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Bio-inspired iron catalysts for degradation of aromatic pollutants and alkane hydroxylation

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Abstract – Today, more and more metalloenzymes are understood at the molecular level. The accumulated knowledge is a very rich source of inspiration for chemists to prepare new catalysts with iron, manganese or copper, which could be cheaper and lead to processes more friendly with environment. We report here two examples. First, the preparation and study with Elf of iron catalysts efficient in the degradation of aromatics by H_2O_2. In particular, we completely characterised iron hydroperoxo and peroxo intermediates that formed upon reaction of H_2O_2 with these iron catalysts. The same complexes activate catechols toward ring cleavage by dioxygen. Overall, these complexes mimic degradation of aromatics by bacteria. The second example of bio-inspired catalyst is a di-iron system able to catalyse the oxidation of alkanes by dioxygen in the presence of hydroquinone at ambient temperature and pressure. This research was done in the framework of a research program sponsored by the Japanese New Energy Development Organisation. The ultimate goal is the biomimetic oxidation of natural gas into methanol for fuel cells. Such artificial systems are still in their infancy, but large potentiality is open to them, in particular if the separation of the Fe(III) to Fe(II) reduction and the Fe(II) oxidation by dioxygen steps is achieved. ***To cite this article: N. Raffard et al., C. R. Chimie 5 (2002) 99–109*** © 2002 Académie des sciences / Éditions scientifiques et médicales Elsevier SAS

iron(III) hydroperoxides / iron(III) / catecholate complexes / di-iron complexes / iron(II) complexes

Résumé – L'immense développement des recherches sur le fonctionnement des métalloenzymes ouvre la voie vers la préparation de nouveaux catalyseurs à base de fer, de manganèse ou de cuivre. Nous présentons deux types de catalyseurs que nous avons préparés en nous inspirant de métalloenzymes. Le premier exemple correspond à des complexes du fer capables de catalyser la dégradation par H_2O_2 de polluants aromatiques. Nous avons pu identifier, par différentes spectroscopies, les intermédiaires Fe(III)OOH ou Fe(III)O_2. Les mêmes complexes peuvent se lier aux catéchols (formés par hydroxylation des aromatiques) pour activer ces derniers vis-à-vis du dioxygène, ce qui conduit à l'ouverture des cycles aromatiques. Ces systèmes artificiels présentent des analogies avec les arène et catéchol dioxygénases des bactéries qui sont capables de se développer sur des hydrocarbures aromatiques. Ces recherches ont été effectuées en collaboration avec la société Elf. Le second exemple concerne l'oxydation des alcanes par le dioxygène en présence d'un donneur d'électrons. Les bactéries méthanotrophes sont capables d'utiliser le méthane comme source de carbone. Le premier enzyme impliqué est la méthane monooxygénase (MMO), qui utilise un site diferrique pour transformer le méthane en méthanol. Nous montrons qu'un complexe diferrique que nous avons synthétisé permet d'oxyder le *n*-hexane en hexanols en présence de dioxygène et d'hydroquinone. ***Pour citer cet article : N. Raffard et al., C. R. Chimie 5 (2002) 99–109*** © 2002 Académie des sciences / Éditions scientifiques et médicales Elsevier SAS

hydroperoxydes de fer(III) / complexes fer(III) / catécholate / complexes diferriques / complexes du fer(II)

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1. Introduction

Today, metalloenzymes are under very intense scrutiny in several laboratories throughout the world. It is quite clear that inorganic chemistry is being enriched by those biochemical studies, since the role of metal ions in living processes often corresponds to new chemistry. More chemistry has been invented by chance over billions of years than by man in 200 years. Thus the study of metalloenzymes gave a formidable impulse to inorganic chemistry throughout the last 30 years. The reverse is also true: inorganic chemists contributed to the understanding of the metalloenzyme function. Illustrations of the back influence of inorganic chemistry on biochemistry can be found in the work of Groves on hemes [1], Holm on Fe–S clusters [2], Lippard [3] and Que [4] on modelling of di-iron-active site containing enzymes.

A potential application to chemistry resulting from the researches on metalloenzymes is catalysis. It is quite possible to prepare artificial complexes that have a catalytic activity similar to that of metalloenzymes. This has been the case for iron porphyrins able to catalyse the hydroxylation of alkanes as inspired from CytP450 [5], for iron complexes able to catalyse the oxidative cleavage by dioxygen of catechols as do intradiol catechol dioxygenases [6] and for Cu-phenolato complexes catalysing the oxidation by air of alcohols into aldehydes [7], so mimicking galactose oxidase.

At this point, we can make a difference between biomimetic and bio-inspired catalysis. Biomimetic chemistry implies a great similarity between the enzyme active site and the artificial catalyst. It is very demanding, since it can be a real challenge to faithfully mimic the active site of an enzyme; such an effort is certainly valuable for the understanding of the function of the enzyme, but it may be not adapted to the research of a low cost and high robustness industrial catalyst. In bio-inspired chemistry, the enzyme is taken as a source of inspiration for the chemist. It can be a good approach for large-scale applications such as depollution, detergents and energy. It also contains a freedom in invention, which is one of the great pleasures of chemistry.

In this paper, we present a review of our own work in collaboration with industry to explore application of bio-inspired catalysis. In the past, with Elf Company, we invented a process to degrade lignin in wood pulp for paper industry [8]. This process was inspired from Mn-dependent ligninases [9] and used TPA/Mn(II) as catalyst and H_2O_2 as oxidizing agent. (Abbreviations used: TPA = tris(pyridylmethyl)amine; N4py = *N*,*N*-bis(2-pyridylmethyl)-*N*-(bis-2-pyridylmethyl)amine; $hfacac^-$ = hexafluoroacetylacetonate; $HBpz_3^-$ = tris(pyrazolyl)borate.) We discovered with the Unilever Company new ways for stain bleaching [10]. We will deal here with our work with Elf Company about the degradation of aromatic pollutants [11], a research inspired from dioxygenases found in bacteria able to grow on aromatic hydrocarbons, and with a new work with Osaka Gas Company about oxidation of alkanes by air in the presence of a reducing agent, a work inspired from the famous Methane MonoOxygenase (MMO) [12].

2. Degradation of aromatic pollutants

Some bacteria are able to grow on aromatic compounds like naphtalene. They accomplish oxidation of aromatic compounds using a cascade of enzymes schematised in Fig. 1.

