

## Oxygenations with Metaloxo Compounds

Reactive Intermediates, Mechanisms, and Models

Oxygen (lat.: oxygenium) being abundantly present in the air (as dioxygen) would in principal possess enough chemical power to spontaneously »oxidise« all organic matter (including the organisms living on earth), i.e. to convert it into an oxygen-rich form. The fact, that it refrains from doing so, has its origin in a naturally established barrier allowing reactions with most organic compounds only after significant supply of energy (ignition); the resulting process of combustion, however, only leads to useless products like carbondioxide. Nevertheless, the high oxidative power of dioxygen *can be used at room temperature* for the synthesis of fine chemicals when metals are utilised, i.e. when for the oxidation of hydrocarbons metaloxo compounds are employed (obtainable from dioxygen via detours) and reactions of that type are of vital importance not only in nature but also in academic and industrial laboratories. With such metaloxo compounds, oxygenation systems and processes we are dealing in our research, and emphasis lies on the clarification of the mostly very complex mechanisms as well as on the synthesis of novel oxygenation reagents and catalysts.

To investigate the fundamental steps of metal mediated oxidation reactions, for instance, so-called model compounds are developed allowing to construct an image of the structure and the reactivity characteristic to the key species occurring, and these model compounds in turn are tested as catalysts. Moreover, intermediates being relevant during oxidations with metaloxo complexes are directly studied with suitable low temperature methods – for instance with the aid of the matrixisolation technique. A further goal is the synthesis of complexes with *novel* metaloxo functions, that can be used for selective oxyfunctionalisations. Selected structural elements of oxidic solids playing essential roles in oxidation catalyses and the reactive centres of oxo transferring metalloenzymes (compare Fig. 1) are acting as paragons.

### Fundamental Steps and Intermediates of metal assisted Oxidations

The development of new and selective oxygenation reagents containing metaloxo functions in the most

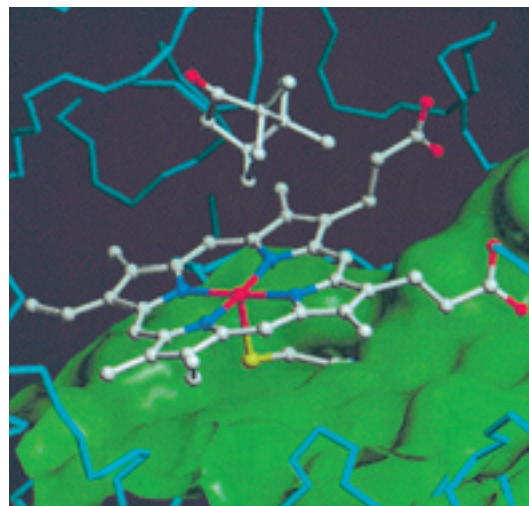
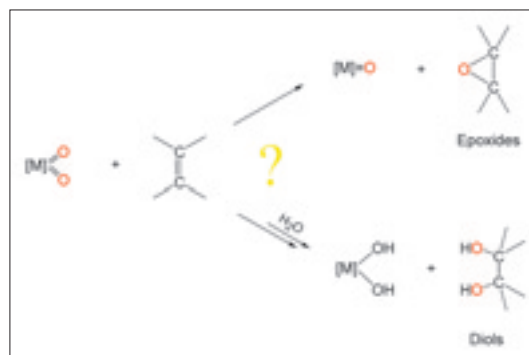


Fig. 1  
Portion of the crystal structure of P450cam with bound camphor showing the ligation of iron (reprinted with permission from ref. 12, Copyright 2000 American Chemical Society).

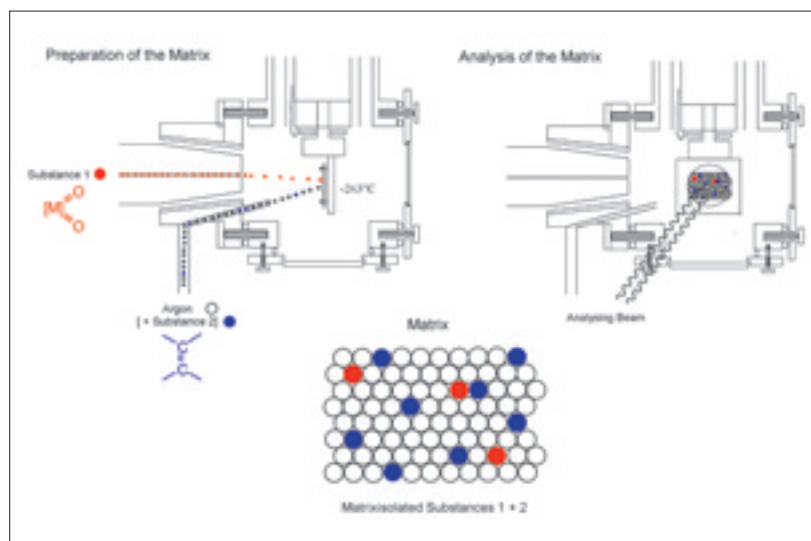
different environments (ligands), requires as its basis a deep understanding with respect to the behaviour of unligated, i.e. »naked« metaloxo units on the reaction-coordinates that are open to them, and this requirement is not a trivial one: Despite simple-looking reaction equations the corresponding reaction mechanisms often have a very complex nature, and many of them are not understood.

