed for other reaction systems such as for example the decomposition and oxidation of methanol, the oxidation and reduction of Pd nanoparticles by CO, etc.[1, 2, 7]
In combination with these experiments, we are aiming at the development of microkinetic concepts and models, which are capable of describing the reaction kinetics at nanostructured surfaces. For several kinetic phenomena such models have already been developed and tested.[2]

In order to transfer back such kinetic models to applied science, it is a critical prerequisite to ensure that the phenomena studied are comparable to those occurring under realistic conditions. In this respect one critical issue is the pressure range: Whereas surface science experiments are typically performed under ultrahigh vacuum conditions, most real surface processes occur near ambient pressure. This problem is often denoted as the “pressure gap” between surface science and heterogeneous catalysis. In order to establish comparability, it is, therefore, crucial to perform kinetic measurements and spectroscopy over the full pressure range from ultrahigh vacuum to ambient conditions. In Fig. 2 it is illustrated, how IR reflection absorption spectroscopy can be utilized towards this aim. In addition to ultrahigh vacuum experiments (10^{-10} mbar), kinetic measurements under high vacuum conditions can be performed with molecular beams and time-resolved IR

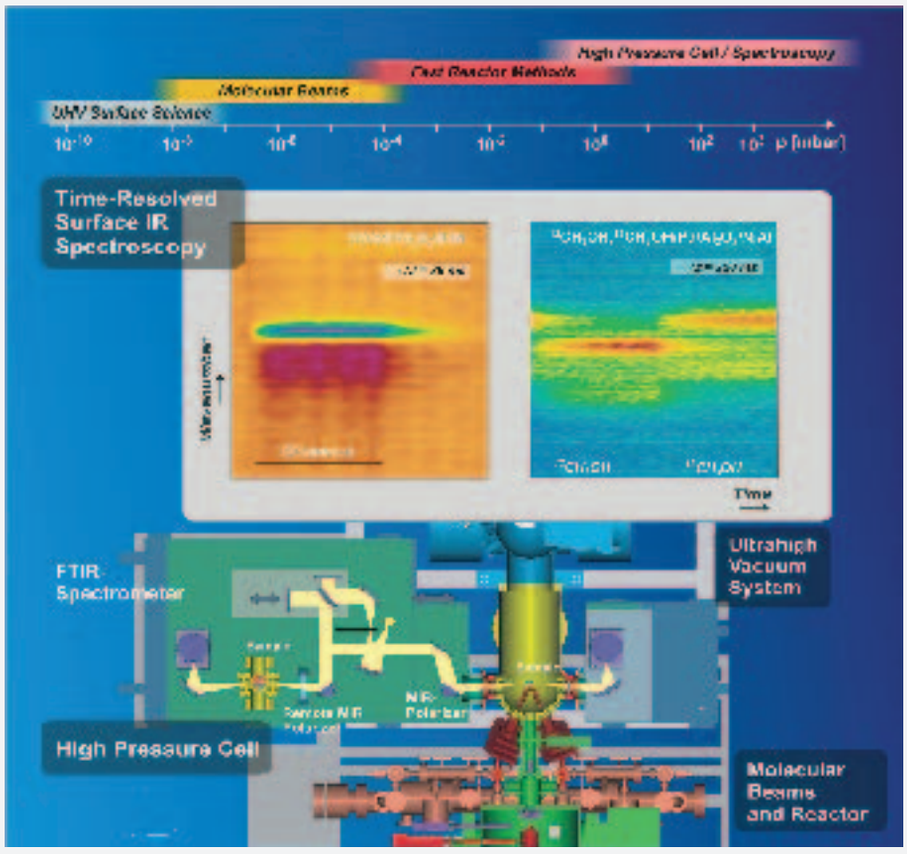


Fig. 3: (top) Kinetic and spectroscopic experiments on model catalysts can be performed from ultrahigh vacuum conditions to atmospheric pressure (IR spectra adapted from [2]). (bottom) Time-resolved surface IR spectroscopy in reflection absorption mode under ultrahigh vacuum conditions, in combination with molecular beams, fast reactor methods and a high-pressure cell using polarization dependent methods.

spectroscopy. At higher pressures up to about 1 mbar, reactors can be used, which are compatible with in-situ IR spectroscopy. In the ambient pressure region high pressure cells can be utilized, but the gas phase absorption may perturb the surface IR spectra. However, the problem can be circumvented by performing polarization-dependent IR spectroscopy (using oxide films on metal substrates on which only p-polarized IR radiation contributes to the surface-derived absorption signal). In this manner, the combination of molecular beams, reactor experiments and IR spectroscopy allows us to perform time-resolved surface spectroscopy and kinetic measurement over the full pressure range from ultrahigh vacuum to ambient conditions.

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Priv. Doz. Dr. Reinhard Denecke

In-situ studies of surface reactions

In order to study the fundamental processes of heterogeneously catalysed reactions in detail, model systems and well-defined conditions are necessary. The aim of our work is to establish new and sophisticated equipment needed to address these questions and to study typical cases. The preferred techniques are photoelectron spectroscopy and molecular beam techniques.

Modellsysteme bei wohldefinierten Bedingungen sind notwendig, um grundlegende Prozesse heterogen-katalysierter Reaktionen im Detail zu untersuchen. Ziel unserer Arbeit ist der Einsatz neuartiger Apparaturen, um solche Fragen anhand typischer Fälle zu studieren. Als vorrangige Messmethoden werden Röntgenphotoelektronenspektroskopie und Molekularstrahlmethoden eingesetzt.

In-situ spectroscopy of surface reactions

CO adsorption and oxidation on Pt(111) are among the most studied model system. Besides their relative simplicity which makes them good candidates for a very deep and detailed understanding, the application of these surface reactions in catalytic converters in automobile exhaust systems adds technological relevance. Using high-resolution x-ray photoelectron spectroscopy at a third generation synchrotron source like BESSY II in Berlin, a microscopic understanding of the adsorption of CO can be obtained. Not only different adsorption sites (on-top and bridge) on the flat (111) surface or the (111) terraces of regularly stepped Pt crystals can be distinguished, but also CO molecules adsorbed on step edges have their individual C 1s binding energy. The high photon flux allows for time-dependent analysis of the quantitative changes of the surface species, as shown in Fig. 1. From similar data for surface reactions kinetic data such as activation energies and prefactors can be derived. Therefore, the complete surface reaction happens under the sharp eyes of our instruments [1-3]. This kind of study is not only limited to small molecules like CO, NO, H_2O, CH_4 and C_2H_6, but also to larger molecules such as benzene and related heterocycles.

Bimetallic surfaces

Besides the characterisation of reactive properties of elemental metal surfaces, the exploration of materials with new and tuneable properties is of fundamental and technological interest. Using ultrathin metal layer systems, contradicting properties can be combined, such as the reactivity of Cr towards CO dissociation and the relatively inert Ru surface. Indeed, a single atomic layer of Cr on Ru already facilitates CO dissociation. Formation of a CrRu surface alloy changes the properties again, opening a wide range of customer design properties. We are using molecular beam techniques, such as sticking coefficient measurements and scattering experiments to determine the properties of these systems. Combined with geometric information from scanning tunnelling microscopy and spectroscopic information from photoemission studies, a detailed and rather complete picture of the reactivity of these surfaces can be obtained, as demonstrated in Fig. 2 [4,5].

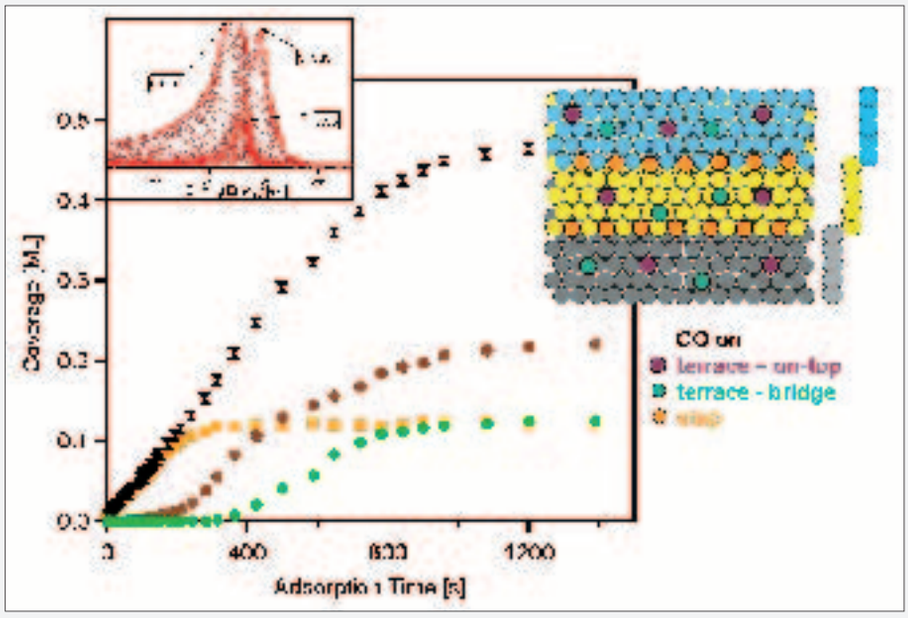

Fig 1.: Quantitative results of a series of C 1s spectra (top left) taken during CO adsorption on Pt(355) at 130 K. The surface model shows the different adsorption sites distinguishable by their C 1s binding energy. The total CO coverage is marked by black symbols. The CO pressure was $1.4 \cdot 10^{-9}$ mbar. The occupation ratio of the terrace adsorbed species differs from the one obtained for the Pt(111) surface, showing a clear influence of the finite width of the terraces on the electronic structure.

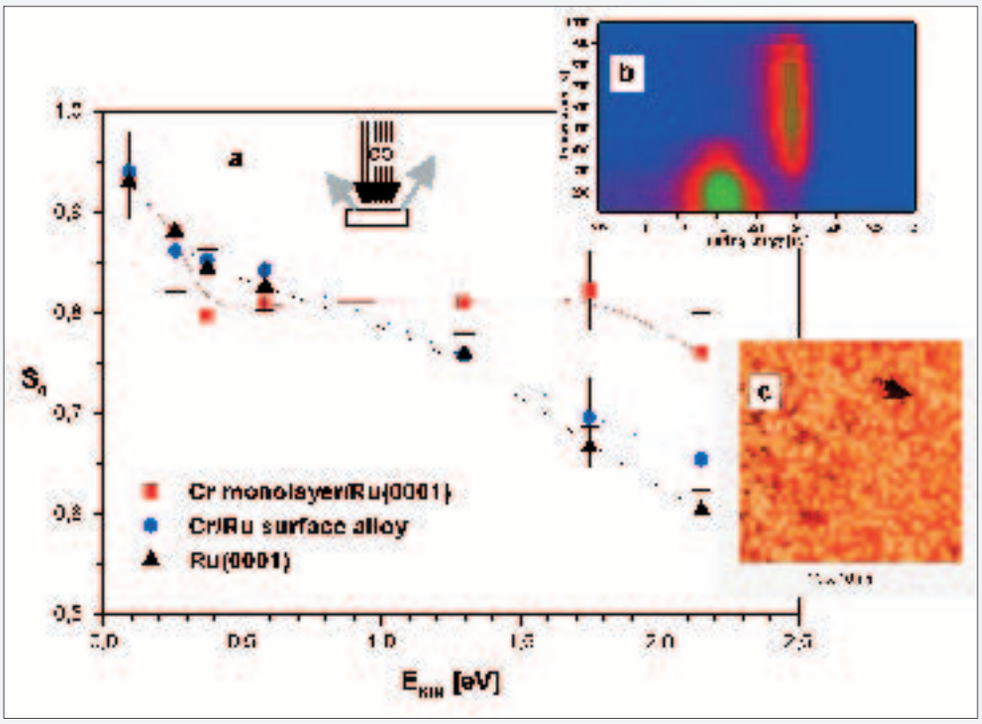

Fig. 2:
Reactivity of Cr-Ru surfaces.
a) Initial sticking coefficients as function of CO kinetic energy, for Ru(0001), a Cr monolayer on Ru(0001) and a CrRu surface alloy. Inset: Sticking coefficient is ratio between adsorbed [impinging (black arrows) - scattered (grey arrows)] and impinging CO molecules; here 2/3.
b) Temperature dependent O 1 s intensities (green: high, blue: low) during dissociation and desorption of CO on a monolayer of Cr on Ru. Molecular CO is seen at 532 eV, atomic oxygen at 530 eV.
c) STM image with chemical contrast of the CrRu surface alloy. Cr atoms are imaged as bright dots [5].

High-pressure XPS

In order to expand the useable pressure range for photoelectron spectroscopy, we have designed and built a differentially pumped spectrometer for in-situ studies up to 1 mbar, depicted in Fig. 3 [6]. Combined with a reaction cell for realistic treatment and characterisation of real and model catalysts at pressures up to 1 bar, investigations to bridge the so-called “pressure gap” between surface science results and their application in technological processes are possible. As a first example, the methanol steam reforming process on PdZn/ZnO catalysts is studied. Being a fullgrown UHV system, also fundamental questions of surface oxide formation on single crystals are studied, as e.g. for Pd oxidation. These oxides, in turn, can be used as supports for nanoscaled catalytic particles.

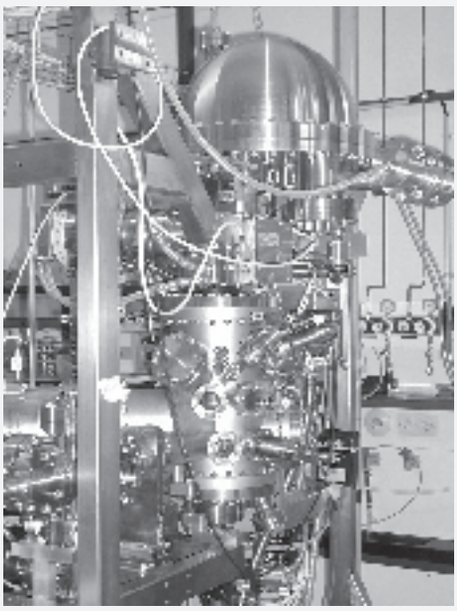

Fig. 3:
Photo of our high-pressure photoelectron spectrometer for XPS up to pressures of 1 mbar. The experimental set-up is based on a modified hemispherical electron energy analyser (Omicron), a modified twin anode x-ray source (Specs), and several differential-pumping stages between sample region and electron detection. The reaction gas is provided in situ either by background dosing or by beam dosing, using a directed gas beam from a small tube.

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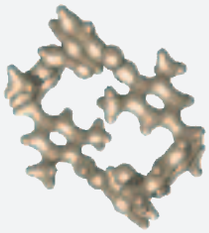
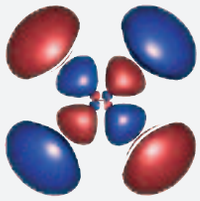
Prof. Dr. Andreas Görling

Development of new quantum chemical methods and their application in chemistry and material science



Quantum chemistry in general and density-functional methods in particular have gained more and more importance in chemistry over the last decades. Today research in chemistry is often driven by a close interplay between experiment and theory. Our group develops and applies new density-functional methods both for finite systems, i.e., molecules or clusters, and for periodic systems, i.e., polymers, molecular wires, surfaces, and solids. Ground and excited electronic states as well as response properties like NMR parameters or hyperpolarizabilities for the characterization of nonlinear optical properties are considered.



Quantenchemie im allgemeinen und Dichtefunktionalmethoden im besonderen haben in den letzten Jahrzehnten mehr und mehr Bedeutung in der Chemie gewonnen. Heutzutage schreitet die Forschung in der Chemie oft im engen Wechselspiel zwischen Experiment und Theorie voran. Unsere Gruppe entwickelt und verwendet neue Dichtefunktionalmethoden sowohl für endliche Systeme, d.h. für Moleküle und Cluster, wie für periodische Systeme, d.h. für Polymere, molekulare Drähte, Oberflächen und Festkörper. Dabei werden elektronische Grundzustände, angeregte elektronische Zustände und auch Responseigenschaften wie NMR-Parameter sowie Hyperpolarisierbarkeiten zur Charakterisierung von nichtlinear-optischen Eigenschaften untersucht.

Chemistry traditionally has been a science dominated by experiment. However, over the last three decades theory has gained more and more importance within chemistry. Nowadays, it is perhaps not yet the rule but at least quite common that articles in originally experimentally oriented chemical journals contain besides experimental results also a section on computations accompanying the experimental work. Indeed research in chemistry more and more is driven by a close interplay between experiment and theory.