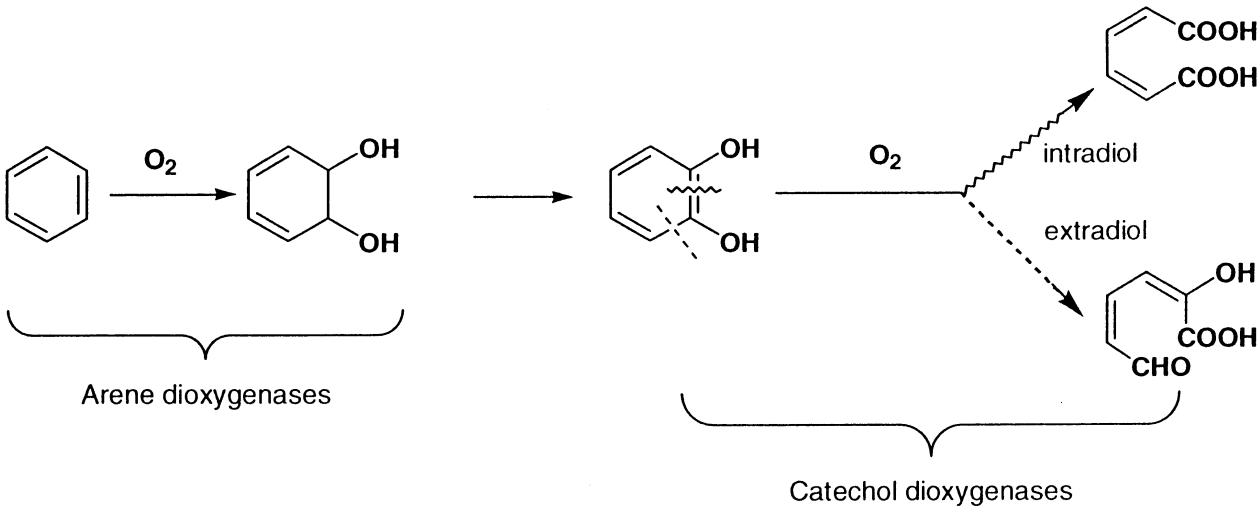


Fig. 1. Degradation of aromatics by bacteria.

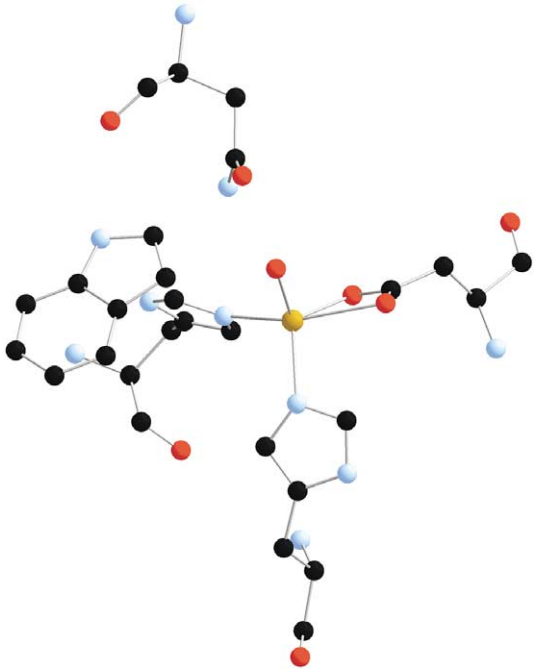


Fig. 2. Active site of the naphtalenedioxygenase (from [13]).

The first type of enzymes is arene dioxygenases, which use dioxygen and electrons to cis-dihydroxylate aromatic rings. The active site of naphtalene dioxygenase has been studied by X-ray diffraction: it contains one Fe(II) linked to a chelating aspartate, two histidines, a water molecule and possibly an asparagine (Fig. 2) [13,14].

The Fe(II) ion can be seen as hexacoordinated or pentacoordinated – if asparagine is not linked – with the water molecule exchangeable with dioxygen. A possible mechanism implies a Fe(III) peroxo or hydroperoxo intermediate [15]. The diol formed is rearomatised to catechol by a dehydrogenase. The catechol is then opened into linear oxidized molecules by catechol dioxygenases, either intradiol (Fe(III) site) or extradiol (Fe(II) site) [16]. For instance, it has been shown [17] that in intradiol dioxygenase the catecholate anion is chelated to the Fe(III) ion before being attacked by dioxygen (Fig. 3).

We decided to use a simple pentadentate ligand to prepare a stable Fe complex with a sixth free position available for dioxygen or H_2O_2 and we synthesized the trispicMeen one described in Fig. 4.

Instead of dioxygen and electrons, we used H_2O_2. In collaboration with Elf Company, we found that indeed this ligand in presence of $Fe(ClO_4)_3$ was very active to catalyse the degradation of aromatics by H_2O_2 at 40 °C in water [11]. Polyaromatic hydrocarbons such as phenanthrene and fluoanthrene were decomposed into a mixture of polycarboxylic acids.

We tried to isolate the Fe(III) complex but we succeeded only in getting the dinuclear complex [(trispic-

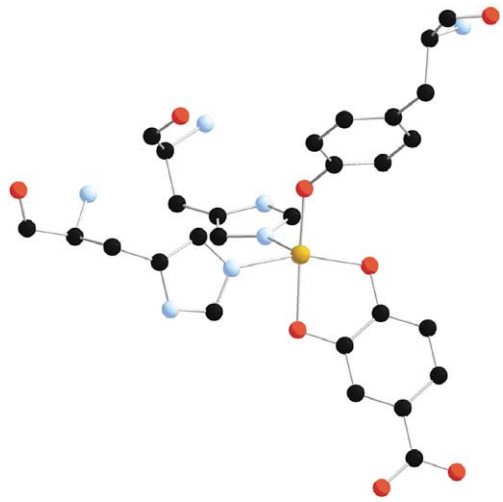


Fig. 3. Active site of 3,4-protocatechuate dioxygenase (from [17]).

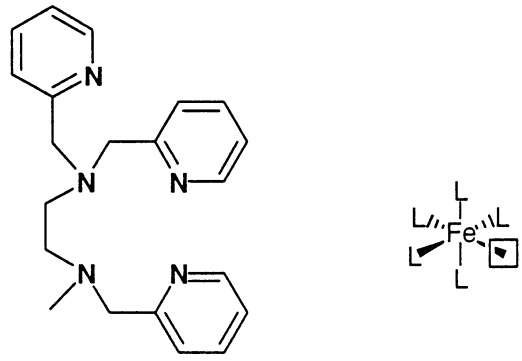


Fig. 4. Ligand trispicMeen.