Fig. 2  
Oxometal moieties in the production of fine chemicals.



For instance, the reactions of metaldioxo moieties with unsaturated hydrocarbons (Fig. 2) leads in some cases to compounds with strained C-C-O three-membered rings (epoxides), in some cases, however, to compounds containing two alcohol functions (diols), and the reasons for that are hardly ever obvious. This is very unsatisfactory, as both epoxides and diols are very important classes of substances not only in academic but also in industrial synthetic chemistry: They can serve as starting materials for the production of polyesters or other plastics, and diols are additionally employed as anti-freezing compounds as well as in the preparation of cosmetics. Moreover, by no means the reactions have to proceed as rudely as written down in Fig. 2 (for instance, in case of the epoxidation reaction simply by transferring an oxygen atom from one to the other side). Naturally, concerning these and other problems there has to be clarity, if research and

Fig. 3  
The matrix assembly



development are supposed to proceed, and it is thus rewarding to bring some light into the enigma. With this concern, we decided to make use of the combination of methods and techniques available today to reexamine well-known oxidation reactions involving stoichiometric reagents like  $\text{CrO}_2\text{Cl}_2$  [1] and  $\text{MnO}_4^-$  in order to obtain deeper insights into these systems. Any information concerning the primary reaction steps of such highvalent metaloxo complexes in contact with organic substrates is very valuable for a better understanding, but the occurring intermediates almost principally have only very short life times, as they aggregate directly after their formation together with other species in solution to give extended, undefined supramolecular compounds, that cannot be analysed and characterised appropriately. In order to get hold of such intermediates, in our group for instance matrix isolation techniques are employed, and it might be instructive to illustrate the principal methodology by outlining exemplarily a recent investigation [2] concerning the reaction of  $\text{MnO}_3\text{Cl}$  with olefins.

By cocondensation at very low temperatures (10 K) the metal oxo compound of interest (e.g.  $\text{MnO}_3\text{Cl}$  or  $\text{CrO}_2\text{Cl}_2$ ) is embedded together with the organic substrate to be oxidized (e.g. an olefin) in a great excess of argon, so that a solid noble gas matrix results. This should look like depicted in Fig. 3: Many argon atoms effectively isolate the two components from each other – the dilution in reality is even much higher than shown in the Figure – but to a small percentage also 1:1 collisional complexes are formed and these are very important: Within these complexes, the two reactants are »seeing« each other already, but they cannot react due to the low temperatures and the rigid argon lattice. Only by submission of external energy a reaction can be

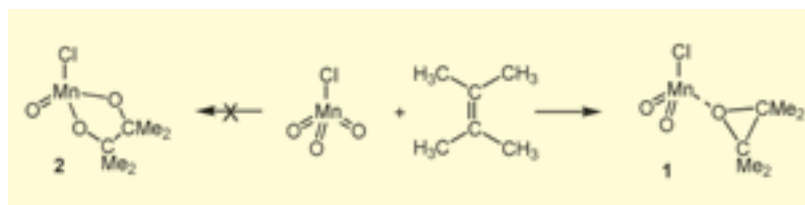


Fig. 4  
The reaction of  $\text{MnO}_3\text{Cl}$  with tetramethylethylene

initiated, and the big advantage of this method is obvious: Irrespective of what is formed then, it will persist, since the inert argon environment impedes aggregation and secondary reactions with excessive reactant, while the low temperatures effectively prohibit intrinsic decomposition reactions. Hence, it is possible to examine the *primary* products of the *bimolecular reactions* unhurriedly – in our case with the aid of infrared spectroscopy – thereby getting information concerning the primary steps and consequently also concerning the mechanisms of such oxygenations.