One reason for the increasingly important role of theory in chemistry is that the methods of computational chemistry, in particular quantum chemistry methods in a wide sense, have become enormously powerful. While 30 years ago only molecules with a handful of atoms could be treated, it is today possible to treat routinely systems with hundreds or even thousands of atoms with reasonably accurate quantum chemistry methods. This development, on the one hand, is a consequence of the rapid increase in the efficiency of computers over the last decades. On the other hand, it is a result of the development of new and more powerful quantum chemistry algorithms and approaches. A second longstanding argument for a prominent role of theory in chemistry is that in chemistry, like in other natural sciences, the ultimate goal is to gain new insight and understanding. A goal that clearly requires to go beyond the compiling of new experimental data and to invoke some kind of theory.

With its growth the field of theory in chemistry developed into several branches. One branch, chemoinformatics, exploits and enlarges with the help of computers the compiled chemical knowledge by methods reaching from data mining to artificial intelligence. However, the majority of chemists concerned with theory in chemistry works with methods based on quantum or classical mechanics. Two lines of work can be distinguis-

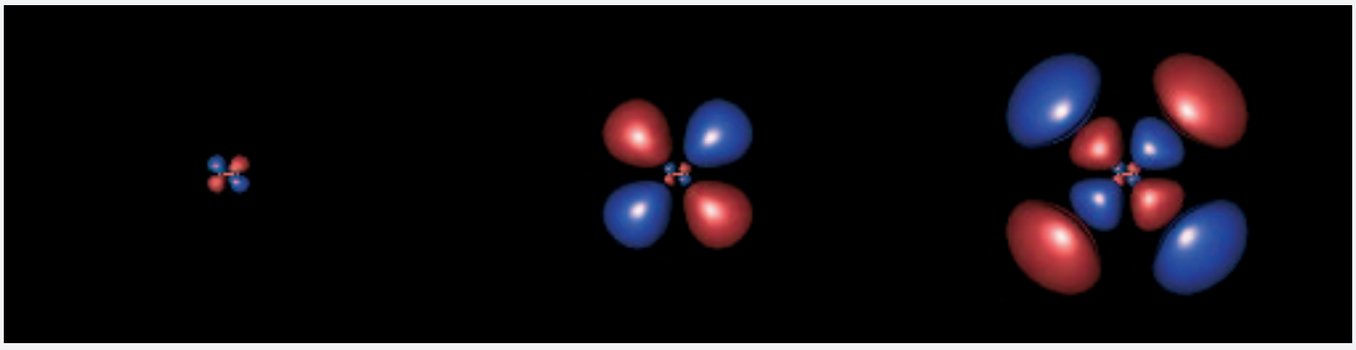


Fig. 1: Orbitals of ethene with b_{2g} symmetry, i.e., the Rydberg series starting from the LUMO ($1b_{2g}$). The contur values are chosen such that approximately 70% of the electron density is contained within the contur surface (90% for the LUMO).

hed, quantum chemistry, i.e., the investigation of the electronic structure of molecules with methods derived from quantum mechanics, and dynamics, i.e., the investigation of the motion of the nuclei of molecules. Within quantum chemistry often a further distinction is drawn between groups who predominantly apply available program packages and groups who develop new quantum chemistry methods and corresponding computer codes. The application of established quantum chemistry codes is often termed computational chemistry. Our group originally was predominantly active in the development of new methods, meanwhile, however, applications also play an important role.

Our activities focus on methods that are based on density-functional theory. Density-functional methods, by now, are the most widely used quantum chemistry methods due to their good ratio of accuracy and computational effort. They enable the investigation of the electronic structure of molecules with hundreds of atoms without relying on the use of experimental data as semiempirical approaches. Density-functional methods therefore are first-principle methods, i.e., methods relying exclusively on basic theories, here quantum mechanics, and as such can be applied in very different areas ranging from traditional inorganic or organic chemistry to biochemistry, material sciences, solid state physics, and even chemical engineering. Characteristic for our group is that finite systems, molecules and clusters, as well as periodic systems, polymers, molecular wires, surfaces, and solids, in particular semiconductors, are considered with roughly equal emphasis. In the following a few typical examples for the work of our group are given.

In recent years we developed new density-functional approaches that are based on so-called orbital-dependent functionals [1]. These methods use information contained in the orbitals in addition to the information provided by the electron density, which is considered in traditional density-functional method. An important achievement of the new density-functional approach is the possibility to calculate orbitals and eigenvalues that reflect the intuitive chemical and physical concepts of, e.g., bonding and antibonding orbitals or of Rydberg series of orbitals. Chemists nowadays almost inevitably think in terms of orbitals if they think about electronic structures. However, if one asks what these orbitals are and where they come from then usually no clear answer is given. Molecular orbitals are considered to be somehow built from atomic hydrogen-like orbitals. One might assume that standard quantum chemistry methods yield the orbitals underlying the thinking of chemists. This, however, is not the case. Hartree-Fock methods yield reasonable occupied orbitals, the unoccupied orbitals, however, in most cases are not even bound orbitals and thus do not describe bound electrons. Traditional density-functional methods usually yield some bound unoccupied orbitals. Nevertheless the orbital and eigenvalue spectra of traditional density-functional methods are qualitatively wrong and, e.g., do not exhibit Rydberg series.

Fig. 1 shows as an example the first members of the series of Rydberg orbitals of ethene starting from the energetically lowest unoccupied orbital, the $1b_{2g}$ orbital, as obtained with a new density-functional method developed by us [2], an effective exact-exchange Kohn-Sham approach named localized Hartree-Fock method. The orbitals determined with the new approach can be employed for various purposes. Most important they provide an improved basis for the calculation of response properties of molecules, like optical excitation spectra, polarizabilities, or NMR parameters. Here we consider a much simpler example demonstrating how such orbitals and their eigenvalues can be directly helpful.

Scanning tunnelling microscopy (STM) experiments of tetralactam macrocycles adsorbed on a gold surface (see Fig. 2 displaying a tetralactam macrocycle) show quite weak STM signals [3]. The question arises whether this is due to electronic or other reasons. A thorough modelling of STM experiments is a formidable task. If, however, reliable orbital eigenvalues, as those provided by the new exact-exchange Kohn-Sham method, are available then first hints can be obtained by comparing the eigenvalues of the energetically highest occupied and the energetically lowest unoccupied molecular orbital with the Fermi level of gold. This comparison shows that the involved orbitals and the Fermi level of gold are energetically close enough such that a significant tunnelling current could be expected. Thus the reason for the weak signal must have a different origin. Indeed a geometry optimization of the tetralactam macrocycle shows that the molecule is not planar but contains methyl groups acting like little feet lifting the π-electron system of the molecule, which contains the relevant orbitals, away from the surface. The weak tunnelling signal thus is a consequence of spatial separation. In Fig. 2 the energetically lowest unoccupied molecular orbital is displayed, in Fig. 3 the electron density of the tetralactam molecule.

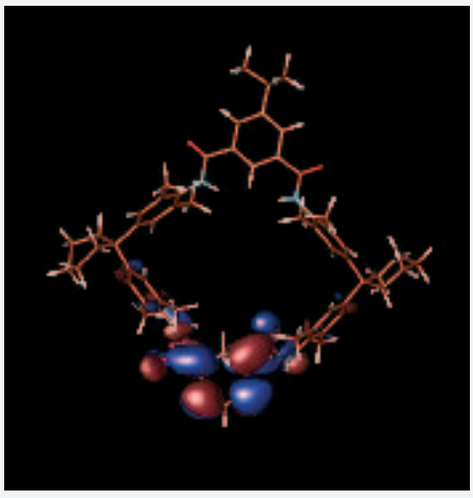


Fig. 2: The energetically lowest unoccupied orbital of a tetralactam macrocycle.

Another central research topic of our group represents time-dependent density-functional theory which enables among other things the modelling of UV/Vis spectra and the treatment of polarizabilities. A time-dependent density-functional method developed by us goes beyond the usually considered linear regime and yields hyperpolarizability tensors which characte-

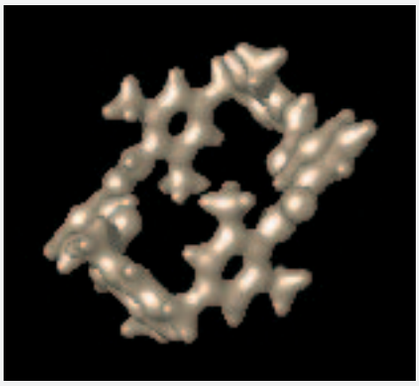


Fig. 3: The electron density of a tetralactam macrocycle.

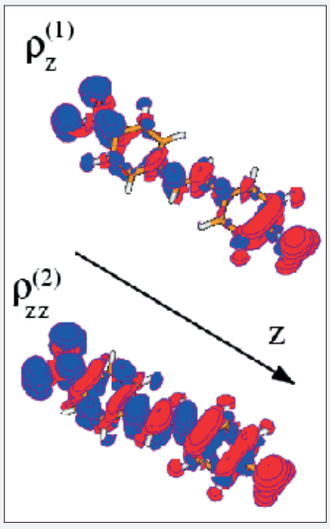


Fig. 4: The first- and second-order response $\rho_z^{(1)}$ and $\rho_{zz}^{(2)}$ for p-nitro-p'-amino-stilbene for a wavelength of 1910 nm. Shown are isodensity surfaces of 0.1 a.u. (blue) and -0.1 a.u. (red) for $\rho_z^{(1)}$ and of 6.0 a.u. (blue) and -6.0 a.u. (red) for $\rho_{zz}^{(2)}$.

rize nonlinear optical properties of molecules [4] [5]. A specific feature of our approach is that it directly yields the nonlinear response of the electron density in space, i.e., the observable underlying nonlinear optical experiments. In Fig. 4 the linear and nonlinear optical response of p-nitro-p'-amino-stilbene is displayed for radiation with a wave length of 1910 nm polarized along the molecular axis. Fig. 4 shows that the electric field of the incoming radiation does not simply shift the electronic charge of a molecules like p-nitro-p'-amino-stilbene from one side of the molecule to the other but that regions where electron density is accumulated change with regions where the electron density is reduced. The polarizability or hyperpolarizability of the molecule results as a sum of the effect of these alternating areas of accumulation and reduction of charge density.

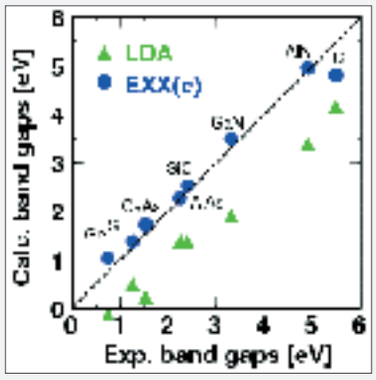


Fig. 5 Comparision of self-consistently calculated LDA and EXX band gaps (in eV) of various semiconductors with experimental data.

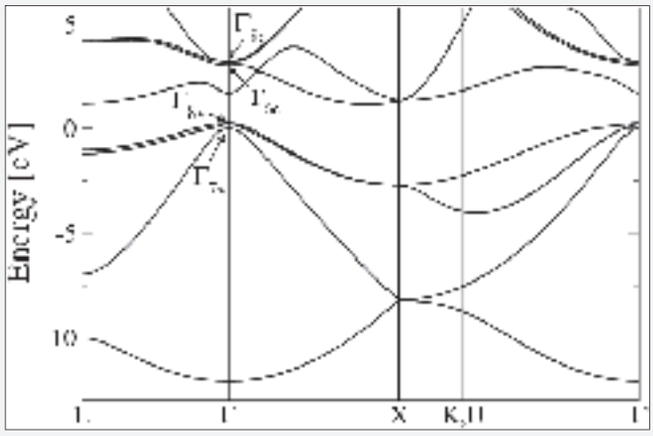


Fig. 6 EXX band structure of Ge including spin-orbit interactions (in eV).

For periodic systems we developed a program package to investigate ground state and optical properties with conventional density-functional methods as well as with new methods employing orbital-dependent functionals. Fig. 5 shows that a new exact-exchange (EXX) Kohn-Sham method yields band gaps clearly superior to conventional methods based on the local density approximation (LDA) [6,7]. Recently we included in this program package the possibility to treat noncollinear spin densities and spin-orbit interactions. For the first time, moreover, a spin-current density-functional treatment could be included to investigate magnetic effects [8]. In Fig. 6, the band structure of Germanium including spin-orbit effects is displayed.

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Prof. Dr. Peter Otto

Theoretical Developments for ab initio Calculations of Nonlinear Optical Properties and Applications to Molecules and Polymers

One branch of theoretical investigations in our group is the study of the interaction of electric and magnetic fields on molecules and polymers. Of special interest are investigations of nonlinear optical properties of organic polymers which are of interest for technical applications. We have developed in the past and still continuing the development of theoretical methods to calculate static and dynamic (hyper)polarizabilities and contributions which arise from vibrations and electron correlation. These methods have been applied to organic molecules and polymers with the goal to predict structure activity relations.

Ein Zweig der theoretischen Untersuchungen in unserer Gruppe befasst sich mit der Untersuchung der Wechselwirkung elektrischer und magnetischer Felder mit Molekülen und Polymeren. Von besonderem Interesse sind die Untersuchungen der nichtlinearen optischen Eigenschaften organischer Polymere, die für technische Anwendungen interessant sind. In der Vergangenheit und auch gegenwärtig entwickeln wir theoretische Methoden um statische und dynamische (Hyp er)polarisierbarkeiten und Beiträge der Schwingungen und der Elektronenkorrelation zu berechnen. Wir haben mit diesen Methoden organische Moleküle und Polymere untersucht mit dem Ziel, Struktur-Aktivitäts Beziehungen vorherzusagen.

I. Introduction

Optical phenomena (processes of light interacting with matter) are by nature nonlinear. Under the action of the electromagnetic field of the light the properties of the matter are changing, e.g. charge distribution, multipole momentum, optical quantities. These changes cause again changes of the properties of light, e.g. frequency, phase, polarization. This dynamical process defines the nonlinearity: the response of the matter in the linear range due to the light effects again the light, which again causes small changes in the properties of the matter (in the nonlinear range), until an equilibrium state has been achieved.

Some classes of molecules, with specified nonlinear optical (NLO) responses (e.g. conjugated organic polymers) are very promising for technical applications[1,2]. They can be used for optical switching elements, modulators and electro-optical devices. These possible applications have enforced the search for new materials with large optical nonlinearity. Therefore many experimental work has been performed to find such materials and to characterize them. This is very important, because other properties, e.g. chemical and mechanical stability over a wide range of temperature, have to be considered for possible applications.

Quantum mechanical investigations can play an important role. On the one hand side they can provide explanations of mechanisms of physical processes and on the other hand they may lead to structure predictions due to structure-activity correlations. In this way many time-consuming and expensive experiments can be avoided in case there is some guide for synthesis available.

II. Methods

Among other groups we have developed the methods[3,4,5] for the calculation of static and dynamic NLO properties of infinite quasi-onedimensional periodic systems based on the time-dependent Coupled-Perturbed Hartree-Fock (CPHF) theory combined with the *ab initio* Hartree-Fock crystal orbital formalism (HFCO)[6,7]. Static and dynamic polarizabilities and hyperpolarizabilities of first and second order have been investigated for molecules, oligomers and polymers. Furthermore we have worked out methods to take vibrational contributions, long-range effects and electron correlation corrections into account.
In the following we present a short selection of theoretical results to demonstrate the importance of the different contributions. Extended Gaussian basis sets, a large number of k-points in the Brillouin zone, and sufficient neighbours' interactions have been employed in the calculations.

III. Selected Results

Organic polymers with delocalization of the π-electrons exhibit very large nonlinear responses. The longitudinal polarizability (along the polymer axis) of this kind of compounds, e.g. poly-

furane (PFu) and poly-pyrrole (PPy) has been investigated by us using CPHF, but no calculations had been reported in the literature for the NLO properties of higher order at the CPHF-CO level. In Table 1 we present longitudinal dynamic polarizabilities and 2nd order hyperpolarizabilities for several polymers[8].

In the CPHF-equations appear terms, which require the derivatives of the wave function with respect to the quasi-momentum k. Usually Pople's analytical method is used. We have developed a new algorithm, which needs much fewer k-points, by optimizing the phase factors of the crystal orbitals such that continuous functions are obtained. The wave function is transformed to real space, the derivatives are computed and transformed back to k-space. The much faster convergence, e.g for the dipole moment is shown in Fig. 1 for poly-carbonitrile.

The HFCO-equations are formulated in the strict neighbours' interaction approximation, i.e. only interactions up to a given number of neighbouring cells are taken explicitly into account. Due to the fact that Coulomb interactions are of the long-range type, one has to correct for the missing interactions. We have developed methods, dividing these corrections as a sum of intermediate and long-range contributions, respectively. In Table 2 and Fig. 2 we show the effect of the long-range interactions for poly-furane.