Meen)ClFe^{III}OFe^{III}Cl(trispicMeen)]$^{2+}$ by reaction of the ligand on the dinuclear $[Cl_3Fe^{III}OFe^{III}Cl_3]^{2-}$ complex [18]. On the opposite, we isolated and crystallized with Fe(II) the complex [Fe^{II}(trispicMeen)Cl]$^{+}$. Its structure is displayed in Fig. 5 [19].

Fe(II) is surrounded by the pentadentate ligand and the sixth position is occupied by a chloride ion.

Independently, Bernal et al. [20] studied this complex and similar ones. They discovered that H_2O_2 gives an intermediate that they identified by UV-vis and EPR spectroscopy as a Fe(III)OOH entity. As this intermediate is a likely candidate to explain the catalysis of oxidation of aromatics we observed, we went further into its characterisation.

As observed by Bernal et al. [20], the spectrum of a methanol solution of [Fe^{II}(trispicMeen)Cl]$^{+}$ changes spectacularly by addition of an excess of hydrogen peroxide. A strong band appears at 540 nm, which was attributed to a LMCT transition between the HOO^{-} group and Fe(III). This absorption remains for one to two hours at room temperature. EPR confirmed that Fe(II) was oxidised to a low spin Fe(III) very

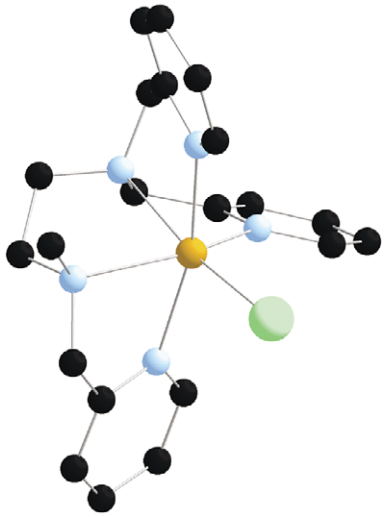


Fig. 5. X-ray crystal structure of $[Fe^{II}(trispicMeen)Cl]^+$ in $[Fe^{II}(trispicMeen)Cl][BPh_4]$ (from [19]).

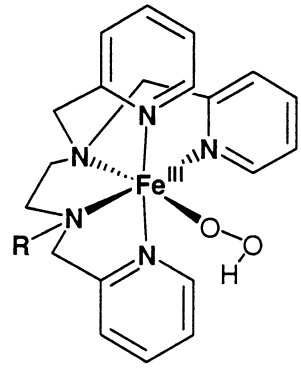


Fig. 6. Proposed structure for $[Fe^{III}(trispicMeen)(OOH)]^{2+}$.

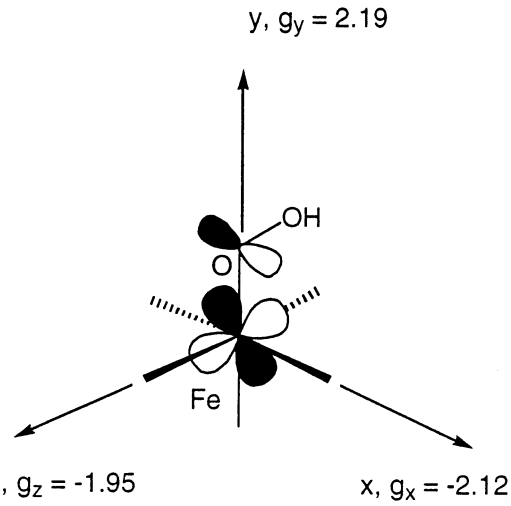


Fig. 7. Representation of the dxy orbital and of the hydroperoxo π orbital in the $[Fe^{III}(trispicMeen)(OOH)]^{2+}$ complex.

similar to that found in activated bleomycin, which was demonstrated to be $(BLM)Fe^{III}OOH$ [21]. Other non-heme Fe(III)OOH complexes have been characterized [22–27].

Resonance Raman spectroscopy using a 568 nm laser excitation allows to observe a vibration at 796 cm^{-1} attributable to a $^{16}O^{16}O$ vibration and another at 617 cm^{-1} attributable to a $Fe^{16}O$ vibration. By using $H_2{}^{18}O_2$, those frequencies shifted to 752 cm^{-1} and 600 cm^{-1} respectively. Using a very simple diatomic model, one computes 751 cm^{-1} and 590 cm^{-1} for the ^{18}O sample, which agrees satisfactorily with the proposed attribution. Introducing some coupling between the vibrators would certainly allow to reach a better agreement. With TPA as ligand, a Fe(III)OOH species was characterised in RR with frequencies at 789 and 626 cm^{-1} [28] and with the N4py [10] ligand, whose frequencies were 790 cm^{-1} and 632 cm^{-1} [29]. All those Fe(III)OOH species seem to have very similar properties. A very likely structure for $[Fe^{III}(trispicMeen)(OOH)]^{2+}$ is shown in Fig. 6.

The g values observed by EPR (1.95, 2.12, 2.19) can be rationalised by the model of Taylor [30] for low spin Fe(III) species. Application of this model gives $\Delta/\lambda = -11.31$ and $V/\lambda = 4.05$, where Δ is the axial distortion energy and V the rhombic one for the $^2T_{2g}$ state [31]. This shows that the ground state can be described (before application of spin orbit coupling) as built on the configuration $d_{yz}{}^2 d_{xz}{}^2 d_{xy}{}^1$. The most destabilized orbital is the orbital d_{xy}. The axes x, y and z are such that $g_x = -2.12$, $g_y = 2.19$, $g_z = -1.95$. Evidently one does not know at this stage the orientation of those axes versus the molecule, but the hydroperoxo group is certainly along x or y since this would explain that the dxy orbital is the most destabilised by interaction with the π* orbital of the hydroperoxo group (Fig. 7).

When one applies this model to bleomycin, one obtains $\Delta/\lambda = -8.74$ and $V/\lambda = 3.04$. This suggests that the d_{xy} orbital is less perturbed by the hydroperoxo group in BLM than that in the $[Fe^{III}(trispicMeen)(OOH)]^{2+}$. This could be related to a shorter distance between Fe and the hydroperoxo group in $[Fe^{III}(trispicMeen)(OOH)]^{2+}$.