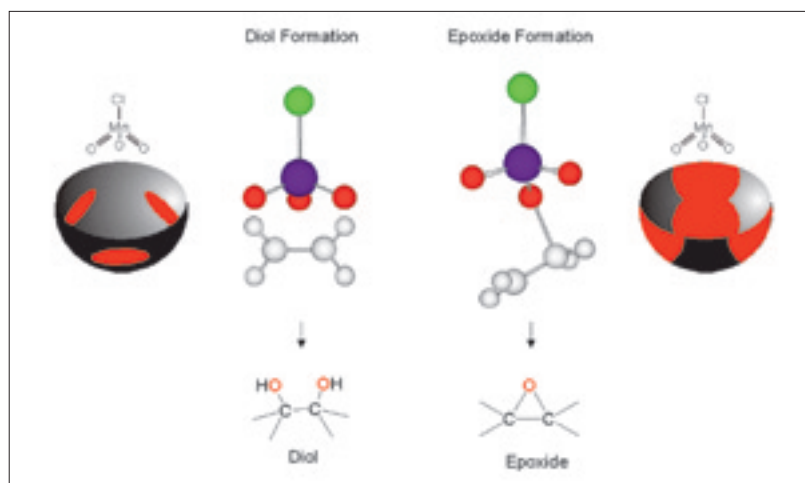


Fig. 5  
Transition states and reaction channels for the system  $\text{MnO}_3\text{Cl}$ /ethylene

### Metallvermittelte Oxygenierungsreaktionen

Verbindungen zwischen Metallen und Sauerstoff sind nicht nur in der Natur, sondern auch in Labor und Technik, wo sie die unterschiedlichsten Aufgaben erfüllen – häufig die Übertragung von Sauerstoff (Oxygenierung) – , allgemein von großer Bedeutung. Diese Substanzklasse (Oxometall-Komplexe) und ihre Reaktionen werden im Arbeitskreis Limberg untersucht, wobei Schwerpunkte auf der Aufklärung der größtenteils sehr komplexen Mechanismen und auf der Synthese neuartiger Oxidationsmittel/katalysatoren liegen: Zur Untersuchung der *Elementarschritte metallvermittelter Oxygenierungsreaktionen* werden beispielsweise so genannte *Modellverbindungen* entwickelt, die es erlauben, ein Bild von der Struktur

bzw. vom Reaktionsverhalten der auftretenden Schlüsselpezies zu konstruieren, und diese Modellverbindungen werden wiederum selbst als Katalysatoren getestet. Zudem werden die Zwischenstufen, die bei Oxidationen mit Oxometall-Verbindungen auftreten, mit Hilfe von geeigneten Tieftemperaturmethoden – wie z. B. der Matrixisolationstechnik (s.o.) – *direkt* untersucht. Ein weiteres Ziel ist die Synthese von *Komplexen mit neuartigen Metall-Oxo-Funktionen*, die sich zur selektiven Oxyfunktionalisierung nutzen lassen. Als Vorbilder dienen beispielsweise ausgewählte Strukturelemente oxidischer Festkörper, die in heterogenen Oxidationskatalysen essentielle Aufgaben erfüllen, oder auch die reaktiven Gruppen sauerstoffübertragender Metalloenzyme.

Applying this technique to the concrete case of  $\text{MnO}_3\text{Cl}$  it was possible to show [2] that the primary product of its reaction with the olefin tetramethylethylene (Fig. 4) is the epoxide complex 1 and not the diolate 2, that could have been expected bearing the permanganate,  $\text{MnO}_4^-$ , reactivity in mind. Why, however, does  $\text{MnO}_3\text{Cl}$  behave so differently in comparison to the related compound  $\text{MnO}_4^-$ ? To address this question, the relevant part of the energetic scenery characteristic for the system was investigated with the aid of quantum chemical calculations, and subsequently it became clear that the answer bases on the transition states of the two different reaction pathways as well as the corresponding reaction channels (compare Fig. 5): Due to a less rigid transition state the channels that lead to epoxidation are broader than those leading to the diolate, so that epoxidation is statistically favoured. [2]