Electron correlation has a very large effect on the nonlinear optical properties and the corrections in percentage are many times larger than for the energy. We have developed and still are working on methods

Poly	$\alpha(-\omega;\omega)$	$\gamma(0;0,0,0)$	$\gamma(-\omega;\omega,0,0)$	$\gamma(-\omega;\omega,\omega,-\omega)$	$\gamma(-3\omega;\omega,\omega,\omega)$
Pyrrole	113.75	7.39(5)	7.45(5)	7.52(5)	7.80(5)
Furane	115.08	1.13(6)	1.14(6)	1.15(6)	1.20(6)
Thiophene	228.59	3.45(6)	3.49(6)	3.53(6)	3.33(6)
p-phenylene	144.56	1.71(6)	1.72(6)	1.72(6)	1.73(6)
aniline	351.46				

Numbers in parentheses are the powers of ten by which the entry is to be multiplied (e.g. 7.39(5) = 7.39 × 10^5).

Table 1. Longitudinal dynamic (hyper)-polarizabilities for polymers with cyclic conjugated elementary cells.

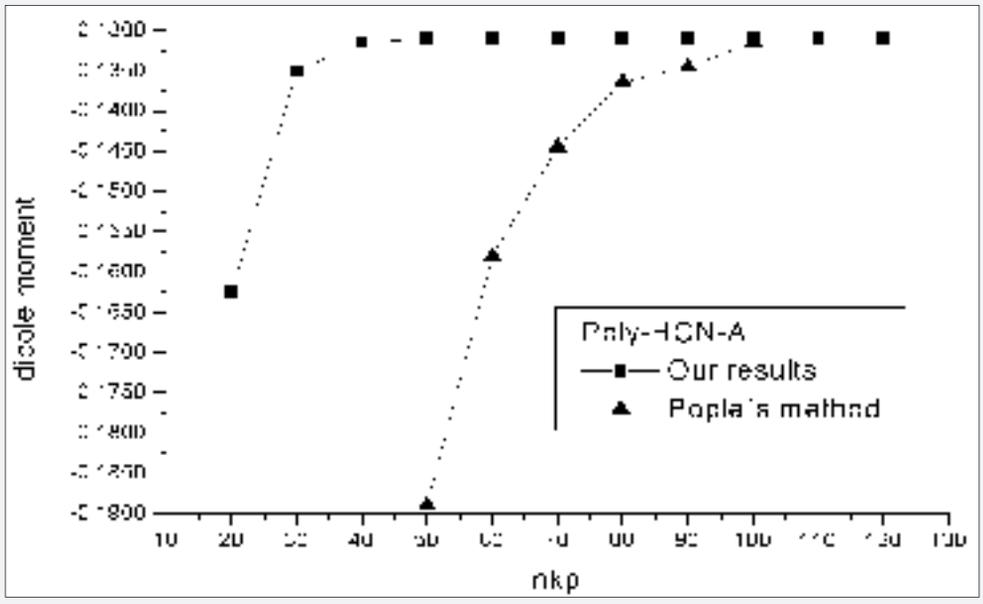

Figure 1. Convergence behaviour of μ depending on the number of k-points for poly-CNH-A.

ω =	0.00	0.01	0.02	0.03
		$\alpha_{zz}(-\omega;\omega)$		
LR	1.1457(2)	1.1500(2)	1.1635(2)	1.1869(2)
NLR	1.1456(2)	1.1499(2)	1.1634(2)	1.1868(2)
		$\gamma_{zzzz}(-\omega;0,0,\omega)$		
LR	1.075(6)	1.0863(6)	1.1231(6)	1.1887(6)
NLR	1.074(6)	1.0858(6)	1.1226(6)	1.1881(6)
		$\gamma_{zzzz}(-\omega;\omega,\omega,-\omega)$		
LR	1.075(6)	1.0983(6)	1.1741(6)	1.3165(6)
NLR	1.074(6)	1.0978(6)	1.1736(6)	1.3159(6)
		$\gamma_{zzzz}(-2\omega;0,\omega,\omega)$		
LR	1.075(6)	1.1106(6)	1.2319(6)	1.4816(6)
NLR	1.074(6)	1.1101(6)	1.2304(6)	1.4809(6)
		$\gamma_{zzzz}(-3\omega;\omega,\omega,-\omega)$		
LR	1.075(6)	1.1488(6)	1.4301(6)	2.2515(6)
NLR	1.074(6)	1.1483(6)	1.4295(6)	2.2502(6)

Numbers in parentheses indicate the power of 10 by which the entry is to be multiplied.

Table 2. CPHF static and dynamic longitudinal polarizability and second hyper polarizabilities of poly-furane with (LR) and without (NLR) long-range interactions for different frequencies.

for polymers at different levels. Only size-consistent procedures can be applied to polymers. Therefore we have implemented into our HFCO-programs the Moeller-Plesset second order perturbation theoretical (MP2) approximation. Furthermore we have developed reduced density matrices functionals based on natural orbitals[9,10], and in addition a new semiempirical approach in context with the "soft Coulomb hole" approximation has been worked out, which leads to very accurate optimized geometries and more than 90 per cent of correlation energy.

In Table 3 we show the effect of correlation corrections calculated within the MP2 approximation for polymers with heterocyclic five-membered ring elementary cells.

It can be seen that these contributions even may change the order of polarizabilities as in the case of poly-pyrrole and poly-furane. Recent detailed investigations on poly-carbonitrile have lead to even much larger changes with respect to the *ab initio* Hartree-Fock results.

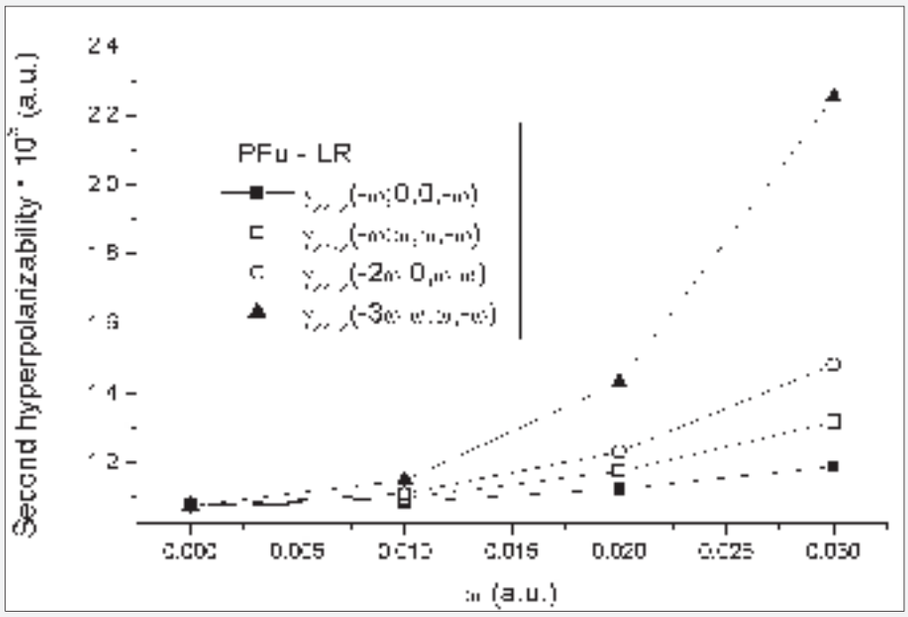

Figure 2. Dynamic longitudinal second hyperpolarizabilities of poly-furane vs. frequency including long-range interactions.

Poly-	α_{zz}(HF)	α_{zz}(MP2)	α_{zz}(HF+MP2)
Pyrrole	113.854	-13.871	99.983
Furane	115.955	-40.693	75.262
Thiophene	178.566	-32.032	146.534

Table 3. Correlation contributions to the longitudinal static polarizabilities of PPy, PFu and PTh.

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In future studies we will apply the theoretical methods to polymers with more complex elementary cells and the extension of the programs to two-dimensional systems.

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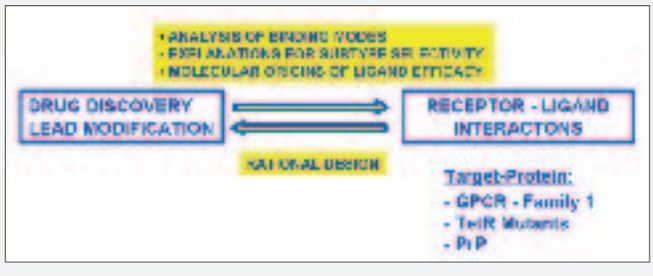
Prof. Dr. Peter Gmeiner

Target Protein – Ligand Interactions: Design, Organic Synthesis and Biological Investigation of Novel Molecular Probes and Potential Drugs

Aiming to discovery novel molecular probes and potential drugs for allosteric target proteins, we investigate the design and synthesis of subtype selective dopamine receptor agonists, -partial agonists and -antagonists as novel antipsychotic agents, molecular probes that can be further developed to radioligands for PET and SPECT, peptidic und nonpeptidic neurotensin receptor agonists controlling dopaminergic systems, solid phase supported methodologies and their application for the discovery of GPCR ligands, synthesis of novel tetracyclin repressor inducer and the discovery of agents for a specific treatment of prion related diseases.

Mit dem Ziel der Entdeckung neuartiger molekularer Sonden und potentieller Arzneistoffe werden untersucht: Design und Synthese subtyp-selektiver Dopaminrezeptor-Agonisten, -Partialagonisten und –Antagonisten als neuartige antipsychotische Wirkstoffe, molekulare Sonden, die für PET und Spect als Radioliganden weiterentwickelt werden können, peptidische und nichtpeptidische Neurotensinrezeptor-Agonisten zur Kontrolle des dopaminergen Systems, Festphasenunterstützte Methoden und ihre Anwendung zur Entdeckung von GPCR Liganden, die Synthese neuartiger Tetracyclin Repressor Induktoren sowie die Entdeckung von Wirkstoffen für die Behandlung Prion- induzierter Erkrankungen.

Aiming to discover small molecules and peptides as molecular probes, Peter Gmeiner's group has substantial experience in the design, organic synthesis and biological investigation of bioactive molecules when class A G-protein coupled receptors (GPCRs), TetR and prion proteins are addressed as allosteric target proteins.



The following topics are of special interest:

Design and synthesis of novel subtype selective dopamine receptor agonists, -partial agonists and -antagonists as novel antipsychotic agents

As model systems for allosteric target proteins, the class I GPCRs $D2_{long}$, $D2_{short}$, D3 and D4 are investigated. Novel neuroreceptor ligands have been found when FAUC 213 represents a selective full antagonist of the dopamine D4 receptor, which proved to reveal antipsychotic properties in a rat model. FAUC 346 and FAUC 365 are analogs of BP 897 being designed for the inhibition of cocaine-seeking. Both benzothiophenes show outstanding dopamine D3 affinity in combination with partial agonism. FAUC 73 represents the first nonaromatic dopamine agonist. Employing CoMFA, a 3D-QSAR study was performed, comparing the structural and biological properties of the conformationally rigidized D4 antagonist clozapine with a series of D4 active N-heteroarylmethyl-N´-phenyl piperazines. Solution and solid phase supported synthesis of rationally designed small molecules revealed interesting insights into the binding and activation processes of the D4 subtype. Furthermore, enantiospecific synthesis and receptor binding profiles of selective D3 agonists were exploited for the construction of a D3 receptor active state model combining a ligand-based and a protein structure-based approach.

Investigation of molecular probes that can be further developed to radioligands for PET and SPECT

In collaboration with C.-M. Becker (Biochemistry) and T. Kuvert (Nuclear Medicine) we try to take advantage of our SAR (structure-activity-relationship) results to develop chemical tools for the development of highly selective imaging agents as *in vivo* markers for D3, D4 and glycine receptors asdisease relevant neuroreceptors.

Peptidic und nonpeptidic neurotensin receptor agonists as molecular probes controlling dopaminergic systems

Taking advantage of our previous work on the concept of "control of target binding and selectivity by conformational rigidization", we developed bioactive type II and type VIa ß-turn mimetics including lactam bridges. A practical methodology was established leading to a series of *Dehydro-Freidinger* lactams. The scaffolds comprise 6-, 7-, 8-, 9- and 10-membered cyclic peptide mimics. According to a series of NMR experiments

involving NOE difference, NOESY, chemical shift changes as a function of the solvent composition, temperature coefficients and anisotropic shielding, conformational behavior can be efficiently controlled by varying both the ring size and, interestingly, the position of the double bond.

Solid phase supported methodologies and their application for the discovery of GPCR ligands

Intending to increase the efficiency of the drug design process, P. Gmeiner's group has developed the concept of click-linkers as a new strategy for the solid phase synthesis of compound libraries when orthogonally functionalized resins proved to be efficient tools.

Synthesis of novel tetracyclin repressor inducers

To discover novel molecular trigger systems and to elucidate mechanisms of interactions between low molecular ligands, TetR and DNA, we study interactive structure-activity-relationships employing newly synthesized TetR ligands in tight collaboration with the group of W. Hillen (Microbiology). Synthesis of 4-ddma-atc and derivatives thereof, and genetic screens led to the atc and dox insensitive system TetR H64K S135L S138L : 4-ddma-atc. Expanding these studies, we elaborated a total synthesis of atypical tc surrogates that are currently investigated biologically towards a series of TetR mutants. Structural manipulations of doxycycline and anhydro-tc led us to 9-amino derivatives selectively inducing the reverse ‚tet-on' phenotype of the TetR-based transregulator (rtTA) without substantially affecting the regulation of gene expression by the positively controlled transactivator tTA.

Discovery of agents for a specific treatment of prion related diseases

To evolve high affinity, conformation-specific ligands for pharmacotherapy of prion protein-related diseases, novel ligands are designed such as to fit into mapped interaction sites, synthesized, and validated in a cell model of prion disease. For the parallel synthesis of focused compound libraries, a solid phase supported methodology especially exploiting click reactions is employed. Ultimately, this iterative approach is expected to yield high-affinity ligands that specifically bind to soluble prion protein, stabilize its conformation, and prevent conversion into a pathogenic conformation. The results from this project are expected to provide also fundamental insights also into drug discovery for related conformational, i.e. neurodegenerative diseases, such as Parkinson's or Alzheimer's disease.

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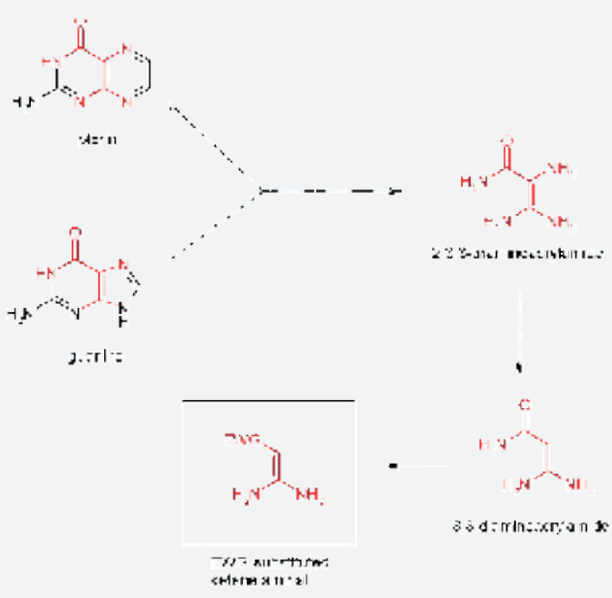
Prof. Dr. Reinhard Troschütz

Synthesis of functional and medicinally interesting analogues of pteridine and purine

Searching for new drugs, analogues of natural compounds i.e. pterine and guanine are synthesized. A common substructure of these heterocycles , a 3,3-diaminoacrylamide, is recognized. This amide , a multifunctional and valuable building block, is used in ring closure reactions to 5- and 6-rings. Hereby a series of new pteridine and purine derivatives with new functionalities and new properties are generated. These compounds can interact with proteines e.g. enzymes and may inhibit them. Some of these heterocycles are inhibitors of the human dihydrofolate reductase und possess interesting antitumor properties. Analogues with a 5-hydroxyindole structure prove to be potent inhibitors of the 5-lipoxygenase, a human enzyme which is involved in the generation of leucotrienes. These 5-hydroxyindoles can serve as potential antiasthmatics.