The $[Fe^{III}(trispicMeen)(OOH)]^{2+}$ model complex is so stable than deprotonation can be achieved in MeOH solution by adding NEt_3 [32]. This can easily be detected by UV–vis: the maximum of absorption in the visible shifts from 540 nm to 740 nm. This is indicative of a lower energy for the charge transfer from the peroxo group to Fe(III). EPR establishes that upon deprotonation Fe(III) turns high spin ($g = 7.5$, $g = 5.9$, $E/D = 0.08$). In RR, vibrations were found at 819 cm^{-1} and 470 cm^{-1} shifting to 776 cm^{-1} and

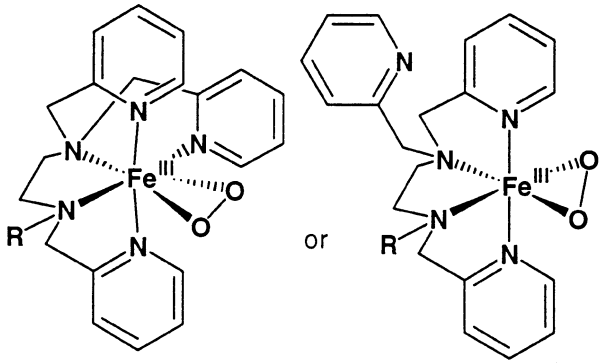


Fig. 8. Proposed structures for $[Fe^{III}(trispicMeen)(OO)]^{+}$.

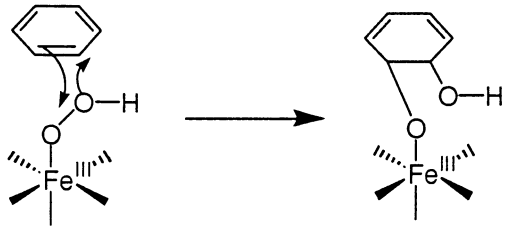


Fig. 9. Proposed cis-dihydroxylation by the Fe(III)OOH species.

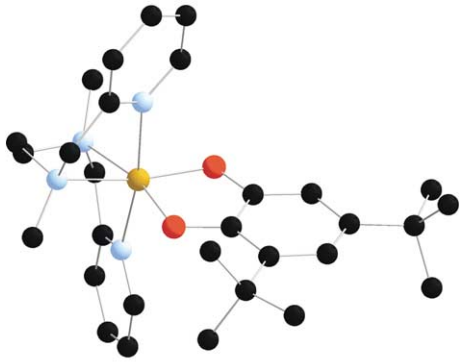


Fig. 10. X-ray crystal structure of $[Fe^{III}(bispicMe_2en)(DBC)]^{+}$ in $[Fe^{III}(bispicMe_2en)(DBC)][BPh_4]$ (from [35]).

454 cm^{-1} by using $^{18}O_2H_2$ [25]. Possible structures of the $[Fe^{III}(trispicMeen)(OO)]^{+}$ derivative are described in Fig. 8.

Similar results were obtained by Jensen et al. [33]. Using the ligand N4py, Ho et al. [34] identified the following frequencies: 827 and 495 cm^{-1}, shifting to 781 and 478 cm^{-1}. The FeO bond seems much weaker in $[Fe^{III}O_2]^{+}$ than in $[Fe^{III}O_2H]^{2+}$, while for the OO bond the reverse is true.

As for oxidation of aromatics by the system trispicMeen/Fe/H_2O_2 it is possible that the aromatics are first hydroxylated by OH radicals formed from the Fe(III)OOH entity. This would lead to phenols and catechols.

Another possibility is that the Fe(III)OOH intermediate itself cis-dihydroxylates an aromatic group, as represented in Fig. 9.

The diol formed could be reoxidised to catechols in the experimental conditions used.

Once the catechols formed by either pathway, their consecutive degradation is easy to understand. We have shown that catecholate can chelate Fe(III) complexes with trispicMeen and similar ligands [35]. For instance, we show in Fig. 10 the structure of the complex $[(bispicMe_2en)Fe^{III}(DBC)]^{+}$, where $bispicMe_2en$ is the tetradentate analogue of trispicMeen and DBC stands for the dianion of 3-5-diterbutylcatechol.

For simplicity, the ligand $bispicMe_2en$ will be noted below L_4^2. Dioxygen breaks the intradiol carbon–carbon bond of the catecholate linked to Fe(III) in a manner similar to what is observed with intradiol catechol dioxygenases and schematised in Fig. 11 [36].

In summary, the reactivity of our catalytic system can be understood by the hydroxylation of aromatic hydrocarbons by the Fe(III)OOH intermediate and the subsequent chelation to Fe(III) of the catechols formed, which induces the breakage of the intradiol carbon–carbon bond by dioxygen as in intradiol catechol dioxygenases.

3. Alkane hydroxylation

Methane is predicted to be a very important source of energy in the future. One possible application is its

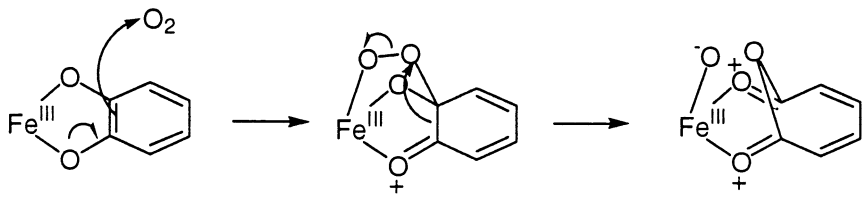


Fig. 11. Intradiol carbon–carbon bond breaking similar to the mechanism observed with intradiol catechol dioxygenases (from reference [36]).