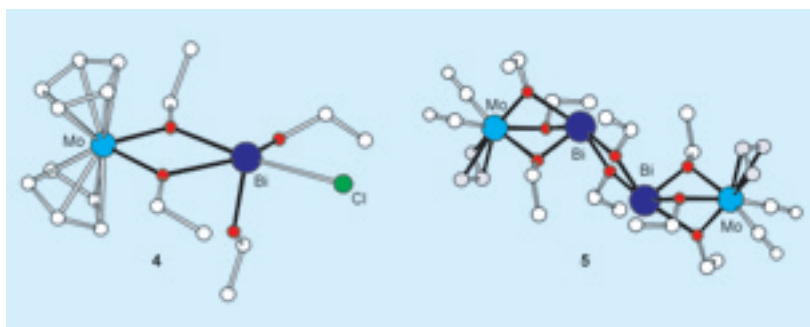


Fig. 6  
The crystal structures of the first molybdenum/bismuth alkoxides

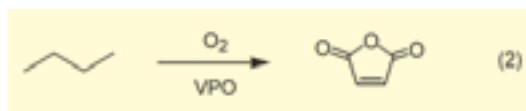
#### Synthesis and Reactions of Molecular Models mimicking the active Sites of metaloxide-based Catalysts

Despite significant research efforts directed toward understanding the general mechanistic features and reaction steps of oxidation catalysis *on surfaces*, many systems can still be regarded as poorly defined, which may in part be due to the fact, that a lot of difficulties are encountered during characterisation of reaction intermediates on surfaces. Heterogeneous catalysts thus sometimes have to be employed as »black boxes«: Reactants are injected and products are formed in good yields with good selectivities, but a complete understanding of the origin of the catalytic behaviour is not yet available. Representative examples are the SOHIO-Process, in which propylene is oxidised at bismuthmolybdate catalysts to give

Eq. 1



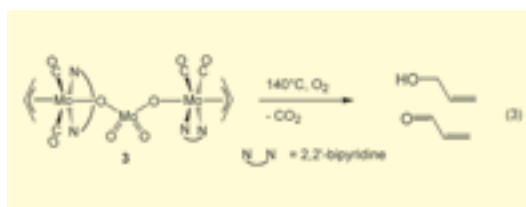
acrolein, or the production of maleic acid anhydride starting from butane at



Eq. 2

vanadylphosphate (VPO) catalysts. Both systems work selectively, both contain two elements in oxidic environments (Mo/Bi and V/P, respectively), that are essential for an efficient catalysis, and in both cases the actual roles of these two elements as well as the oxidation mechanisms in general are still discussed controversially.

For several years we have been dealing with the modelling of surface intermediates occurring during heterogeneous processes by *molecular compounds* as well as the possibilities and limits of such an approach. So far the abovementioned SOHIO process has been the main focus (compare Eq. 1). The primary step is here assumed to consist of an H atom abstraction, that leads to  $\pi$ -allylmolybdenum units embedded into the oxo ligand sphere of the solid state surface. [3] These are envisioned to subsequently react via shifts of the allyl ligands to the oxo functions of the catalysts surface, and inter alia bridging oxo functions ([Mo-O-Mo] or [Mo-O-Bi]) are discussed in this context. [3b] Consequently, we have pursued the synthesis of the first complexes containing a ( $\pi$ -allyl)Mo-O-Mo moiety and succeeded with the isolation of compounds like for instance 3 [4]



Eq. 3

Thermolysis of 3 in the presence of  $\text{O}_2$  yields as volatile products both allyl alcohol and acrolein. Accordingly, not only the trapping of the allyl ligands by oxo functions has been achieved, but also a reaction in analogy to the subsequent step relevant to the SOHIO Process, the second H atom abstraction to give acrolein. Hence, a molybdenum compound like 3 is capable of mimicking the last two steps within this technical process already. As mentioned above, alternatively to Mo-O-Mo groups Mo-O-Bi moieties are discussed [3b] as possible sites where the trapping of the allyl

ligands occurs. In so far, it would of course also be very interesting to gain access to molecular Mo-O-Bi compounds, too, and first steps into this direction have been undertaken by us: At the outset of our work not even molecular compounds with oxygen-containing ligands were existent in the literature, and consequently an entry into this area via alkoxide chemistry, that in many ways – chemically as well as technically – is quite related to oxo chemistry, seemed recommendable. Following this strategy we were recently able to synthesise and isolate the first heterometallic Mo/Bi alkoxide complexes (compare for instance 4 [5] and 5 [6] in Fig. 6).