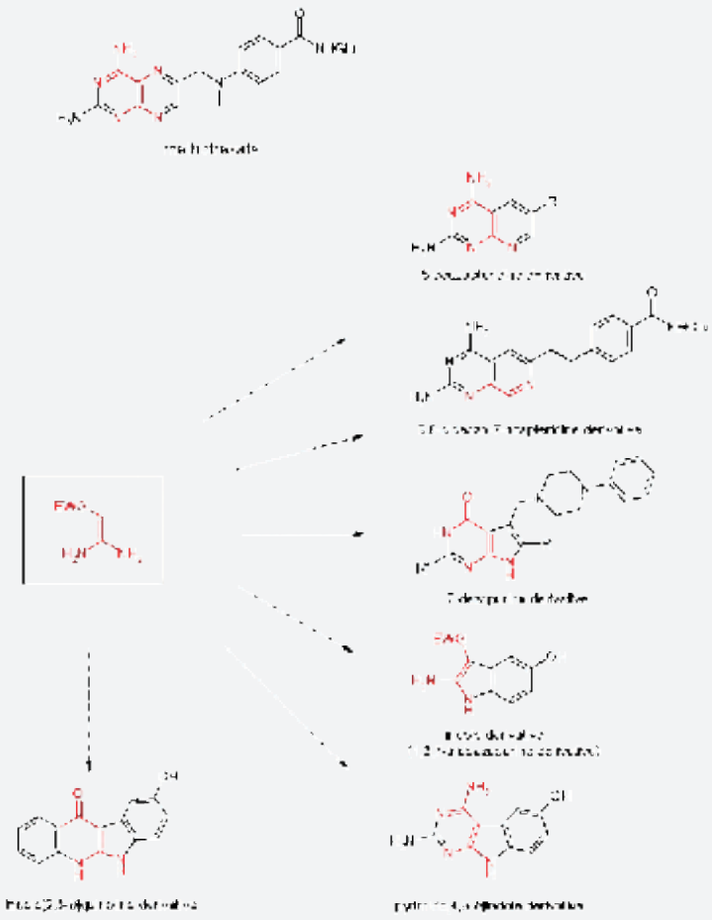
Auf der Suche nach neuen Arzneistoffen werden gezielt Analoga der Naturstoffe Pterin und Guanin hergestellt, in denen ein oder mehrere Stickstoffatome durch Kohlenstoffatome ersetzt sind. Als gemeinsames Strukturelement dieser Naturstoffe wird ein 3,3-Diaminoacrylamid, das auch als EWG-substituiertes Ketenaminal bezeichnet werden kann, erkannt und als multifunktionaler Synthesebaustein für gezielte Ringschlussreaktionen herangezogen.
Hierdurch entstehen eine Reihe von Pteridin-und Purin-Derivaten mit neuen Funktionalitäten und veränderten Eigenschaften, wodurch Wechselwirkungen z.B. mit Proteinen möglich sind. Einige der hergestellten Heterocyclen stellen Hemmstoffe der humanen Dihydrofolatreduktase dar und besitzen hierdurch eine Antitumor-Wirkung. Verbindungen vom 5-Hydroxyindol-Typ erweisen sich als potente Hemmstoffe der 5-Lipoxygenase, die im Astmageschehen eine wichtige Rolle spielt.

Searching for new drugs with new activities or less side effects, we are dealing with the specific variation of natural compounds which play an important role in the human organism. We selected two classes of natural compounds: the pteridines and the purins . Folic acid and its derivatives and guanine and adenine are important members of these classes. The latter serve as building blocks in the DNA synthesis.
Looking at the formula of pterine, a functional pteridine derivative or guanine, a purine derivative, you will find a common substructure in which all nitrogen atoms are bonded to a carbon scaffold. The name of this substructure is 2,3,3-triaminoacrylamide. Our first modification was the deletion of an amino group in position 2, generating a 3,3-diaminoacrylamide. This substance can be regarded as an enediamine or ketene aminal with an electron withdrawing amide group (EWG). Generally spoken this class of compounds can be seen as EWG-substituted ketene aminals. These compounds possess electrophilic and nucleophilic reaction centers and represent valuable building blocks for the synthesis of heterocycles especially pteridine and purine analogues. We performed special ring closure reactions with EWG-substituted ketene aminals and received a set of deazapteridines and deazapurines with new radicals and functionalities.
This strategy can be regarded as a building block driven heterocyclic chemistry with the focus on analogues of pteridine and purine as potential medicinal agents.



EWG-substituted ketene aminal

In preceding experiments we have synthesized several analogues of the folic acid derivative methotrexate (MTX), a powerful antitumor drug, by using EWG substituted ketene aminals. Extensive tests by the National Institute of Health (NIH) at Be-



EWG-ketene aminal based pteridine and purine analogues

thesda, USA, showed that some analogues are equipotent to MTX. These analogues are inhibitors of the human enzyme dihydrofolate reductase, which is responsible for the production of C_1-building blocks, which are needed in the DNA synthesis. An inhibition of this enzyme in fast growing tumor cells will cause death of tumor cells.

In a further project we synthesized rigid analogues of piritrexim, a lipophilic MTX-analogue. In these compounds the conformational flexibility is reduced by an internal carbon bridge. The biological tests and computer simulations and docking experiments (cooperation with Dr. H. Lanig, Computer-Chemie-Centrum, Friedrich-Alexander-Universität Erlangen) revealed that a too strong rigidisation leads to a decrease of activity.

In the series of purine analogues we have performed several ring closure reactions with EWG substituted ketene aminals and C_1N- and C_2-building blocks e.g. α-bromoketones or α-bromoaldehydes or 1,4-quinones e.g. 1,4-benzoquinone or quinoline-5,8-dione. By this way we were able to prepare purine analogues of the pyrrolo[2,3-*d*]pyrimidine or 5-hydroxyindole type; the latter can be regarded as a 1,3,7-trideazapurine.These compounds can be further cyclized to functional pyrimido[4,5-*b*]indoles, which are structurally related to the antitumor acting ellipticine, an natural alkaloid from *Ochrosia elliptica.* Some of these pyrimido[4,5-*b*] indoles, which possess an additional aromatic or heteroaromatic ring, showed antitumor activities comparable to ellipticine.

Functional 1,3,7-trideazapurines e.g. indoles with a 5-hydroxy group and an aminoalkyl moiety in position 2 showed redox activities and a good inhibition of the human 5-lipoxygenase, an important enzyme in the arachidonic acid cascade. Inhibitors of 5-lipoxygenase represent promising antiasthmatic agents. At present we prepare further indole derivatives for an extensive structure-activity-relationship analysis.

In cooperation with P. Gmeiners group we have performed structure variations of CNS-active drugs e.g. clozapine or fenoldopam, which interact with different dopamine receptors. We prepared aminosubstituted bicyclic analogues of clozapine and found interesting effects on the dopamine D4-receptor.

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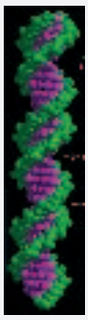
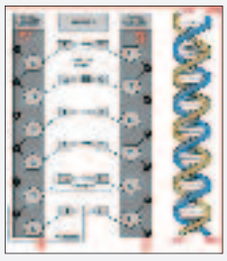
Prof. Dr. Monika Pischetsrieder

Protein- and DNA Modifications by Heat Treatment of Food, Cellular Interactions of Food Components

Foods are complex chemical systems which interact intricately with the human organism. Particularly during processing and heating of food stuffs, a plethora of chemical changes occur, which have hardly been elucidated. However, the recent example of acrylamide has impressively demonstrated that substances formed in heated foods can have critical consequences for the consumer's health. In order to systematically trace protein modification in processed food, the food chemistry group applies high resolution methods of proteom and metabolom analysis. Newly identified components are subsequently tested in intact cellular systems to reveal their impact on different metabolic pathways. Furthermore, our group showed for the first time that sugar degradation products, which are formed in several foods as well as in medicinal products, trigger DNA modifications in the human organism, potentially leading to mutagenic events. We are also interested in the development of highly specific and sensitive immunochemical assays to ensure high levels of food safety and quality.



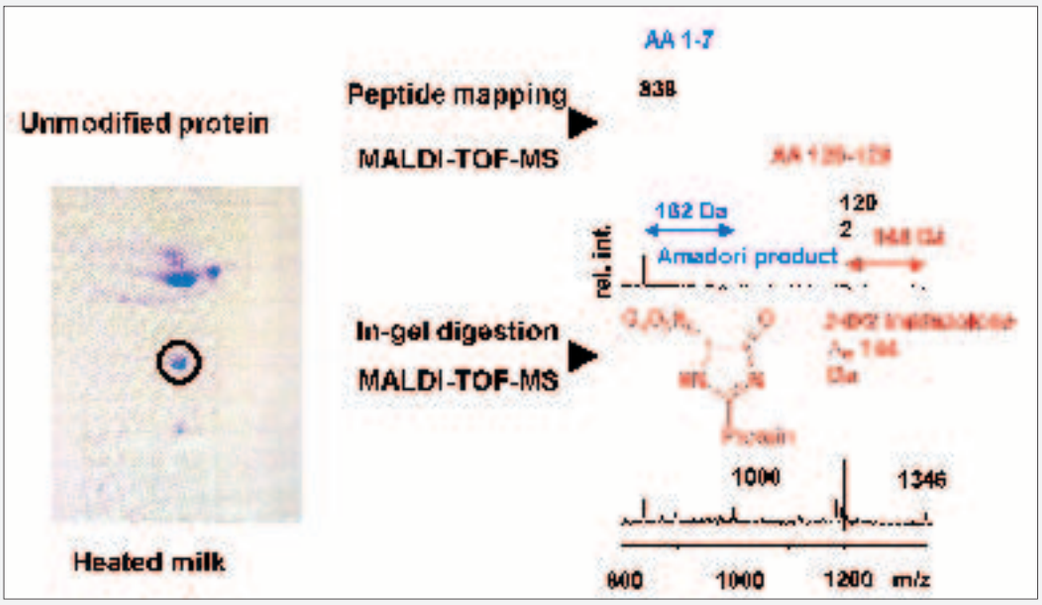


Lebensmittel stellen chemisch komplexe Systeme dar, die in bisher kaum überschaubarer Weise mit dem Organismus des Konsumenten in Wechselwirkung treten. Besonders bei der Verarbeitung und beim Erhitzen von Lebensmitteln treten vielfältige chemische Veränderungen auf, die bisher nur punktuell aufgeklärt werden konnten. Wie das Beispiel Acrylamid jedoch gezeigt hat, können Inhaltsstoffe von verarbeiteten Lebensmitteln weit reichende Konsequenzen für den Verbraucher haben. Um Proteinmodifizierungen in Lebensmitteln erstmals systematisch zu erfassen, werden am Lehrstuhl für Lebensmittelchemie moderne hoch auflösende Methoden der Proteom- und Metabolomanalytik eingesetzt. Gleichzeitig wird in intakten zellulären Systemen die Wirkung dieser neuen Inhaltsstoffe auf Stoffwechselvorgänge getestet. Weiterhin konnte gezeigt werden, dass Abbauprodukte von Zuckern, die ebenfalls in vielen Lebensmitteln, aber auch in Medizinprodukten vorkommen, nach der Aufnahme im menschlichen Organismus zu DNA-Veränderungen führen und damit über ein mutagenes Potential verfügen. Unsere Arbeitsgruppe beschäftigt sich darüber hinaus auch mit der Entwicklung hochspezifischer und sensitiver immunochemischer Nachweisverfahren, mit denen die hohen Anforderungen an Lebensmittelsicherheit und –qualität kontrolliert werden können.

During heating and processing of foods, proteins are modified, for example, by reaction with sugars (glycation), oxidation or non-enzymatic cross-linking. As a result, the nutritional value is largely decreased due to blockage of essential amino acids. Toxicologically relevant products are formed and changes in protein conformation lead to different biological and technological properties. Similar protein modifications are also observed in the human organism. Particularly proteins with a long biological half-life become gradually glycated and oxidized, leading to the formation of advanced glycation or oxidation end-products (AGEs and AOPs). High levels of AGEs are observed in elderly persons or patients with diabetes mellitus or renal failure[1], where they can promote the development of disease related complications.

Proteomic studies of processed foods

Milk is usually thermally processed before it reaches the consumer. Due to the presence of high sugar concentrations, the milk proteins can be severely damaged by glycation and also oxidation during processing. In spite of physiological and technological consequences for the consumer, the chemical nature of the protein changes have not been fully elucidated. In our group, proteomic tools are, therefore, applied to systematically reveal protein modifications which occur during heat treatment of milk. The protein fraction of heated milk is separated by 2D gel electrophoresis. After in-gel digestion, the proteins are further analyzed by matrix assisted laser desorption/ ionization time of flight mass spectroscopy (MALDI-TOF-MS). The studies are carried out in cooperation with the Institute of Biochemistry and Molecular Medicine. In first model studies, we were able to systematically study glycation products of a model protein with several carbohydrate precursors. After peptide mapping, the structures and the binding sites of the major reaction products were identified by MALDI-TOF-MS[2]. MALDI-TOF-MS after peptide mapping was also introduced as a very gentle method to assess labile protein modifications, which are generally degraded during protein hydrolysis. Furthermore, this method allows, for the first time, site specific quantification of adducts of food proteins. The systematic



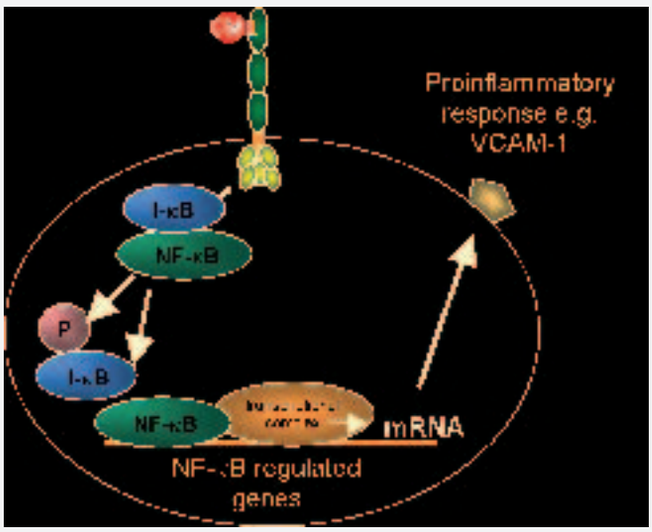
Protein modifications in processed milk are systematically monitored by 2D gel electrophoresis with subsequent in-gel digestion, MALDI-TOF-MS and comparison of the data with unmodified milk proteins

knowledge of the nature and concentrations of secondary food contaminations will facilitate an integral evaluation of the physiological, toxicological and technological consequences of food processing.

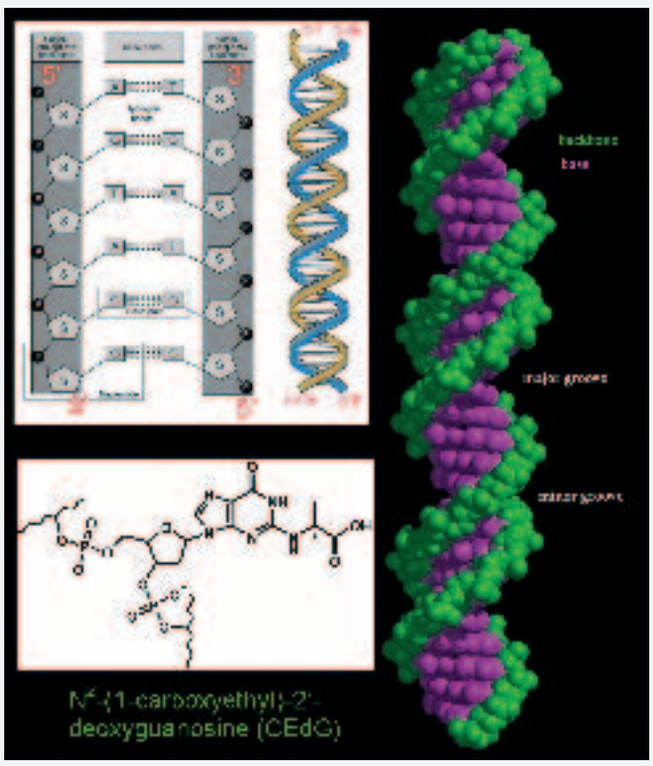
Impact of Maillard products on physiological processes

Maillard products, which are formed from sugars and amino acids under harsh conditions, such as roasting or frying, comprise a vast diversity of chemical substances. The cancerogenic acrylamid, which is found, for example, in French fries, is a prominent example of the substantial impact of Maillard products on the consumer's health. In the food chemistry group, we use intact cellular systems to determine pro-inflammatory and cytotoxic effects of food derived Maillard products.

Carboxymethyllysine, for example, was identified as a lysine modification which triggers pro-inflammatory reactions in endothelial or smooth muscle cells of the vasculature[3]. The cellular response was shown to be dependent upon a specific receptor named RAGE. Thus, receptor mediated pro-inflammatory responses to AGE may play a key role in the pathogeneses of diabetes or uremia. On the other hand, Maillard products also showed antioxidative effects by preventing LDL oxidation[4]. Since oxidized LDL is associated with an increased risk for atherosclerosis, certain Maillard products may also have beneficial effects on the human health.