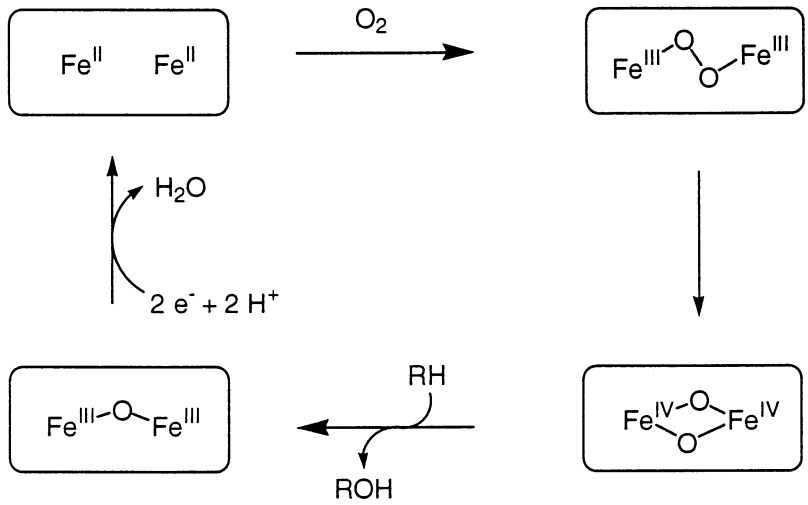


Fig. 12. Simplified catalytic cycle of Methane Monooxygenase (MMO).

transformation into methanol, which has the advantage to be a liquid and thus to be easier to handle. Methanol could then be used as carburant as such or in fuel cells. Methanol can be prepared from syn gas at high pressure and high temperature but a direct conversion of methane into methanol at ambient pressure and temperature would be extremely valuable.

Such a transformation is accomplished by bacteria that use methane as a source of C and energy. The first transformation operated by these bacteria is the oxidation of methane into methanol according to the equation:

$$CH_4 + O_2 + 2\,e^- + 2\,H^+ \rightarrow CH_3OH + H_2O$$

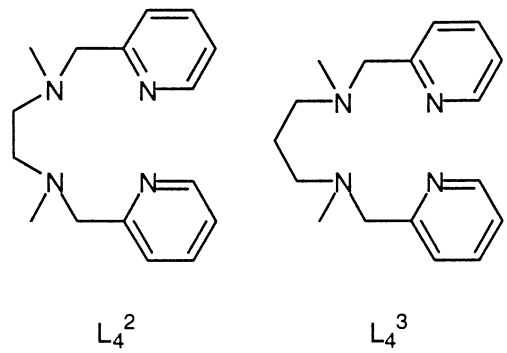
The enzyme responsible for this transformation is Methane Monooxygenase (MMO) and has been wonderfully studied by two American groups, those of Lipscomb [12] (University of Minnesota) and Lippard [37] (MIT). The enzyme contains a dinuclear iron site, which in its native form is in the Fe(III)Fe(III) oxidation state. A highly simplified catalytic cycle is shown in Fig. 12

The active form (called intermediate Q) is a dinuclear Fe(IV)O_2Fe(IV) identified by different spectroscopies [38], which is known as the diamond core. Efforts are being done to chemically model this fantastic enzyme [3]. One of the best achievements is the isolation of Fe(IV)O_2Fe(III) entities, which have never been identified before and even thought of [39].

Consideration of the structure of intermediate Q invites us to use tetradentate ligands. We selected bispicMe_2en and bispicMe_2pn to study the influence of the length of the linear tetradentate ligand. We note these ligands L_4^2 and L_4^3 respectively for simplicity (Fig. 13).

Complexes of Fe with the ligand L_4^2 or derivatives have already been studied by us and others. A dinuclear $[L_4^2Fe^{II}(AcO)_2Fe^{II}L_4^2]^{2+}$ complex has been described by Hazell et al. [40]. We have ourselves described $L_4^2Fe^{II}Cl_2$ and $[L_4^2Fe^{III}Cl_2]^+$ complexes in which the methyl groups have been replaced by benzyl ones [41]. Arusalmy et al. [42] have studied the chemistry of L_4^2 with hydrogens in place of methyl groups. Reaction of L_4^2 with Fe(III)$(ClO_4)_3$ gives the dinuclear $[L_4^2(OH)Fe^{III}OFe^{III}(OH_2)L_4^2]^{3+}$ complex, in which the hydroxyl group and the water molecule are linked by an hydrogen bond [43]. Dissolution of this complex in acetonitrile gives the $[L_4^2Fe^{III}O(OH)Fe^{III}L_4^2]^{2+}$ complex, which presents the diamond core identified in MMO. This reaction can be reversed by addition of water. The $[L_4^2Fe^{III}O(AcO)Fe^{III}L_4^2]^{3+}$ complex has been described by Okuno et al. [44]. The complex $[L_4^2Fe^{II}(MeCN)_2]^{2+}$ has been described by Chen and Que [45].

We found that reaction of one equivalent of L_4^2 with one equivalent of $Fe^{III}Cl_3$ gives the symmetric dinuclear complex $[L_4^2ClFe^{III}OFe^{III}ClL_4^2]^{2+}$, the structure of which is displayed in Fig. 14 [46].



L_4^2 L_4^3

Fig. 13. L_4^2 and L_4^3 ligands.

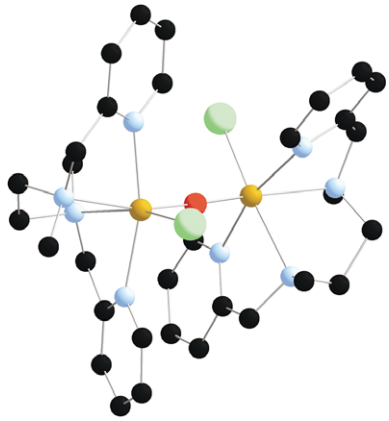


Fig. 14. X-ray crystal structure of $[L_4^2ClFe^{III}OFe^{III}ClL_4^2]^{2+}$ in $[L_4^2ClFe^{III}OFe^{III}ClL_4^2](Cl_2)$.

Several symmetric complexes of this kind have already been obtained [18,42,47–49].

The ligand L_4^3 has not been very much studied [50]. To our surprise, we found that its reaction with $Fe^{III}Cl_3$ gives the asymmetric dinuclear $L_4^3ClFe^{III}OFe^{III}Cl_3$ complex (Fig. 15) and not the symmetric dinuclear one. Other asymmetric complexes have been described [51,52]. It has to be noted that in $[L_4^2ClFe^{III}OFe^{III}ClL_4^2]^{2+}$ the ligand is in a cis α conformation, while in $L_4^3ClFe^{III}OFe^{III}Cl_3$ the ligand has a cis β conformation. The aptitude of L_4^3 type ligands to adopt the cis β conformation has already been noted [50]. The formation of the asymmetric dinuclear complex versus the symmetric one may be due to an instability of the complex between L_4^3 and Fe(III) or to a steric hindrance between the L_4^3 ligands in the symmetric complex.