The accessibility of this novel class of substances brings the target of designing functional molecules one step closer, and furthermore it laid the basis for continuative studies in another discipline: As mentioned, for the successful propylene oxidation both Mo and Bi are needed, and it is also known, that metal alkoxides are excellent precursors for the deposition of metal oxides. Considering, that for the first time (and uniquely) we had molecular compounds at hand, that are composed of Mo as well as Bi centres being linked by alkoxide ligands, naturally the question arose, whether such complexes can also serve as suitable single-source precursors for the deposition of novel molybdenum-oxo/bismuthoxo structures on inert supports. When one of these Mo/Bi alkoxides was treated with excessive silica gel and the resulting material subsequently heated to 350 °C in the presence of dioxygen, SEM/EDX analyses revealed bismuthoxo clusters with sizes between 30 and 1000 nm that could be found together with molybdenumoxo particles of lower nuclearity spread over the silica surface. The fact, that this material is capable of catalysing the oxidation of propylene to acrolein at very low pressures, allows valuable inferences on the mechanism of the technical process. [7]

The methodological approach applied for the Mo/Bi catalytic system is inherited in current research also for the investigation of vanadiumoxide catalysed processes: Reactive moieties and intermediates playing relevant roles on the surfaces of vanadiumoxide-based catalysts during the oxygenation/dehydrogenation of organic substrates represent the focus of actual modelling studies.

### Biomimetic metaloxo chemistry

#### C-H activation

Within complex 6 (Fig. 8)  $\text{CrO}_2\text{Cl}_2$  reacts with its spiroketone ligand selectively via cleavage of only the  $\alpha$ -keto C-H bond finally yielding the  $\text{Cr}^{\text{V}}$  complex 7 under very mild conditions (-50 °C). [8] This is

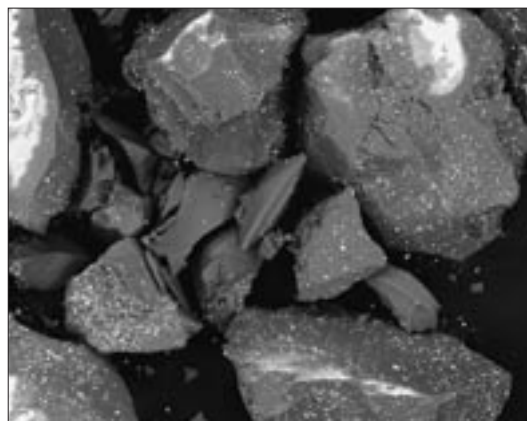


Fig. 7  
SEM micrograph for some of the silica grains after calcination at 350 °C in the presence of oxygen; the white spots represent the bismuthoxo clusters.

remarkable, since C-H activation by chromyl chloride, normally proceeds only at temperatures around 70 °C with sufficient rates and then not in a selective fashion. [9] Our finding can be rationalised assuming that the rigid framework of the bulky ketone forces the complex 6 to adopt an arrangement where a  $\text{Cr}=\text{O}$  group of  $\text{CrO}_2\text{Cl}_2$  comes to lie in close proximity to the  $\alpha$ -keto C-H bond (compare Fig. 8), as suggested by quantum chemical calculations. [8, 10] The system should thereby be positioned quite high on the H atom transfer barrier already, and consequently an increase in reactivity and selectivity is reached. The same principle is used in nature by the cytochromes P450: [11] These metalloenzymes are capable of catalytically hydroxylating C-H bonds via high valent, highly reactive (porphyrin) $\text{Fe}^{\text{IV}}=\text{O}$  radical cation units formed *in situ* during the process of  $\text{O}_2$  activation at (porphyrin) $\text{Fe}^{\text{III}}$  moieties. The crystal structure of such a moiety is shown (within its protein surroundings) exemplarily in Fig. 1 together with a substrate camphor molecule ready to get oxygenated [12]. Oxygenations in the inside of such enzymes proceed at room temperature with excellent selectivities, since the organic substrates (in Fig. 1 camphor) are prear-

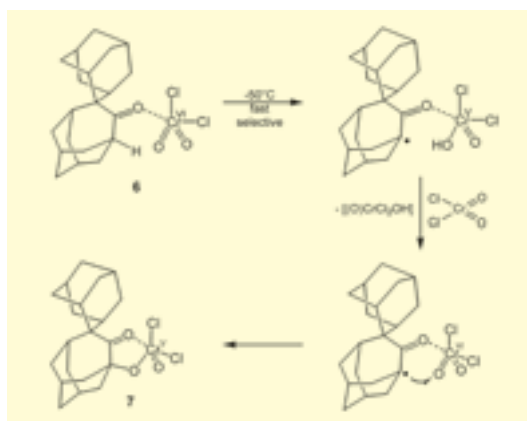


Fig. 8  
Selective H atom abstraction and radical trapping with  $\text{CrO}_2\text{Cl}_2$