CML binds to the RAGE receptor and leads to pro-inflammatory reactions via the activation of the transcription factor NF-κB



Reaction of DNA with reactive sugar degradation products leads to CEdG adducts (the DNA structure is from www.web.uconn.edu)

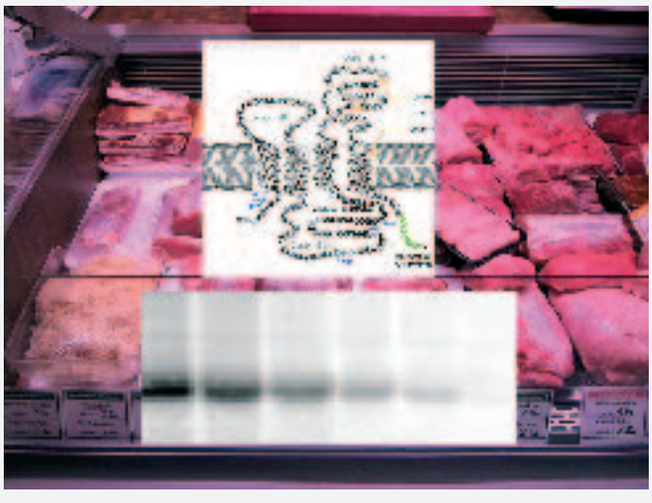
DNA-glycation in vivo

The formation of advanced glycation end-products (AGEs) in the human organism by the reaction of carbonyl compounds, such as sugars, with proteins and their deleterious role in the development of numerous diseases is, in the meantime, a well established concept. Reactive carbohydrate precursors are either ingested through our nutrition or represent natural metabolites. Early studies from our group suggest that AGEs can similarly form from reactive carbonyls and DNA, leading to DNA damage such as increased mutation frequency. More recently, we developed an immunochemical assay to measure DNA-AGEs in human urine[5] as well as a direct method to quantify DNA-AGEs in tissues using high performance liquid chromatography coupled with two-dimensional mass spectrometry detection (LCMS/MS)[6]. Due to the high sensitivity of both methods, it is now possible to investigate factors which promote DNA-AGE formation in vivo and study the consequences of this reaction for the human organism.

Development of highly sensitive immunoassays to ensure food safety and quality

The quality and safety of our food is a leading concern in our society challenging food chemistry research as well as official food control. The insight that even traces of contaminants can have major consequences for the consumer calls for new analytical tools with high performance.

Immunochemial methods, which are based on the selective recognition of the target molecule by an antibody, often allow highly specific and highly sensitive analysis. In the food chemistry group, immunochemical tools are used to develop new analytical concepts addressing current food safety issues.



CNS contaminations in meat are detected by an immunological assay using PLP as a novel marker protein (PLP structure is taken from www.nave.em.mpg)

BSE, for example, is most likely transmitted to the human by the ingestion of brain and spinal cord tissue (CNS) from infected animals. Since BSE tests of cattle do not provide sufficient safety, brain and spinal cord have been excluded from the food chain. In order to enforce this ban, reliable analytical methods are required to detect traces of CNS in meat products. In cooperation with the Institute of Biochemistry and Molecular Medicine in Erlangen and the Bundesforschungsanstalt für Ernährung und Lebensmittel in Kulmbach, a novel marker for CNS contamination was developed and a highly sensitive and specific immunoassay was established. The method is currently applied to screen regional meat products.

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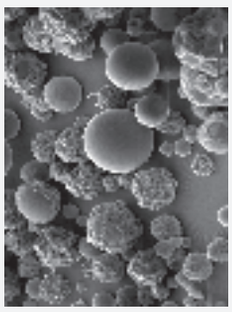
Prof. Dr. Geoffrey Lee

Process-Induced Changes in the Native Structure of Globular Proteins

Our research activities develop and refine a number of technologies that are used to manufacture stable protein powders on the laboratory and pilot scale. These systems have exciting applications as modern drug delivery instruments in three areas. First, protein powders for inhalation, which must meet stringent specifications on particle size and particulate surface characteristics such as morphology, stickiness, etc. Secondly, protein powders for application with needle-free, ballistic injectors. These must have high density to impart sufficient momentum to enable epidermal penetration. Thirdly, protein powders are also an alternative to the freeze-drying or freezing of bulk protein solutions produced by recombinant DNA-technology. Our research effort is focused on the uses of the processes spray-drying, spray freeze-drying and microparticle coating to manufacture stable protein particles for these applications. The preservation of the structural integrity of protein molecules during particle formation is the major scientific problem that must be addressed in this work. The Department of Pharmaceutics is equipped with a battery of analytical techniques necessary to characterize protein structural properties, viz SEC, HPLC, DSC, FT-IR, ESCA (access), gel electrophoresis, WAXS, fluorimetry.



Spray-Drying of Proteins

Of the potentially damaging processes that occur during spray-drying (see Fig. 1) the most dangerous are the adsorption of protein molecules to the rapidly expanding water/air-interface of the atomized spray solution and the enthalpy uptake of the droplets/particles on their passage through the drying chamber. The extent of damage depends in a way not yet elucidated on the size and complex structural characteristics of the protein molecules. A 2.5 kDa peptide showed, for example, an increase in total aggregates from 0.71 % to just 0.79 %. FT-IR analysis of the amide I bands of this peptide showed a shift from a fully disordered secondary structural state in the spray solution (1640 cm^{-1}) to approximately 20 % anti-parallel β-sheet structure in the spray-dried solid (1690 cm^{-1}). An extensive study of changes in the amide I spectrum of the spray-dried homopolypeptide poly-L-lysine showed that enhanced formation of anti-parallel β-sheet is a result not only of energetically favorable intramolecular hydrogen bonding, but also of steric constraints as the peptide molecules approach each other in the medium of a drying droplet. A glycolated IgG of 150 kDa showed formation of up to 20 % total aggregates on spray-drying, yet a similar quantitative shift to the formation of antiparallel β-sheet structure occured in the spray-dried solid. Bearing in mind the high drying air temperatures used in these spray-drying processes (inlet and outlet temperatures typically of 130 °C/90 °C) even the magnitude of this damage to a large protein is modest. This is a result of a combination of low droplet surface temperatures during drying (typically around 40 °C - the wet bulb) and short resistance time of the droplets/particles in the drying chamber. The latter vary between 1 s and 30 s in machines of relevance for the spray-drying of pharmaceutical proteins. Indeed, calculations have shown that the constant rate period of droplet drying lasts but a few ms. Measurements of dynamic surface tension of proteins in this ms range (see Fig. 2) illustrate clearly that a substantial surface excess (Γ = mg/m^2) of protein can be built up at the water/air-interface in this short time frame. Unfolding of the protein molecules present at the

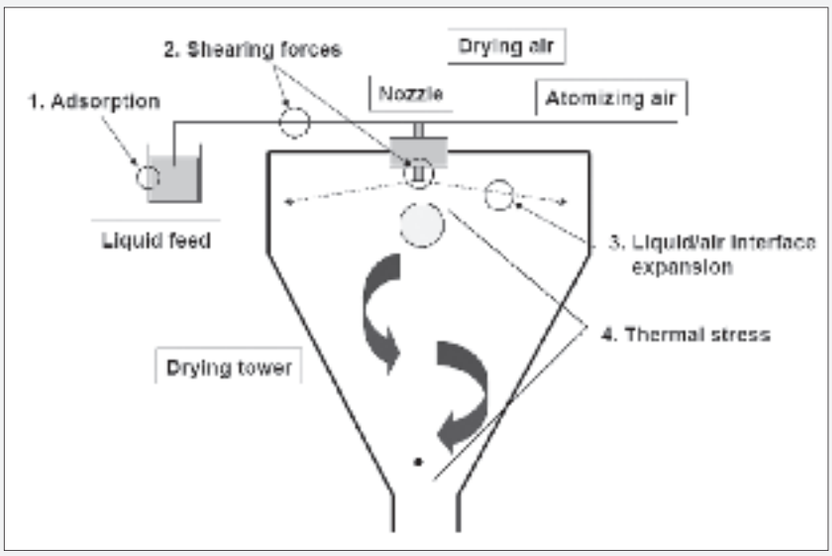


Figure 1

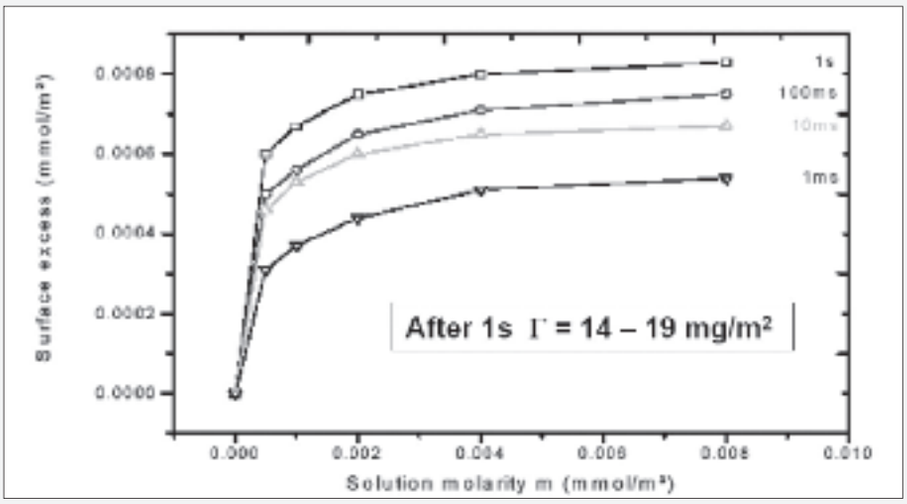


Figure 2

water/air-interface may lead to their aggregation. The use of electron spectroscopy for chemical analysis (ESCA) allows us to detect quantitatively the protein in the surface of the dried particles. Surface excesses of 7 times the equilibrium bulk concentration were, for example, measured with lactate dehydrogenase in spray-dried trehalose particles. A major cause of protein damage during spray-drying is, however, the increasing particle surface temperature after the critical point. This could be clearly demonstrated with spray-dried catalase in the range of inlet/outlet air temperatures of 90 °C/55 °C - 220 °C/ 130 °C. The degree of protein inactivation increases exponentially from 1 % to 70 % with higher drying air temperature.

Both causes of protein damage during spray-drying can be tackled by formulation methods. Disaccharides or polyols can greatly reduce the extent of heat damage to a protein molecule during the spray-drying. Inclusion of 30 parts sorbitol to 70 parts IgG reduced spray-drying induced aggregates from 20 % to 1.5 %. This stabilizing effect cannot be attributed to the glassy immobilization concept, since the glass transition temperature, T_g, of the sorbitol/IgG binary mixture increases after the critical point, but never reaches the outlet air temperature. A water replacement mechanism is more likely operative, as was also evident in the amide I spectra of spray-dried poly-L-lysine plus trehalose. Air/water-interface-induced aggregation can be fully ameliorated by adding a surfactant to the spray solution. ESCA shows how the protein is progressively excluded from the surface of the particles with increasing surfactant concentration (Fig. 3). Since the final surface composition of the particles in this case is approximately 80 % surfactant and 20 % disaccharide, the surfactant evidently binds to the protein in bulk solution, rather than competitively adsorbing to the air/water-interface. Current work examines the use of non aqueous solvents for spray-drying proteins of low water solubility and the effects of formulation on particle stickiness and deposition within a model lung.

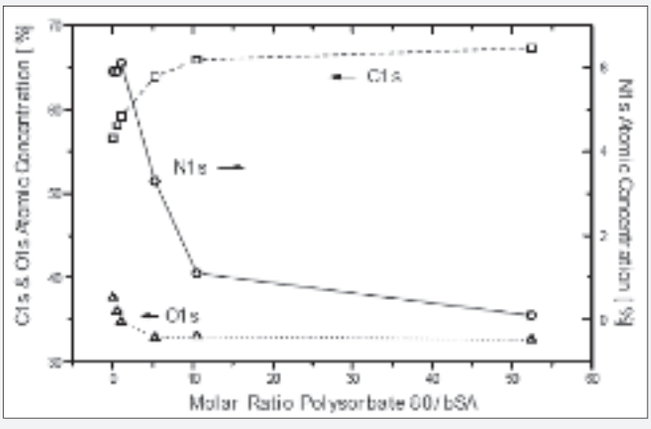


Figure 3

Spray Freeze-Drying

A protein solution is atomized via an ultrasonic nozzle into a bath of a cryogenic liquid, such as LN_2. Judicious nozzle selection produces particles in the size range 20 - 80 µm suitable for application with a ballistic, needle-free injector. Many problems associated with low particle density need, however, first to be solved. Fig. 4a shows a scanning electron micrograph of SFD pure catalase of 120 kDa. The highly porous structure is a result of repressed ice crystal growth during the extremely rapid freezing of the micrometer-sized droplets. The tap density lies typically in the range of < 20 kg/m³, which is much too low for particle breaching of the epidermis. An additional problem is the effect of the high pressure wave within the ballistic injector (< 80 bar) on protein integrity. Both

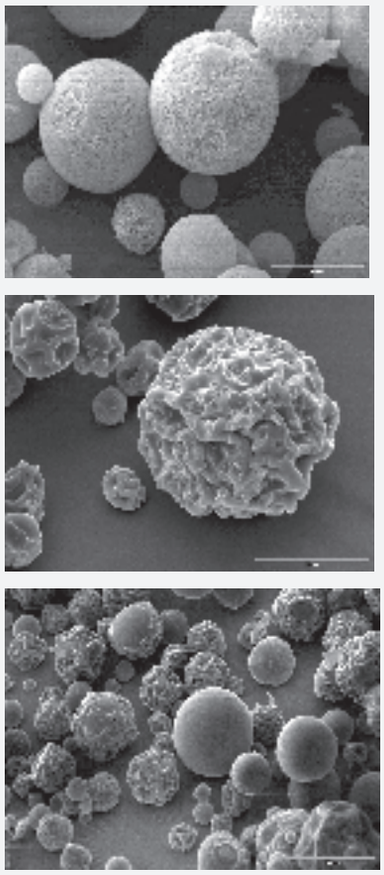


Figure 4 a - c

protein aggregation and loss of activity can be measured after actuation of such powders. Incorporation of disaccharides or polyols also stabilizes the protein against this stress, but the particle density is increased only up to approximately 150 kg/m^3. Extensive studies have identified a carrier particle comprising protein plus trehalose/mannitol and a dextran or hydroxyethyl starch. The particles now have a collapsed appearance (Fig. 4b) and tap densities of up to 700 kg/m^3 are measured. The polymer increases the glass transition temperature of the freeze concentrate, T_g', formed on shock freezing of the droplets in the LN_2. This now lies above the product temperature measured during the primary drying phase of freeze-drying, promoting collapse of the highly porous freeze concentrate structure according to WLF theory. The polymer promotes plastic flow of the frozen solid solution, causing reduction in porosity. The use of such polymers in protein-containing particles also sharply reduces the degree of comminution occuring on actuation with the ballistic injector. Intriguingly, two distinctive particle populations exist within the SFD protein/disaccharide/polymer powders (see Fig. 4c). The first comprises the shriveled, collapsed particle morphology required for ballistic delivery. The second composes non-collapsed, smooth particles. The reasons for this phenomenon are currently under intense scrutiny. We are also attempting to produce high-density, collapsed particles of pure proteins suitable for delivery with the ballistic injector, but this is a challenging task.

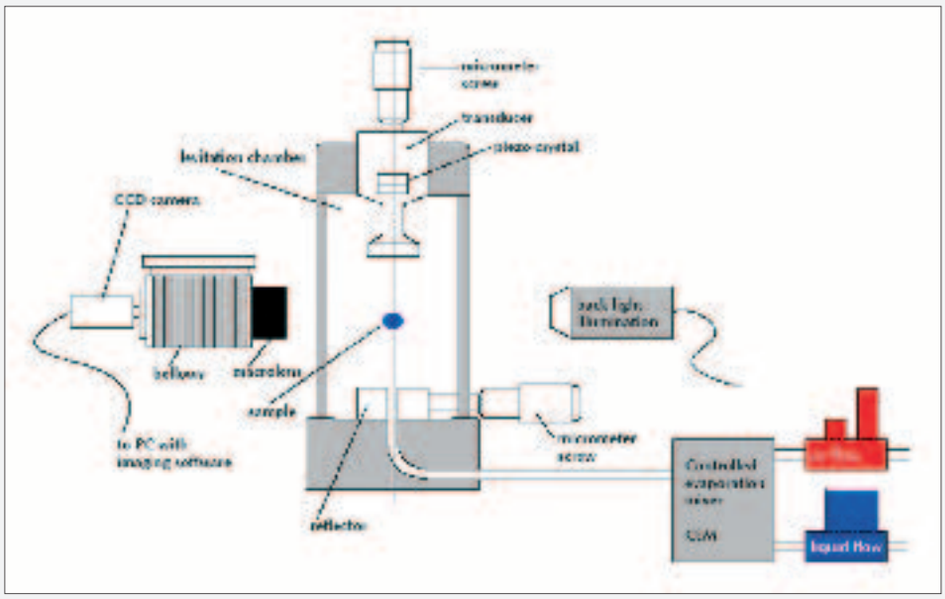


Figure 5

Single Droplet Levitation

The drying kinetics and development of particle morphology of protein containing systems are accessible quantitatively using single droplet levitation. A solution droplet of diameter ≤ 1000 µm is levitated in the standing wave formed between transducer and reflector of an ultrasonic generator (Fig. 5). The drying air temperature, relative humidity and flow rate through the levitator chamber can be exactly controlled, allowing determination of the influence of these conditions on droplet drying rate and particle formation. Additionally, an infrared camera allows exact measurement of droplet/particle surface temperature. This device - initially developed in Fluid Dynamics - allows measurement of drying kinetics and particle formation both before and after the critical point of drying. Although the drying conditions are non-adiabatic, the results provide vital information about the stresses experienced by a protein molecule during spray-drying. Consider the example in Fig. 6, where the changing aspect ratio around the critical point gives a quantitative measure of changes occuring in particle shape at this point. The measured particle surface temperature shows us which enthalpy stress is being applied to the protein at any time during drying. By selective removal of the droplet/particle at various times during drying, we can follow the kinetics of protein unfolding and aggregation. This unique technique shows us at what time - before, at or after the critical point - damage to the protein takes place.