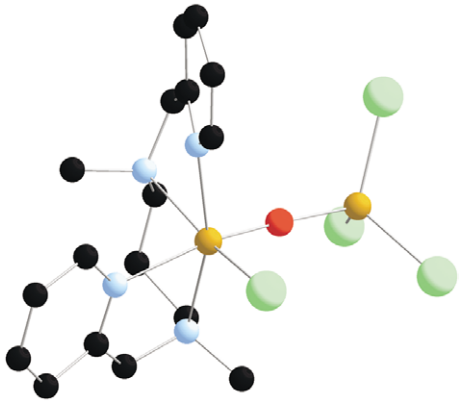


Fig. 15. X-ray crystal structure of $L_4^3ClFe^{III}OFe^{III}Cl_3$.

The complex $[L_4^2ClFe^{III}OFe^{III}ClL_4^2]^{2+}$ was found inactive in catalysis of alkane oxidation with dioxygen and reductant. On the opposite, the asymmetric complex $L_4^3ClFe^{III}OFe^{III}Cl_3$ gave (in 16 h and using O_2 in the presence of trimethylhydroquinone as an electron donor, in MeCN) almost uniquely hexane-derived alcohols with the following turnovers: 1.1 for 1-ol, 3.7 for 2-ol and 5.2 for 3-ol. Those results were improved by fixation of the catalyst on silica and also in presence of acetate (Table 1). They are quite exceptional, although we have no indication on the mechanism of this oxidation.

The rare examples of non-heme model systems able to catalyse alkane oxidation by O_2 and a reducing agent, have been quoted in a recent review by Costas et al. [4]. The only one giving a high alcohol to ketone ratio is the complex $(HBpz_3)(hfacac)Fe^{III}OFe^{III}(hfacac)(HBpz_3)$ studied by Kitajima et al. in 1988 [53].

A highly speculative hypothesis to explain the catalysis we observed would be the reduction of $L_4^3ClFe^{III}OFe^{III}Cl_3$ by the trimethylhydroquinone, followed by reoxidation by dioxygen to give a Fe(IV)O intermediate capable to transfer an oxygen atom into a CH bond. If this is the case, the poor yields observed here can be understood by the fact that the Fe(IV)O intermediate is generated in the presence of the reductant. It has to be noted that, in MMO, these steps are carefully separated. In order to explore such an exciting scheme, we have synthesised the Fe(II) complexes with L_4^2 and L_4^3. Indeed it is possible to obtain $L_4^3Fe^{II}Cl_2$ and $L_4^2Fe^{II}Cl_2$ as monocrystals (Fig. 16).

These monomers can be obtained by direct reaction of the ligands with $FeCl_2$ or by electrochemical reduction of the Fe(III) dimers.

We then studied the reactivity of these Fe(II) complexes with dioxygen. Indeed we noted that $L_4^2Fe^{II}Cl_2$ is stable in MeCN under air, while $L_4^3Fe^{II}Cl_2$ is oxidised into $L_4^3ClFe^{III}OFe^{III}Cl_3$, although the stoichiometry of this oxidation is not yet clear. Why, of the two

Table 1. Oxidation of *n*-hexane by O_2 with L_4^3 catalyst/trimethylhydroquinone/acetic acid. The yields are given as turnover numbers (T.N.) based on the Fe^{III} catalytic system after 16 hours. Reaction conditions: 1 atm O_2 at 25 °C in 2.6 ml of dry acetonitrile; final concentration for the catalyst in the reaction mixture 0.33 m mol l^{-1}. catalyst/*n*-hexane/trimethylhydroquinone/acetic acid 1/3000/350/250. L_4^3 designates the ligand *N*,*N*'-dimethyl-*N*,*N*'-bis(2-pyridylmethyl)propane-1,3-diamine.

System	1-ol	2-ol	3-ol	2-one	3-one
$L_4^3ClFe^{III}OFe^{III}Cl_3$	1.1	3.7	5.2	0.1	0.1
L_4^3 grafted on silica + $FeCl_3$	2.0	7.1	10.0	0.4	0.6
L_4^3 grafted on silica+$[Fe_2OCl_6]^{2-}$ + AcO^-	4.0	13.4	18.2	1.1	1.2

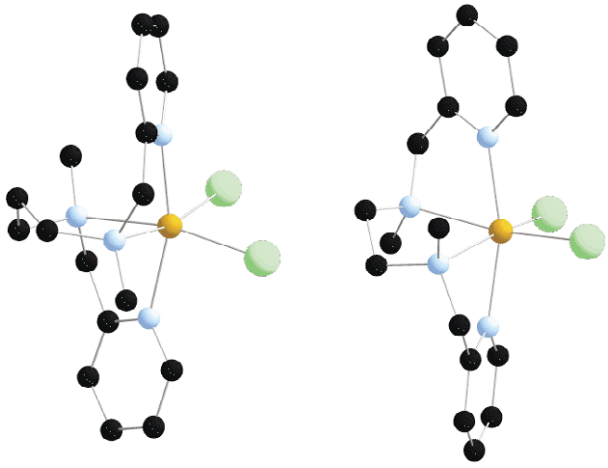


Fig. 16. X-ray crystal structure of $L_4{}^2Fe^{II}Cl_2$ and $L_4{}^3Fe^{II}Cl_2$.

similar Fe(II) complexes, only $L_4{}^3Fe^{II}Cl_2$ reacts with dioxygen? Electrochemistry allowed us to answer that question.

As shown in Fig. 17, the oxidation in MeCN of $L_4{}^3Fe^{II}Cl_2$ (0.28 V/SCE) occurs at a higher potential than that of $L_4{}^2Fe^{II}Cl_2$ (0.18 V/SCE). Moreover, a striking difference between the two complexes appears on the reverse scan. Upon reduction of the Fe(III) species, two new waves are observed at negative potentials for $L_4{}^3Fe^{II}Cl_2$, but not for $L_4{}^2Fe^{II}Cl_2$ (Figs. 17 and 18).

The first wave is attributed to the reduction of $FeCl_4^-$ (–0.05 V/SCE) and the more negative one to the reduction of $L_4{}^3ClFe^{III}OFe^{III}Cl_3$ (–0.29 V/SCE) (Fig. 18). The equilibrium displayed in Fig. 19 explains these observations.