### Prof. Dr. Christian Limberg

Born 1965. Chemistry studies at the University Bochum. 1992 Doctorate (rer. nat.) with a subject on perfluororganotellurium-compounds. 1993–94 Post-doctorate in Oxford (D. Phil. Thesis on molybdenum alkoxides). 1999 Habilitation on molybdenum and chromium oxo-complexes. 2000 Heisenberg scholarship. 2001 Deputy professor at the TU München. 2002 Rejection of three professorship offers (Düsseldorf, Hamburg, TU Berlin). Since 2003 full professor at the Humboldt-Universität zu Berlin.

### Contact

Humboldt-Universität zu Berlin  
Faculty of Mathematics and Natural Sciences I  
Department of Chemistry  
Brook-Taylor-Str. 2  
D-12489 Berlin-Adlershof  
Phone: +49-30-2093-7382  
Fax: +49-30-2093-6966  
E-Mail: christian.limberg@chemie.hu-berlin.de  
www.uni-heidelberg.de/institute/fak12/AC/limberg/

### Members of the working group

Dipl.-Chem. Cristina Wipert Rodrigues; Dipl.-Chem. Frederic Pilz; Dipl.-Chem. Marcus Brandt; Dipl.-Chem. Stefan Roggan; Dipl.-Chem. Elke Hoppe; Dr. Burkhard Ziemer; Christel Jankowski; Petra Neubauer; Ruth Kubica

ranged in a manner, that – like in 6 – lowers the energetic barriers for these processes and allows only *one* C-H unit to be attacked by the oxo ligand being introduced at the iron centre in Fig. 1 after reaction with O<sub>2</sub>.

In a thematically independent project we have investigated the O<sub>2</sub> activation properties of ruthenium, that follows iron in its group within the periodic table. We were able to show that in hydrochloric acid solution H<sub>3</sub>[RuCl<sub>6</sub>] is capable of functioning as an effective pre-catalyst for the chlorination of olefins and aromatics (Fig. 9). [13] The chlorine source is here HCl (not as usual the more expensive, corrosive Cl<sub>2</sub>) and as the oxidising agent dioxygen can be employed! The mechanism of O<sub>2</sub>-activation (i.e. the formation of the active species) and the subsequent chlorine transfer are topics of current research. Furthermore it is investigated whether or not the reaction can be directed by the addition of suitable ligands.

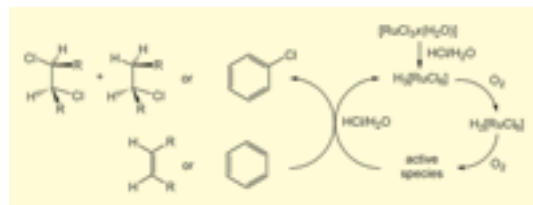


Fig. 9

Rutheniumtrichloride as pre-catalyst for chlorinations within the system O<sub>2</sub>/HCl/H<sub>2</sub>O.

### Water oxidation and dioxygen activation

Photosynthetic water oxidation to *evolve* dioxygen occurs at an active site of the photosystem II comprising four oxo-bridged manganese atoms [14]. This manganese complex is conceived in one current theory [15] as losing hydrogen atoms from water molecules bound as terminal ligands to two of the four manganese atoms. Each loss of a hydrogen atom thus advances the substrate ligands successively from aquo to hydroxo, and ultimately, to oxo ligands. The first three oxidations are characterized as manganese-centred, with the electrons lost from the contingent of unpaired metal d-electrons, while the protons are lost from ligands to the manganese. The fourth oxidation is not stabilized at manganese, but instead results directly in O<sub>2</sub> formation and release. With this background we are currently developing novel manganeseoxo complexes, which – in dependence on the ligand environment – are capable of either biomimetically eliminating or activating dioxygen. Highly oxidized manga-

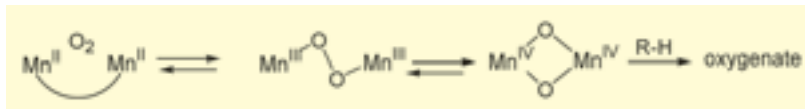


Fig. 10

The interplay between manganese complexes and dioxygen

neseoxo compounds obtained in the course of such studies should also be employable for the oxidation of hydrocarbons. (Fig. 10)

### Literature

Review: C. Limberg, *Angew. Chem.* 2003, in press.

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