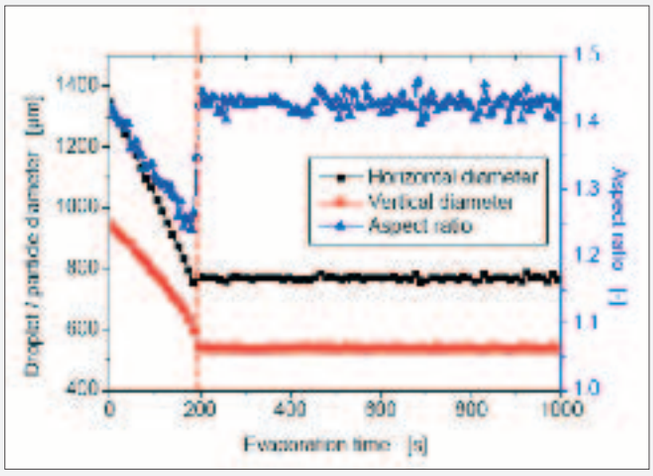


Figure 6

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Prof. Tim Clark

From signal transduction to electron transfer

The research group develops and applies calculation techniques for investigating the mechanisms of chemical and biological processes. Our main interests lie in the mechanisms of reactions of ligands coordinated to redox-active metal centers, reactions of organic radicals and conformational changes in proteins that lead to biological signal transduction.

Die Gruppe entwickelt Rechenmethoden zur Simulation von chemischen und biologischen Systemen und setzt sie ein, um mechanistische Fragestellungen zu bearbeiten. Dabei liegen die Schwerpunkte bei den Mechanismen von Reaktionen an redoxaktiven Metallzentren, bei Reaktionen von organischen Radikalen und bei Konformationsänderungen von Proteinen, die zu biologischen Schaltfunktionen führen.

The two main research directions of the group are the development and application of computational techniques for investigating inorganic, organic and biological reaction mechanisms and for *in silico* development and optimization of pharmaceuticals (Computer-Aided Drug Design, CADD). The group participates actively in SFB473 "*Mechanisms of Transcriptional Regulation*" and SFB583 "*Redox-active metal complexes: Control of reactivity via molecular architecture*" and in the "Parashift"-interdisciplinary joint project involving the Universities of Erlangen, Aberdeen, Edinburgh, Oxford, Portsmouth and Southampton.

Redox-active Metal Complexes

Electron-transfer catalysis [1] is a general mechanism for the catalysis of organic reactions in the coordination sphere of redox-active metals. Reaction barriers are reduced by one-electron oxidation ("hole catalysis") or reduction ("electron catalysis" of the reactive ligand system by the metal center. This electron transfer is not usually observable experimentally because it only occurs in a limited region of the reaction coordinate close to the transition state. Furthermore, the separation of two electrons by the electron-transfer step often leads to a change of multiplicity to a higher spin state (*Two-State-Reactivity*, TSR). [2] Figure 1 shows a comparison of the calculated (DFT) spin densities of the ring-closure transition state along the reaction path for the dimerization of phosphaacetylene to give 1,4-diphosphete for the reaction in the CpCo-complex and for the unperturbed radical anion. The similarity of the two spin-density distributions supports the interpretation of the reaction as being catalyzed by electron-transfer from the cobalt center to the $C_2H_2P_2$ moiety.

We find that this type of catalysis is remarkably common and have demonstrated that the oligomerization of acetylene (to

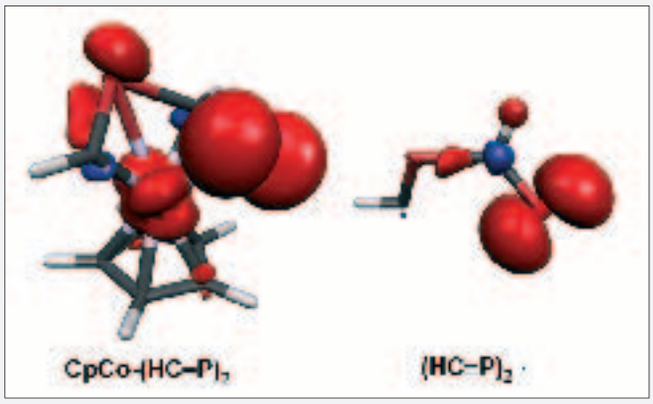


Figure 1: Calculated (B3LYP/6-31G*) spin densities for the ring-closure transition state to give 1,3-diphosphete during the dimerization of phosphaacetylene. The similarity of the two spin-density distributions demonstrates that the cobalt-catalyzed reaction involves transfer of one electron to the reactive ligand.

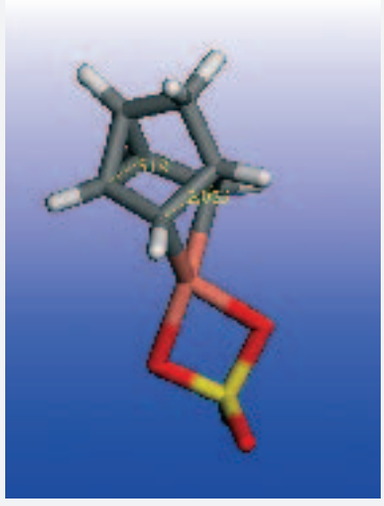


Figure 2: The calculated (CCSD/6-31+G(d)) transition state for the $CuSO_4$-catalyzed rearrangement of quadricyclane to norbornadiene. The polycyclic ligand has a very similar geometry to that found for the transition state of the C_7H_7 radical-cation rearrangement [3] and the $CuSO_4$-molecule twists by 90° in the course of the rearrangement.

cyclobutadiene complexes or benzene) and the dimerization of phospaacetylenes are catalyzed by reduction, whereas catalysis of the rearrangement of quadricyclane to norbornadiene involves oxidation of the hydrocarbon. Figure 2 shows the calculated structure of the transition state for the quadricyclane → norbornadiene rearrangement catalyzed by complexation to a single Cu(II) sulfate molecule.

CH-Activation

In a joint research project with Dr. Graham Ball (University of New South Wales, Australia), we have investigated the agostically bound complex of cyclohexane with $CpRe(CO)_2$. [4] The complex can be observed by NMR within a narrow temperature range around 180 K by photolysis of $CpRe(CO)_3$ in cyclohexane solution. DFT- and *ab initio* (MP2) calculations confirm the experimental observation that the agostic Re-H-C bond occurs preferentially with an axial hydrogen atom. The calculated NMR chemical shifts and coupling constants underline the non-equivalence of the axial and equatorial hydrogens of the bound CH_2-group. Figure 3 shows the MP2-calculated structure of an axially bound complex.

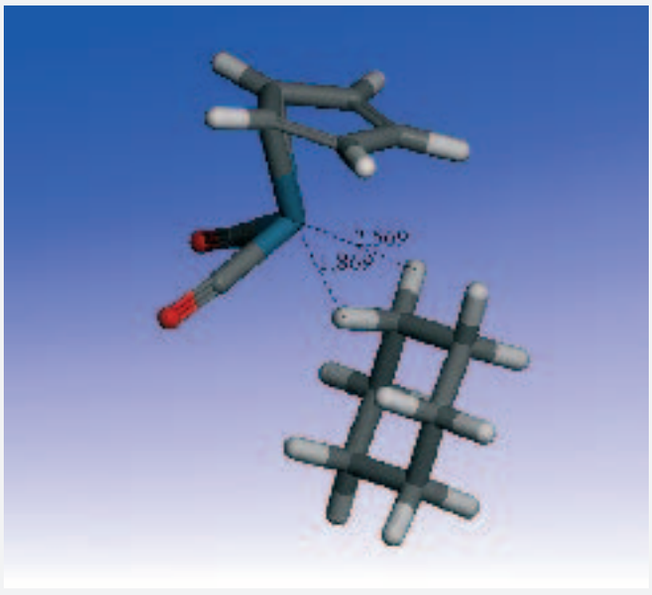


Figure 3: The MP2/6-31G(d) optimized structure of an axially-bound CpRe(cyclo-C_6H_{12}) complex. The calculated ^{1}H-chemical shift of the bound axial hydrogen atom is -9.7 ppm, compared with +2.3 ppm for the equatorial hydrogen on the same carbon. The corresponding observed shifts for an equilibrium mixture of roughly 70% axially and 30% equatorially-bound isomers are -6.2 and +0.5 ppm.

Radical Reaction Mechanisms

So-called *radical clocks* are often used in mechanistic organic and biological chemistry to detect radical intermediates. The central assumption underlying their use is that the rate constant of the unimolecular rearrangement used as a standard with which to compare the rates of competing reactions remains constant. We have shown [5] that complexation with lithium cations catalyzes the rate of ring-closure of the 1-hexen-6-yl radical to cyclopentylmethyl significantly. More recent calculations indicate that complexation with a fluoride ion does not affect the rate of the 5-*endo* cyclization significantly, but that it accelerates the competing 6-*exo* process to give the cyclohexyl radical very significantly. This effect is also found in model calculations of the radical-clock system in the active site of cytochrome P450. Figure 4 shows the calculated transition state for ring-closure to the cyclohexyl radical with a complexed fluoride ion.

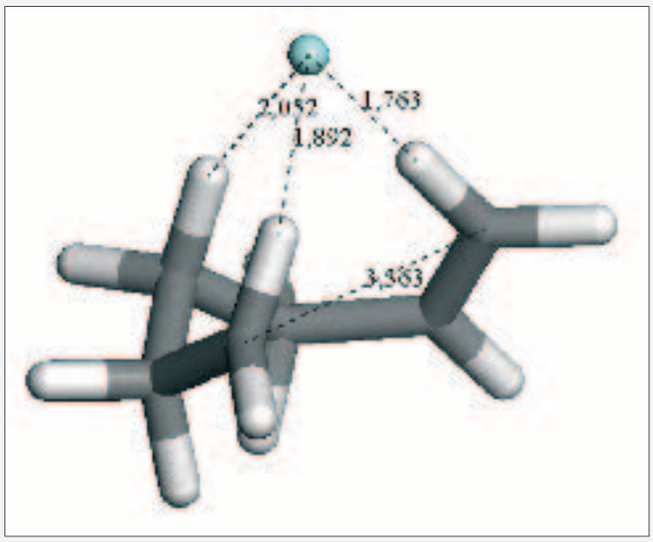


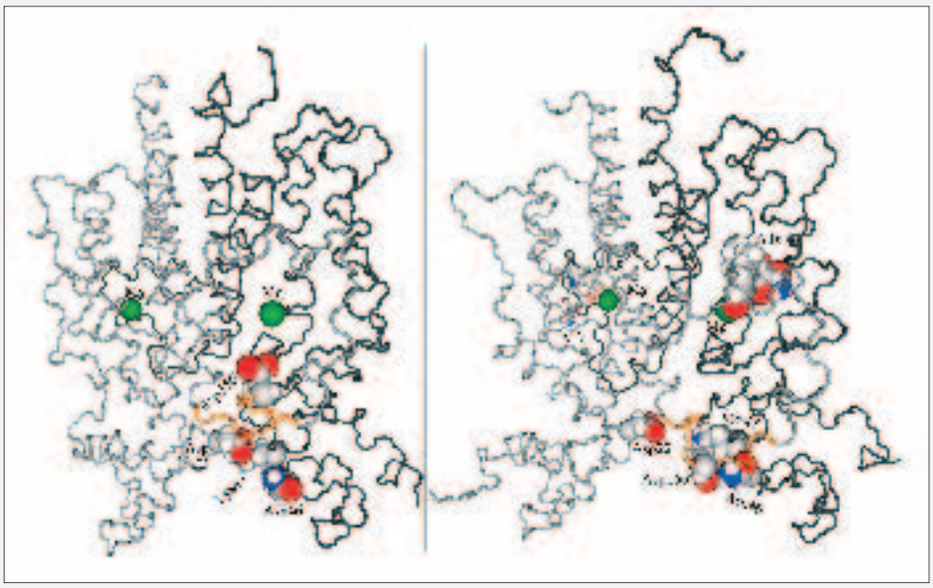
Figure 4: The calculated (QCISD/6-31+G(d)) transition state for the ring-closure of the 1-hexen-6-yl radical complexed with the fluoride anion to the fluoride complex of the cyclohexenyl radical. The fluoride binds via three CH…F hydrogen bonds.

The Mechanism of Induction of the Tetracycline Repressor

The Tetracycline Repressor (TetR) is a signal-transduction protein that regulates the expression of the Tetracycline Antiporter (TetA), a membrane-bound protein that removes tetracycline antibiotics for bacterial cells. TetR binds to two operons to regulate both its own expression and that of TetA. Tetracyclines bind very strongly to dimeric TetR and induce an allosteric change that results in the protein dissociating from the DNA and thus inducing expression of the two proteins. We have investigated this regulatory system, which is of particular importance because of its use as a “gene switch” that allows genes to be turned on and off at will, using a variety of calculational techniques.
Firstly, the structure of tetracycline and its derivatives in aqueous solution at physiological temperatures is by no means

clear, so that we have investigated both the conformation and the tautomeric forms of tetracycline itself [6] and 5a,6-anhydrotetracycline [7] using DFT and *ab initio* calculations with simulated solvent effects.

Time-resolved fluorescence spectroscopy has been used to investigate the structure of TetR in solution, but interpretation of the results is difficult. We have investigated fluorescence resonant energy transfer (FRET) in TetR using molecular dynamics and QM/MM semiempirical molecular orbital configuration interaction calculations. [8] The results suggest that the "rotamer model" usually used to interpret the result of FRET experiments is correct in that distinct rotamers of tryptophan side chains can be observed, but that the individual fluorescence-decay rates suggested by multi-exponential fits to the experimental data are not caused by different rotamers, but rather by the width of the distribution of FRET rate constants in the real protein.



Fígure 5: Comparison of the non-induced (left) and induced (with 5a,6-anhydrotetracycline, right) forms of the Tetracycline Repressor. The protein is dimeric with two magnesium ions in the binding pockets (shown green). The inducer coordinates to the magnesium ions, displacing an aspartate and thus setting a cascade of rearrangements of salt bridges and hydrogen bonds into motion. These rearrangements result in the two DNA-binding heads (at the bottom of the structures) moving apart on induction.

Allosteric changes in proteins usually occur over time scales on the order of microseconds, which makes them inaccessible for current molecular-dynamics (MD) simulations. In the case of TetR, the nature of the allosteric change is known roughly from X-ray structures of induced and non-induced forms of the protein. However, several flexible loops are not resolved in the X-ray structures, so that a complete picture of the mechanism of induction cannot be derived from the X-ray structures alone. We have performed long time-scale (50 ns) MD simulations on non-induced TetR and its induced forms with tetracycline and 5a,6-anhydrotetracycline. Analyzing the low-frequency normal vibrational modes obtained from these three simulations reveals that the induced forms show a very low-frequency vibration that corresponds closely to the allosteric change deduced from the X-ray structures. Further analysis of the structures and interaction energies obtained from the simulations allows us to identify a clear and easily understood mechanism for the allosteric change. This mechanism [9] is shown schematically in Figure 5.

This mechanism also leads to a complete understanding of the molecular features necessary for induction of TetR.

Method Development

We recently introduced an extension of the AM1 semiempirical molecular orbital technique with *d*-orbitals using the multipole formalism introduced by Thiel and co-workers and have published parameters for P, S, Cl and Mo [10] and for the metals Al, Si, Ti and Zr. [11] The first-row transition metals are now being parameterized.

A major effort is focused on the development of new, non-atomistic descriptions of molecules for drug-design and modeling. This work involves developing new local properties [12] and analytical descriptions of molecular shapes and intermolecular binding properties. [13] These techniques will be used for a new generation of non-atomistic simulation techniques using anisotropic united atoms.

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Prof. Dr. Andreas Kometz / Dr. Ulrich Barth

Chemical Education on the Friedrich-Alexander-University

Because of the very critical questioning of the education of natural science of pupils in Germany today there are many initiatives to improve this situation. The University of Erlangen-Nürnberg, especially the Didactics of Chemistry, wants to solve this task. Two projects / initiatives will be introduced: the advanced training centre for chemistry teachers and the project "Chemobil". It enters especially into the starting point of exploration for designing and the evaluation of chemical microscale experiments for pupils.