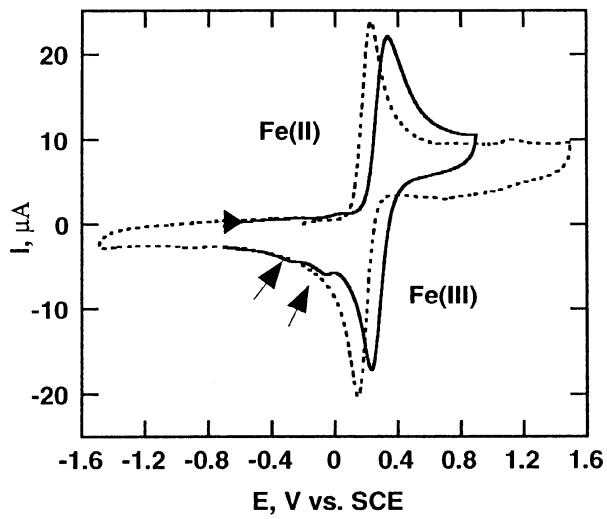


Fig. 17. Cyclic voltammetry of 1 mM acetonitrile solutions of $L_4{}^3Fe^{II}Cl_2$ (solid line) and $L_4{}^2Fe^{II}Cl_2$ (dotted line) in the presence of 0.1 M TEAP at 20 °C. Scan rate: 100 mV s^{-1}.

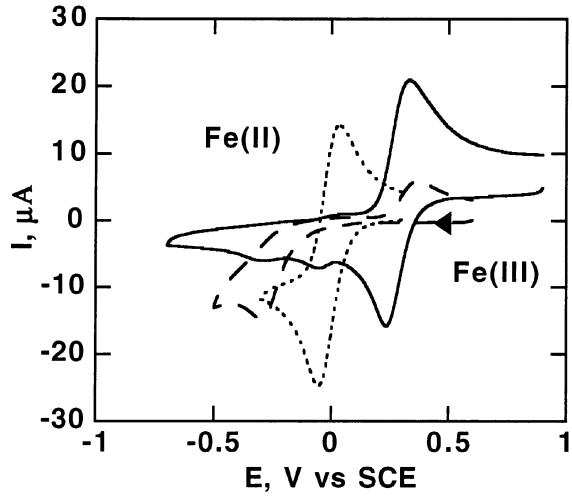


Fig. 18. Cyclic voltammetry of 1 mM acetonitrile solutions of $L_4{}^3Fe^{II}Cl_2$ (solid line) starting from the Fe(III) form, $Fe^{III}Cl_4^-$ (dotted line) and $L_4{}^3Fe^{III}OFe^{III}Cl_3$ (dashed line) in the presence of 0.1 M TEAP at 20 °C. Scan rate: 100 mV s^{-1}.

The complex $L_4{}^3Fe^{II}Cl_2$ partly dissociates into $L_4{}^3Fe^{II}(OH)_2$, $L_4{}^3$ and $Fe^{II}Cl_4^{2-}$. The electrochemical oxidation of $L_4{}^3Fe^{II}(OH)_2$ and $Fe^{II}Cl_4^{2-}$ leads to $[L_4{}^3Fe^{III}(OH)_2]^+$ and $Fe^{III}Cl_4^-$ which form by condensation $L_4{}^3ClFe^{III}OFe^{III}Cl_3$. The reactivity with O_2 of $L_4{}^3Fe^{II}Cl_2$ is thus related to a slight instability of this complex in MeCN. It is intriguing to note that the ligand $L_4{}^3$, which allows oxidation of Fe(II) by O_2, is precisely the one that led to the catalytic oxidation of hexane. Further research is being done on these systems, in particular to test the stoichiometric oxidation of alkanes by $O_2 + L_4{}^3Fe^{II}Cl_2$.

Finally, it may be important to associate both Fe atoms close to each other in an assembling ligand, since in MMO they are maintained in proximity through all the catalytic cycle [12]. Using the hexadentate ligand $L_6{}^34M$ depicted in Fig. 20, we have obtained the $(L_6{}^34M)Fe^{II}{}_2Cl_4$ dinuclear complex, the structure of which is displayed in Fig. 21.

In this structure, Fe(II) ions are pentacoordinated with two chloride and the tertiary amino group in the equatorial plane and the two lutidine groups in axial positions. The interesting aspect of this complex is that both metal ions are maintained inside a single assembling ligand.

In acetonitrile in the presence of air, this complex is oxidised slowly, to give crystals of a tetranuclear $(L_6{}^34M)Fe^{III}{}_4O_3Cl_6$, which contains four Fe(III) in a row bridged by oxo groups (Fig. 22).

The reactivity with O_2 of the pentacoordinated Fe(II) sites of $(L_6{}^34M)Fe^{II}{}_2Cl_4$ is very interesting and

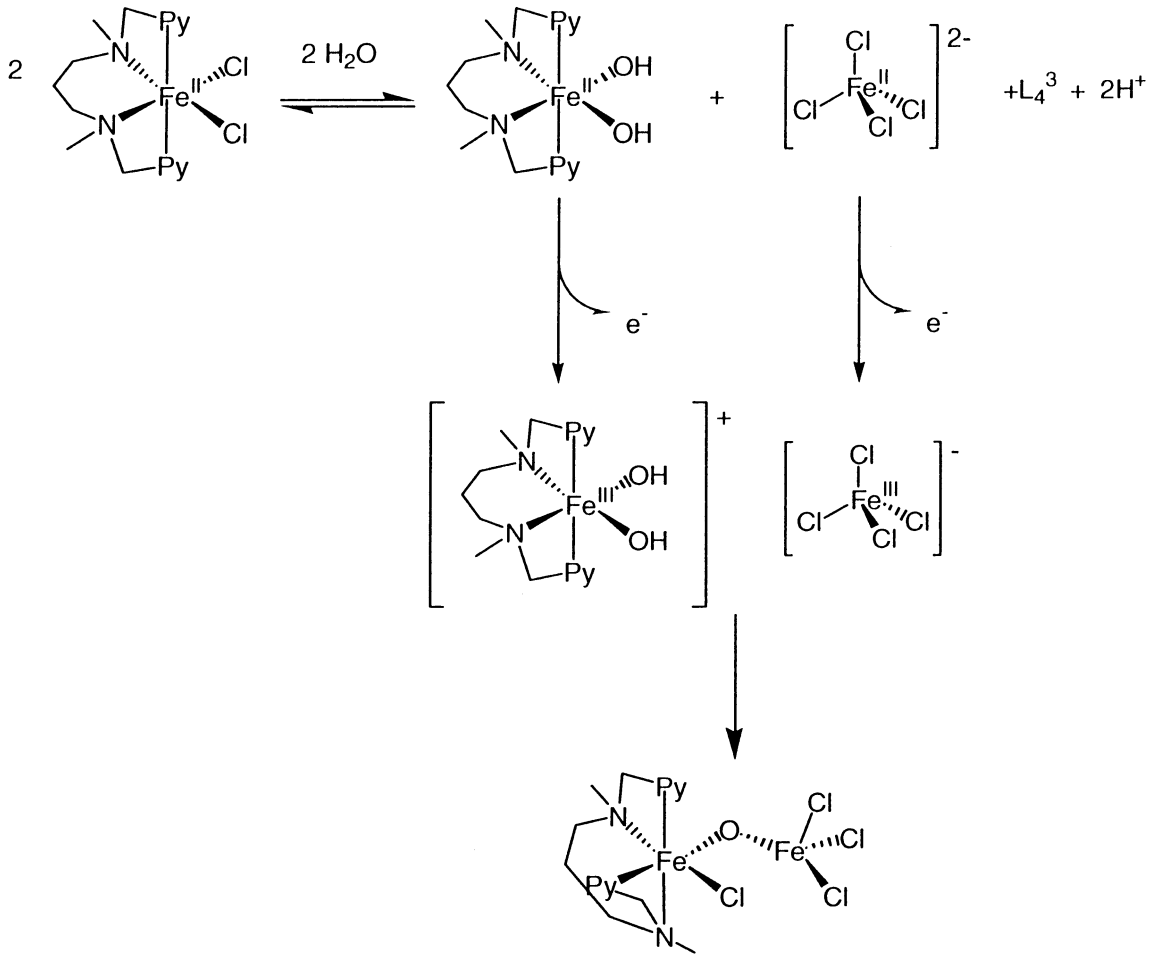


Fig. 19. Equilibria involved in acetonitrile for $L_4{}^3Fe^{II}Cl_2$.

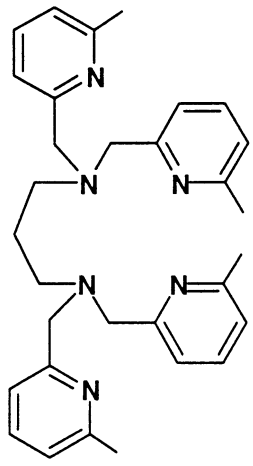


Fig. 20. $L_6{}^3$4M ligand.

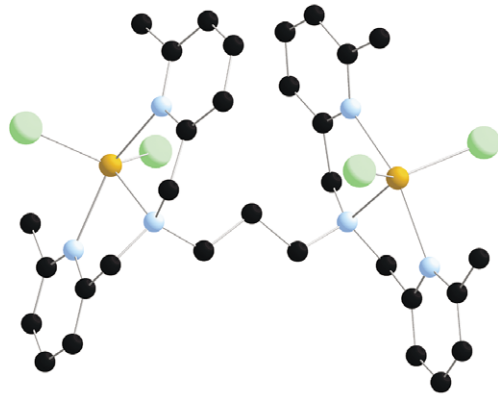


Fig. 21. X-ray crystal structure of $(L_6{}^3$4M$)Fe^{II}{}_2Cl_4$.

the mechanism of the formation the tetranuclear species is under study. Certainly, assembling ligands could lead to better catalysts by maintaining cooperativity between the Fe ions at every step.

4. Conclusion

We have shown that Fe(III)OOH and Fe(III)OO species are quite accessible by using pentadentate ligands that protect Fe and nevertheless let one position free for peroxo ligation. These species are suffi

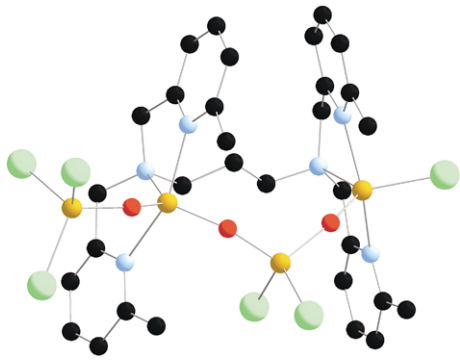


Fig. 22. X-ray crystal structure of $(L_6{}^3 4M)Fe^{III}{}_4O_3Cl_6$.

ciently oxidising to degrade aromatic pollutants and could be grafted on silica to get interesting catalysts. In the future, it could be possible to modify those molecules in order to achieve specific cis-dihydroxylation of aromatics. Such results have been already presented by Chen et Que using a bulky tetradentate ligand [54]. Evidently mutants of bacteria (with the dehydrogenase blocked) can be efficiently used to prepare *cis*-diols [55]. But bio-inspired catalysts could be simpler to use and less expensive.

From an academic point of view, it is also interesting to accumulate knowledge on those iron–peroxo species, which till recently were regarded as rare and to understand their cleavage mode and their reactivity.

Oxidation of methane into methanol is a real challenge for chemists. Biotechnology solutions could be found, but there is certainly place for research of bio-inspired catalysts. Recent advances are encouraging. The mechanism of MMO is not far from being understood thanks to the contributions of the groups of Lispcomb, Que and Lippard. One difficulty with models is to separate the reduction step of the Fe(II-I)Fe(III) state to the Fe(II)Fe(II) one from the step implying oxidation of Fe(II)Fe(II) by dioxygen. Another difficulty will be the source of the electrons, if one wants to use industrially a mono-oxygenase strategy. We arrive then at the question of the quest of electrons, which inevitably, if we look at Nature, seems to orient research toward photovoltaics and artificial photosynthesis. This opens another exciting chapter of bio-inspired chemistry.

. Supplementary Material

Crystallographic data for the structures shown in Figs. 14, 15 and 16 have been deposited at the Cambridge Crystallographic Data Centre as supplementary publication No. CCDC 171970 ($L_4{}^2Fe^{II}Cl_2$), No. CCDC 171971 ($L_4{}^3Fe^{II}Cl_2$), No. CCDC 171972 ($L_4{}^2ClFe^{III}OFe^{III}ClL_4{}^2)Cl_2$, No. CCDC 171973 ($L_4{}^2ClFe^{III}OFe^{III}Cl_3$).

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