Da naturwissenschaftliche Bildung von Lernenden gegenwärtig in Deutschland sehr kritisch hinterfragt wird, gibt es viele Initiativen diese Situation zu verbessern. Auch die Didaktik der Chemie der Universität Erlangen-Nürnberg stellt sich dieser Aufgabe. Zwei Projekte bzw. Initiativen werden vorgestellt: das Chemielehrer-Fortbildungszentrum und das Projekt „Chemobil". Insbesondere wird dabei auf den Forschungsansatz zur Entwicklung und Erprobung von chemischen Schülerexperimenten in Halbmikrotechnik-Geräten eingegangen.

As it is the case with the entire education system, the teaching of natural sciences is undergoing a very critical analysis. Chemistry occupies one of the last places in the scale of popularity of schoolchildren, a fact that should give food for thought and spur us on to action! One possible approach to make up ground in this area is the „In-service Training Centre for Teachers of Chemistry", the Project „Chemobil", which has been supported by the GDCh and other activities for Teachers and Pupils.

http://www.chemiedidaktik.ewf.uni-erlangen.de/

In-service Training Centre for Teachers of Chemistry

In addition to training students to become teachers at a Bavarian school[1], the Faculty of the Teaching Methodology of Chemistry also attends to scientific in-service training of teachers. The In-service Training Centre for Teachers of Chemistry at the University of Erlangen-Nürnberg is incorporated into the Chair of Didactics of Chemistry.

The work of the In-service Training Centre is guided by the three principles "competence – cooperation – authenticity" which are closely related to each other. The trainer's competence is crucial to the quality of the training. Professional and qualified competence is achieved through close cooperation with experts from universities, schools and companies. Therefore

http://www.gdchfbz.ewf.uni-erlangen.de/

[1]The Bavarian school system comprises four years of primary education starting at the ages 5 or 6 and up to 8 ensuing years of secondary education. After primary school pupils have to decide for one of the three different school types: general secondary school (grade 5 to 9/10), secondary high school (grade 5 to 10) and grammar school (grade 5 to 12).

an in-service training on a certain subject is often organised by several trainers from the fields of education and industry.

Various aspects of the subject (e.g. topical scientific information, didactic stimuli, practical realisation in lessons, economic significance) can thus be taught without prejudice to authenticity. Considering all this, the specific aims of in-service training are:

- further development of scientific teaching
- application of didactic research to practical teaching
- actual assistance in teaching classes
- assistance with realising new syllabi.

In terms of content, the main emphasis is put on the following fields in accord with the faculty's priorities:

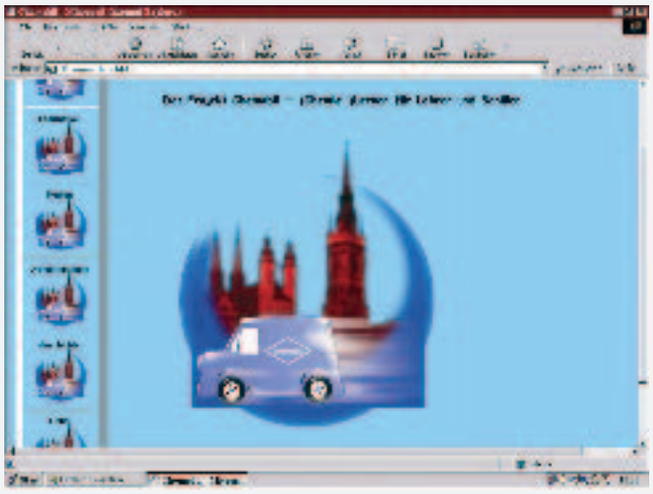
- experimental chemistry for schools
- methodological competence
- cooperation of university and schools.

Of utmost importance is the integration of current scientific results of basic and applied research into modern chemistry teaching. These aims of in-service training correlate highly with the ideas and expectations of participating teachers. The evaluation of trainings shows how much especially trainings in methodological competence as well as in mastering chemical experiments are demanded. Primary and general secondary school teachers have a particularly high need for scientific in-service training, since they are often not qualified for scientific subjects but (have to) teach them.
In 2006, the In-service Training Centre for Teachers of Chemistry at the University of Erlangen-Nürnberg is going to organise about 55 in-service trainings for teachers of all school types.

The Chemobil Project – Chemistry Lessons for Teachers and Schoolchildren

The new scientific approach of the scheme consists in the preparation, carrying out and evaluation of regional (i.e. in the immediate surroundings of the school) experimentally oriented training sessions for chemistry teachers and the offer of special experimental practical sessions for schoolchildren at their schools.

This model has proved helpful as it guarantees the practical further training of chemistry teachers outside the conurbations as well, and chemistry lessons can be more excitingly designed through practically relevant experiments.
This is also evident from the large amount of use the Chemobil enjoys and the positive response of the target group.
The first subjects to be offered and readily accepted, satisfying the everyday experiences of learners as well as modern scientific results, are ‚The use of computers in chemistry lessons" and „Modern energy technologies".
For this, extensive teaching media to support the experimental work of learners (20 environmentally friendly and relatively affordable school experiments in each case with photocopied handouts) have been developed and provided to the chemistry teachers.
Participants can obtain the above-mentioned materials and have an opportunity in the practical to carry out the school experiments and then discuss them.



http://www.chemobil.de

Other activities for school chemistry in Erlangen-Nürnberg – Microscale Chemistry Experiments for pupils / students

"Worldwide, a so-called microscale movement is taking place. The idea is simple: convert existing experiments to microscale and save on chemicals. This will save costs, it will be safer for the students and it will cause much less waste. Moreover, processes will take place much faster so that even the slower organic syntheses will become available as student experiments. Demonstration experiments can become student lab experiments without causing an increase in the amount of chemicals used."[2]

What is Microscale Chemistry?

"Microscale chemistry is an environmentally safe pollution prevention method of performing chemical processes using small quantities of chemicals with out compromising the quality and standard of chemical applications in education and industry.
Microscale Chemistry is performed by using:

- drastically reduced amounts of chemicals,
- safe and easy manipulative techniques,
- Miniature labware and high quality skills."[3]

Why Microscale Experiments?

"Microscale Chemistry offers many benefits:

- It reduces chemical use promoting waste reduction ….
- It offers vastly improved laboratory safety by
    - o Better Laboratory Air Quality.
    - o Least Exposure to Toxic Chemicals.
    - o No Fire and Explosion Hazards.
    - o No Spills and Accidents.

[2]http://staff.science.uva.nl/~joling/microschaal/microinfo.html
[3]http://www.microscale.org/about.asp

- It sharply reduces laboratory cost.
- It requires shorter experiment time.
- It implements excellent laboratory manipulative techniques.
- It lowers glass breakage cost.
- It saves storage space.
- It improves laboratory skills.
- It provides clean and productive environment.
- It promotes the principle of 3Rs: Reduce, Recover and Recycle.
- It creates the sense of ‚Green Chemistry'.
- It changes the psychology of people using chemicals.
- It is user friendly to people with physical disabilities."[4]

History of our microscale unit: system of cuvettes

In 1988 Legall and Kuhnert designed a new microscale system – the cuvettes[5]– and after 1990 Kometz evaluated the cuvettes for using in schools[6,7] .

The cuvettes consist of complete transparent plastic units[8] which permit the performance of chemical experiments at pupils desks and the demonstration of chemical reactions by projections in front of a large circle of persons.

The system offers the possibility of combination with other semi-micro and microscale units and it is also possible to combine the different cuvettes with one another.

Temporary there exist 7 different cuvettes (cell K 1 … cell K 7). For example:

- Gas generator with pneumatic trough (Cell K 1),
- Gas generator with two gas washers (Cell K 2),
- Self-regulating gas generator "Kipp" (Cell K 3).

Examples of possible uses are the generation of following gasses: H_2, O_2, N_2, CO_2, SO_2 and NO_2.

A model practical project: Modern Energy Technologies

In the model practical session there are four subject areas which are focused on:

- experiments to show the properties of oxygen and hydrogen;
- experiments an primary and secondary elements;
- experiments with solar cells, hydrogen and methanol fuel cells, as well as
- experiments an spontaneous endothermic and exothermic reaction –
  salt hydrates as heat reservoirs and cooling mixtures[9].

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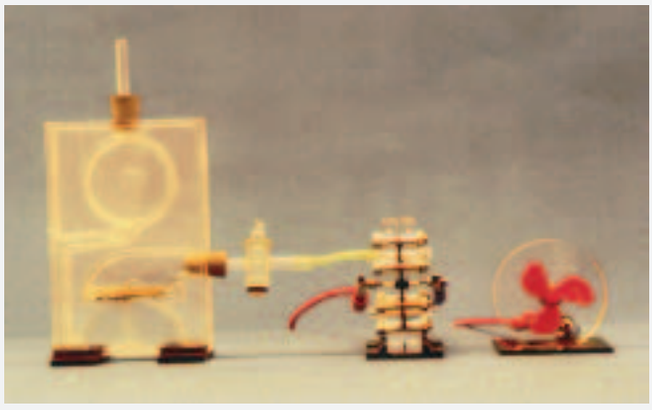
Cell K 1: $CaCO_3 \rightarrow CaO + CO_2$

Cell K 2: $Cu + 4\ HNO_3 \rightarrow Cu(NO_3)_2 + 2\ NO_2\uparrow + 2\ H_2O$



Cell K 3: $Zn + 2\ HCl \rightarrow H_2\uparrow + ZnCl_2$
(in combination with a hydrogen fuel cell)

[4]http://www.microscale.org/about.asp
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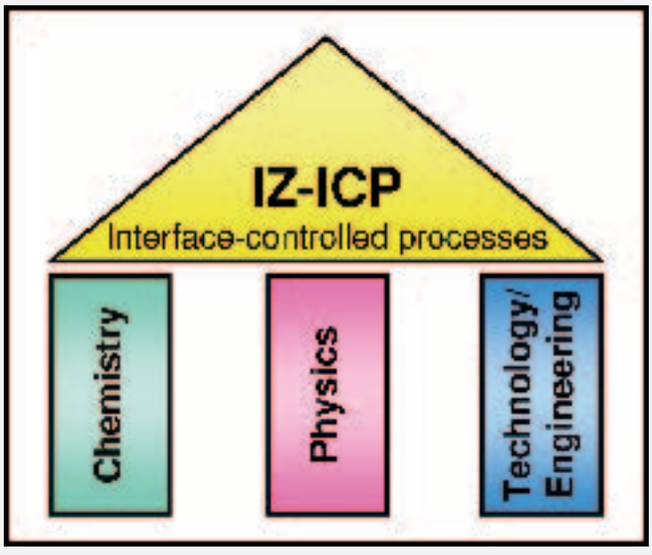
Prof. Dr. Rainer Fink

Interdisciplinary Center for „Inter-face-controlled processes (IZ-ICP)“

Present members of the IZ-ICP: PD Reinhard Denecke, Prof. Rainer Fink, Prof. Jörg Libuda, Prof. Hans-Peter Steinrück (all from Physical Chemistry), Prof. Andreas Görling (Theoretical Chemistry), Prof. Thomas Fauster, Prof. Klaus Heinz, PD Stefan Müller, Prof. Lothar Ley, PD Jürgen Ristein (all from Physics), Prof. Oleg Pankratov, Dr. Günther Schwarz (Theoretical Physics), Prof. Wolfgang Peukert (Chemistry and Bioengineering. CBI), Prof. Patrick Schmuki (Material Science),

Interfaces play a key role in nature and in technology. For instance bonding of molecules to surfaces, chemical reactions, the properties of electronic or the biocompatibility of materials are only few examples, which demonstrate the importance of external and internal interfaces and the processes occurring at the respective interfaces. In order to control these processes it is essential to fully understand these processes down to the molecular or atomic length scale.



The Interdisciplinary Center for “Interface-controlled processes” (IZ-ICP), which has formed in December 2004, focuses on the influence of interfaces on the physical and chemical properties. The basic idea behind these investigations is to modify solid surfaces to control the structural properties of the interface which consequently affect the electronic, optical or chemical properties of the system under investigation. E.g., by the proper choice of materials or material combinations, the electronic and chemical properties of ultrathin metal films can be modified to optimize the catalytic activity. On the other hand, one may control the molecular orientation in organic thin films by adequate substrate crystals in order to affect the electronic and optical properties in thus prepared devices (e.g., sensors, light-emitting devices). From the present knowledge interface properties cannot be easily predicted, since the structural arrangements at the interfaces (solid-solid, solid-liquid, solid-gas interfaces) scale with the complexity of the interacting species. So far, only in very few cases the geometric structure of e.g. complex organic-inorganic heterointerfaces could be estimated theoretically to explore the resulting electronic properties. Further interests include the more complex hybrid materials, interfaces for spin-injection devices etc.

The IZ-ICP represents an ideal platform to mix the expertise from different areas in the natural sciences (physics, chemistry, theoretical physics/chemistry) and technical disciplines (material sciences, chemical and bioengineering, modelling). This interdisciplinary approach opens not only a manifold of research activities but also utilizes synergy effects also with respect to effective use of resources. In addition the research activities, the IZ-ICP has started with an interdisciplinary graduate course programme to improve the student and graduate education.

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Prof. Dr. Andreas Hirsch

Interdisziplinäres Zentrum für Molekulare Materialien (IZMM)

Interdisciplinary Center for Molecular Materials

Molecular materials represent a fundamental and interdisciplinary research area at the interface between Chemistry, Physics and Materials Science. At the same time they provide the basis for a variety of future technologies. Materials based on defined molecular building blocks are characterized by tuneable performance, which is of great importance for high end applications in nanoelectronics, medicine and energy conversion technology.

The IZMM at the Friedrich-Alexander-Universität Erlangen Nürnberg serves as a platform for interdisciplinary research projects in the field of *Molecular Materials* and *Nanotechnology*. Currently 14 groups from the Chemistry and Physics Department of the FAU (i.e. Prof. Dr. Andreas Hirsch (chair), Prof. Dr. Heiko Weber (vize chair), Prof. Dr. Nicolai Burzlaff, Prof. Dr. John Gladysz, Prof. Dr. Timothy Clark, Prof. Dr. Rainer Fink, Prof. Dr. Andreas Görling, Prof. Dr. Dirk Guldi, Prof. Dr. Horst Kisch, Prof. Dr. Carola Kryschi, Prof. Dr. Lothar Ley, Prof. Dr. Paul Müller, Prof. Dr. Hans-Peter Steinrück, Prof. Dr. Ulrich Zenneck) are involved in the IZMM. Their complementary research expertise spans from the synthesis and the supramolecular oganization of new molecular architectures including fullerenes, carbon nanotubes, polyyines, porpyhrins and dendrimers to the development of opto-electronic devices. Next to molecules also nanoparticles, ultrathin layers and interfaces are investigated. Physical characterization is achieved, for example, by single-molecule conductivity measurements, by time resolved photophysical investigations and modern microscopy techniques including TEM, STM and AFM.

The research at the IZMM is supported by a variety of organizations such as DFG, BMBF, EU and the Bayerische Forschungsstiftung. In addition close scientific collaboration with industrial laboratories serves as a major stimulus for developing new applications for molecular materials. Modern student training programs in particular the subject *Molecular Science* which was recently established at the FAU as a consecutive Bachelor/Master curriculum as well as recruitment of excellent international graduates and Post-Docs guarantees a continuous supply of highly qualified researches for the IZMM.

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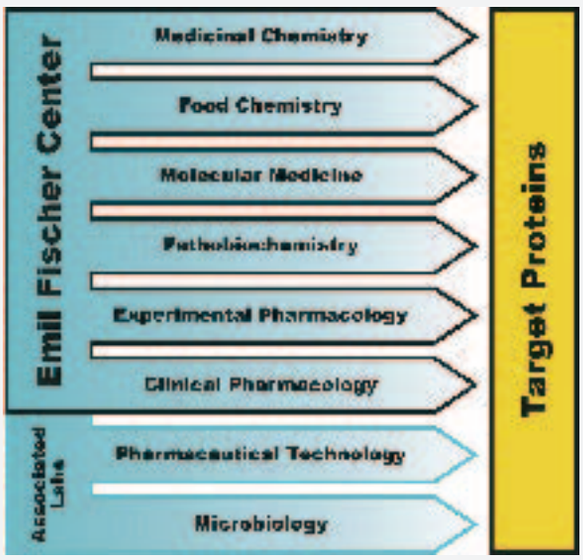
Prof. Dr. Peter Gmeiner

Emil Fischer Center for "Target Proteins"

Present laboratories of the Emil Fischer Center: Lehrstühle für Pharmazeutische Chemie, Lebensmittelchemie, Biochemie und Molekulare Medizin, Biochemie und Pathobiochemie, Experimentelle Pharmakologie und Toxikologie und Klinische Pharmakologie und Toxikologie; associated labs: Lehrstühle für Pharmazeutische Technologie und Mikrobiologie.

Target protein-ligand interactions.

With the aim to identify novel neurotropic agents and to elucidate the molecular function and localization of signaling proteins, low molecular weight ligands are systematically synthesized and evaluated *in vitro* with respect to their biological activity. G-protein coupled neuroreceptors, Tet-repressors, and prions are addressed as target proteins. Drug kinetics determining target proteins (drug metabolizing enzymes and transporters) taking influence on the concentration of pharmaceutical substances at their location of action and thereby on their activity, are also investigated. Employing techniques of pharmacogenomics, the influence of genetic variability on protein-ligand interactions and on the resulting drug efficacies is evaluated. Using high-resolution protein chemical methods, the structure of the interaction domains of disease-related neurotransmitter receptors, especially of glycine- and glutamate receptors, and their modifications in the context of hereditary CNS diseases are elucidated.



Identification of target proteins.

Novel protein markers of use for the surveillance of hazardous BSE material within the scope of food analytics are identified.

The laboratories address the elucidation of synaptic target protein complexes involved in neuronal signal transduction and their malfunctions in case of neurological diseases. In doing so, an intracellular Ca^{2+} channel could be identified as a molecular complex partner of the NMDA receptor. Cytoprotective proteins, the knock-down or over-expression of which being of potential therapeutic interest, are identified by means of cDNA arrays.

Target protein modification and formulation.

Protein modifications occurring during food treatment, but also *in vivo* under pathological conditions, represent a major research focus. Chemical changes are documented employing modern (bio)analytical methods and functional consequences are evaluated by means of biological tests. Structural modifications of proteins, occurring during physical-chemical or technological treatment, are acquired quantitatively, and particle formation for needle-free parenteral application of proteins is explored.

Target proteins in signal transduction.

In order to understand the relevance of target proteins in nuclear signal transduction and consequently to construct efficient artificial, externally controllable signaling structures for controlling the expression of any target protein, modes of action are mechanistically elucidated. In cooperation with the chair of microbiology, the signalers for these target proteins are varied, employing the method of targeted evolution, and their interaction with the target proteins is determined quantitatively. The structural modifications of the target proteins induced by the signalers are examined biophysically and desired properties are utilized for the construction of transgenic disease models.

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Prof. Dr. Ulrich Nickel

GRK 312: Homogeneous and Heterogeneous Electron Transfer

The graduate kolleg, funded by the Deutsche Forschungsgemeinschaft, was initiated 1996 by ten research groups from chemistry, physics and engineering. Although during the funding period several changes in the casting Pis occurred. the following groups from the Department of Inorganic Chemistry (i.e., van Eldik, Kisch and Zenneck), Department of Organic Chemistry (i.e., Gladysz, Hirsch and Saalfrank), Department of Physical Chemistry (i.e., Kryschi, Nickel and Schneider) and Computer Center for Chemistry (i.e., Clark) are participating in the final stage of funding.

In line with the central importance that electron transfer reactions have in nature and engineering the projects of this graduate school constitute a broad and interdisciplinary field. In particular, it ranges from the synthesis of mono- and multinuclear metal complexes as well as functionalized fullerene derivatives and studies about the redox activity to spectroscopical, electrochemical and kinetic investigations. Hereby, the emphasis is placed on electron transfer processes in homogeneous solution and heterogeneous electron exchange reactions at semiconductor / solution interfaces. The different projects concentrate on mechanistic insights into already known reactions and the exploration of novel catalytic processes that are triggered by electron transfer. Besides thermal reactions, photochemical reactions are also the center of interest. At last, our activities will be concluded by theoretical work on modeling the structure of reacting species and the rates of electron transfer steps. Some of the projects, whose objectives are related to basic research, will dwell on important potential applications such as waste water and chemical use of solar energy.

The kolleg supported predominantly chemists, but also physicists with a particular emphasis on molecular spectroscopy. It served to enhance the education and training of the Ph.D. students in experimental and theoretical aspects related to the aforementioned research fields through a variety of teaching programs, ranging from guest speakers, workshops, mini-symposia and coordinated classes and seminars. The grantees have been integrative parts in running the different events, which helped in shaping their organization and communication skills. Repeatedly conducted colloquia helped, on one hand, to monitor the progress and, on the other hand, to tighten social contacts among the grantees and, in turn, to facilitate the exchange of experience and to guarantee mutual support.

The foremost essential reaction step in many artificial and natural chemical systems is either a homogeneous or heterogeneous electron transfer. Therefore, the most important objectives of the research program were to elucidate the mechanism of electron transfer reactions through the application of suitable techniques and to synthesize novel, tailored compounds, which are of theoretical, spectroscopical and catalytic interest. Over time the following three thrusts were pursued.

In the context of *thermal electron transfer reactions* redox active mono- and multinuclear organometallo complexes were synthesized and their catalytic activity (i.e., C-C couplings) were tested. Intramolecular electron transfer in novel multinuclear, mixed valence, homo- and heteronuclear metal-crownethers were established through UV- and temperature dependent Mossbauer spectroscopy.

Central for the thrust on *photoinduced electron transfer reactions* were studies on photoinduced charge separation and charge recombination in homogeneous and heterogeneous phases through various spectroscopic techniques (i.e., steady-state and time-resolved fluorescence, transient absorption spectroscopy, Raman spectroscopy and cyclic voltametry). In light of enhancing our general understanding of photophysical primary processes the work was built on covalently linked systems, in which electron donor, electron acceptor and the nature of the bridge were systematically varied. Work, which was more of preparative nature, stressed studies on electron transfer effects at the surface of semiconductors.

With regards to the third thrust, quantum chemical calculations (i.e., ab initio, semi-empirical and DFT calculations) were performed. In addition to independent research objectives, such as modeling of electron transfer in polymers or DNA bases, support of the spectroscopy groups was the primary objective of this thrust. It also helped to test and confirm the quality and validity of the theory models through the reproduction of experimentally determined features in electronically open shell systems. Moreover, calculations of molecular features (i.e., geometry, etc.) involved different electronically excited states and charge transfer states, or the modeling of Raman spectra of adsorbed species.

Within the framework of the Marcus theory of electron transfer reactions many of the basic aspects of thermal and photoinduced electron transfer processes were rationalized soundly. However, in many instances details, which are inadequately described in parameterized models, are decisive about the behavior of real systems and, in turn, about the practical use in, for example, electron transfer catalysts. In this context, the research activities were often directed towards investigations and quantifications of effects that stem from small structural variations on the nature of the charge transfer states and the associated reaction rates.

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Prof. Dr. Wolfgang Peukert

GRK 1161
Disperse Systems for Electronic Applications

The graduate program funded by the Deutsche Forschungsgemeinschaft was started in 2005 as a collaborative initiative of seven research groups from the Departments of Electronic Devices (H. Ryssel), Material Science and Engineering (H. Münstedt, A. Roosen, A. Winnacker), Particle Technology (W. Peukert), Physical Chemistry (C. Kryschi) and Technical Physics (L. Ley) of the University of Erlangen and one adjoined research group from the Department of Experimental Physics (D. Haarer) of the University of Bayreuth.

The objective of this graduate program is to open new ways for education of graduate students along the innovative topic of the printable electronics. The scientific challenge is the demonstration of simple electronic circuits from printable nanoparticulate pastes. The advantages of flexible production of polymers are thus combined with the advantages of silicon technology. This approach opens new applications in the field of low price flexible electronics, *e.g.* integrated circuits for consumer products, radio frequency tags or flexible and transparent coatings for displays. The teaching addresses disperse systems for electronics in cooperation with DEGUSSA company. From the very beginning, innovative tools for project management will be integrated. Each PhD-student will be supervised by two interdisciplinary groups from the university as well as by an expert from DEGUSSA. The curriculum includes exclusively for the graduate school designed lectures given by all involved groups from the university and DEGUSSA, special lab experiments both at the university and at DEGUSSA. Furthermore, a variety of special courses are available which cover all technical aspects as well as courses on project management and economics. These are complemented by seminars, summer schools and invited lectures from researchers from abroad. The PhD-students will spend up to 3 month at DEGUSSA's Science to Business Center Nanotronics. In addition, each student will be a few weeks to a lab abroad. The graduate school is organised along the knowledge chain of printable electronics and may thus contribute to the further structural development of the university.

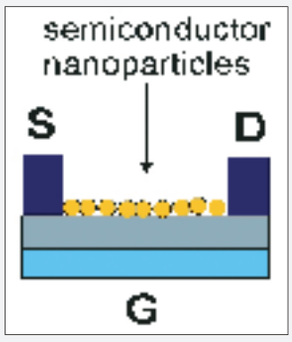

Figure 1: Field-effect transistor with source S, drain D and gate G.

The global objective of all research activities is the development of surface-functionalized semiconductor nanoparticles tailored for self-assembling to chemically resistant, electrically conducting percolation networks that function as active material in a electronic device prototype (*e.g.* field-effect transistor).

The achievement of this ambitious objective does not only require wet-chemistry treatments of nanoparticle surfaces, the formulation for the stabilization of suspensions, the progression of suitable printing technologies and the development of flexible polymer substrates with strong adhesion forces to nanoparticles but also the thorough investigation and characterization of the electronic and structural properties of the single nanoparticle and its percolation network. The study of the nanoparticle topologies will be conducted using forefront microscopy techniques (*e.g.* SEM, STM and TEM), whereas the electric conductivity of single nanoparticle and aggregates is determined by STS and with a microscopic 4-point method. The charge carrier mobility in thin semiconductor nanoparticle film is measured using the time of flight technique and the xerography.

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Prof. Dr. Horst Kisch

SFB 583
Redox-Active Metal Complexes: Control of Reactivity via Molecular Architecture

The Collaborative Research Center SFB 583 was initiated in 2001 by the Deutsche Forschungsgemeinschaft and unifies 14 research groups from the Institute of Inorganic Chemistry (Dahlenburg, Ivanovic-Burmanzovic, Kisch, van Eldik, Zenneck), Institute of Organic Chemistry (Gasteiger, Gladysz, Hirsch, Jux, Saalfrank), Institute of Physical and Theoretical Chemistry (Fink, Guldi, Steinrück), Institute of Physics III (Müller), and Computer-Chemistry Center (Clark).

In nature and chemical industry metal complexes are of eminent importance. Without photosynthesis by green plants we would have no air to breath and no food to eat. Without industrial catalysis no fertilizers and plastic materials would be available. In both areas redox-active metal complexes play a key role, since they are able to activate inert molecules for selective low-energy transformations. Their catalytic activity is governed by two basic factors, the electronic and steric properties, both being largely determined by the redox state of the metal and the shape of the surrounding ligands. Both aspects are unified in the title of SFB 583 – control of reactivity via molecular architecture.

The goal of this research network is the broad elucidation of metal induced redox reactions and the control of these important elementary processes through the molecular structure of the participating metal complexes. Detailed kinetic and theoretical studies help obtaining basic mechanistic information.

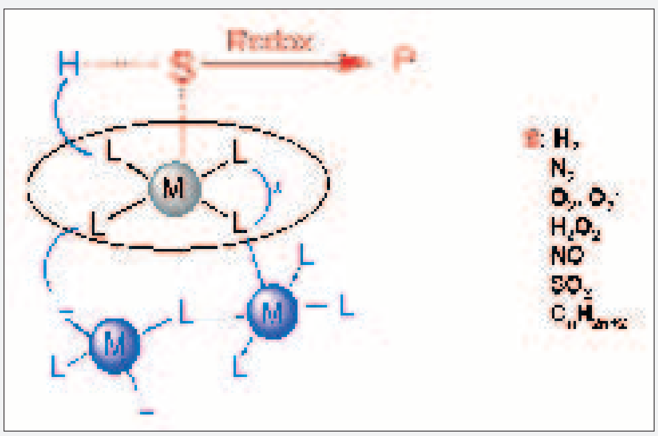

Figure 1: Activation of substrate S and redox transformation to P.

Accordingly, one part of the projects deals with the synthesis of a wide variety of homogeneous and heterogeneous architectures for molecule activation. It includes mono- and polynuclear metal complexes containing chiral and biomimetic ligands reaching from water soluble porphyrins, dendrimers, chains of sp-carbon atoms, fullerenes, and carbon tubes to even semiconductors.

The influence of these novel architectures is investigated on the coordination of small molecules like hydrogen, oxygen, superoxide, nitrogen oxide, sulfur dioxide, and alkanes (Fig. 1) and subsequent redox activation through thermal and photochemical processes. In thermal reactions, attempts are made for a rational control of asymmetric hydrogenation of olefins and ketons. In photochemical systems, research is focused on achieving efficient light-induced charge separation. As an example, the covalent attachment of a semiconductor like titania to a transition metal complex induces an efficient photoredox activation of oxygen and alkanes. Covalently linked porphyrin-fullerene complexes generate long-lived charge-separated states upon photoexcitation, as a consequence of a strong intramolecular charge-transfer interaction. Unconventional water soluble porphyrins allow mimicking the first step of P450 catalyzed transformations, i.e. the substitution of a water ligand; the mechanism of this process can be tailored by selection of the appropriate pH value. Similarly, the redox activation of hydrogen peroxide and superoxide can be controlled by selection of appropriate complex structures. Time resolved detection of intermediates in solution in combination with temperature and pressure dependent kinetic measurements allows obtaining detailed mechanistic information. Noncovalent interactions in the outer coordination shell of extended redox-active fullerene-dendrimer architectures may mimic effects observed in haemoprotein systems. Complementary to these architectures are linear chains of up to 28 sp-carbon atoms bridging two platinum centers. Selection of the chain length controls the electronic properties of these unprecedented compounds. Special attention is paid to weak substrate–metal and metal-metal interactions both in solution and on the surface of solid metal complexes studied by a broad variety of methods including picosecond flash photolysis in solution and modern surface analytical methods for in situ observation of redox processes on molecular and

atomic scales. Furthermore, new types of polynuclear wheel-shaped coordination compounds exhibit unusual phenomena like molecular magnetism connecting chemical with physical research. In addition to these experimental studies the physical and theoretical quantification of observed functionalities is studied by quantum mechanical calculations. Examples are the evaluation of relative stabilities of proposed intermediates, the change of substrate electronic structure upon coordination at the metal, and a detailed analysis of the elementary steps of electron transfer catalysis.

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SFB 473
Mechanisms of Transcriptional Regulation

Within 12 projects the Collaborative Research Center *SFB 473* deals with reaction mechanisms, molecular biological and cell biological aspects that are relevant to the control of transcription. *SFB 473* integrates different research groups from the faculties of science and medicine (i.e., the groups of Prof. Dr. T. Stamminger, Prof. Dr. W. Hillen, Prof. Dr. T. Clark, Prof. Dr. P.Gmeiner, Prof. Dr. Jürgen Behrens, Prof. Dr. H. Sticht, Dr. S. Hoth, Dr. R. Slany, Dr. S. Hashemolhosseini, PD Dr. F. Titgemeyer, and Prof. Dr. M. Wegner).

The main thrust topic is separated in three major tasks: The first major task entitled „modulations and interactions in transcription factors“ covers molecular and mechanistic aspects of proteins that control the activation / repression of transcription, whereas the task „signaling chains towards transcription factors“ focuses on investigations related to the uptake of environmental signals and their extra- and intracellular processing. The third task „transcription factors active in differentiation“ concentrates on regulation activities, which affect the cellular and organismic differentiation.

Two projects from the Fachgruppe Chemie contribute to the objectives of the first task. In particular, Prof. Dr. Gmeiner is concentrating on the synthesis of new tetracyclines. In collaboration with Prof. Dr. Hillen, he studies the interaction of the new compounds with the tetracycline repressor. The latter and its derivatives control – depending on the presence of the antibiotic tetracycline or its derivatives – the expression of the corresponding resistance proteins. The protein recognizes selectively nM quantities of tetracycline, binds the antibiotic and performs an allosteric conformation change, which induces the release of a DNA sequence this is bound. As an immediate consequence the expression of the resistance genes is induced. X-ray analysis has provided insight into the structures of the induced and DNA bound states of the protein. Importantly, the DNA binding domain and the tetracycline binding pocket are located in different parts of the protein, so that a transfer of information between the different regions must take place. The groups of Prof. Dr. Clark and Dr. Lanig perform classical and quantum mechanical modeling at the Tet repressor protein and its complexes with the aim to shed light onto the mechanics of protein internal movements underlying the induction process. These efforts should establish a theoretical basis for the understanding of conformational changes in allosteric proteins in general.

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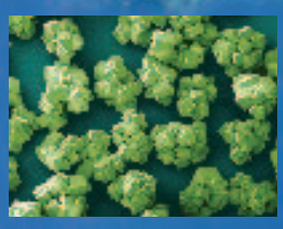

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