

Characterization and alkane oxidation activity of a diastereopure seven-coordinate iron(III) alkylperoxo complex†

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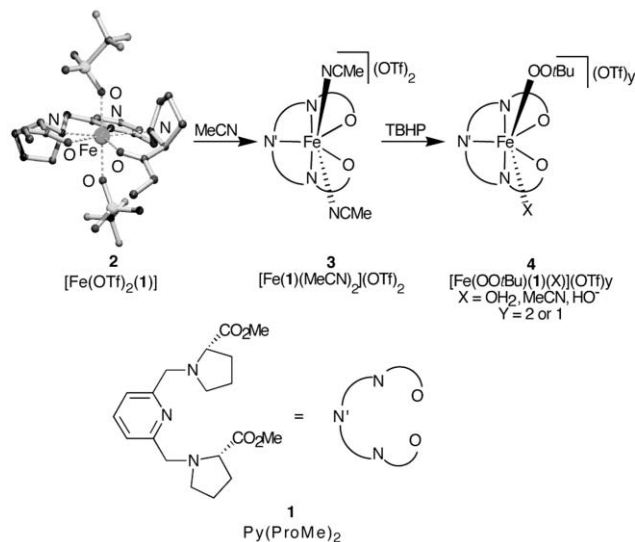
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Spectroscopic characterization and alkane oxidation studies of a diastereopure seven-coordinate high-spin iron(III) alkylperoxo complex based on the chiral *N,N,N*-bis(*L*-prolinato)pyridine ligand Py(ProMe)₂ (**1**) are reported.

In recent years, iron(III)-peroxo species have been observed as intermediates in many biological oxidations catalyzed by mononuclear, non-heme iron enzymes^{1–3} and in the antitumor drug bleomycin.⁴ In addition, high-valent iron(IV) and iron(V) oxo-species have been postulated as possible products of iron(III)-peroxo species decomposition by homolysis or heterolysis of the O–O bond.⁵ Several alkylperoxo iron(III) intermediates of enzyme model compounds were trapped at low temperatures and studied spectroscopically.⁶ These low-spin⁷ and high-spin⁸ alkylperoxoiron(III) complexes display very different spectroscopic features, notably in their Raman, EPR and Mössbauer spectra. Theoretical calculations on [Fe(OO*t*Bu)(OH_x)(L)]^{x+} (*x* = 1 or 2) revealed different decomposition pathways for a low-spin (*L* = TPA, tris(2-pyridylmethyl)amine) and a high-spin complex (*L* = 6-Me₃TPA).⁹ This seems to be the consequence of the high energy barrier of the LFeO–O*t*Bu homolytic cleavage process of the high-spin Fe(III) alkylperoxo complex as compared to that of the process with low-spin intermediates. Hence, the reactivity of the alkylperoxo intermediates depends on the spin state of Fe(III) ion. The homolytic LFe–OO*t*Bu bond cleavage yielding back the starting Fe(II) complex and *t*BuOO• for the high-spin [Fe^{III}(OOR)(6-Me₃-TPA)(O₂CAr)]⁺ complex was proposed by Que *et al.* as the reasonable alternative decay pathway of the high-spin intermediates.¹⁰ However, more recently the decomposition of the high-spin [Fe^{III}(OO*t*Bu)(HOO*t*Bu)BPMC] ²⁺ complex (BPMC = (*R,R*)-*N,N'*-bis-(2-pyridylmethyl)-*N,N'*-dimethyl-1,2-cyclohexane diamine) *via* O–O homolytic cleavage of the FeO–O*t*Bu bond to yield a high-valent iron species [Fe^{IV}(OH)(OO*t*Bu)BPMC] ²⁺ was reported.^{8d} These observations show that the fate of high-spin iron(III) alkylperoxo species is not straightforward.

As most of the studied alkylperoxo iron(III) intermediates contain achiral ligands, except for the recently published studies

on (*R,R*)-BPMC, ^{8d} we have set out to explore the reactivity of enantiopure iron(II) complexes with alkylperoxides and the potential of possible Fe(III)–OO*t*Bu intermediates in selective oxidation reactions. Previously, we reported the synthesis and the solid state and solution studies of diastereopure, high-spin Fe(II) complex [Fe(OTf)₂(**1**)] (**2**) with an unusual pentagonal bipyramidal geometry (pbp) (Scheme 1).¹¹ Solution studies revealed the integrity of complex **2** in solution with the Py(ProMe)₂ ligand (**1**) retaining its pentagonal planar coordination of the NN'NOO donor atoms around the Fe(II) center as was found in the solid state. The triflate anions which are coordinated at the axial positions of the pbp in **2** can be substituted for solvent molecules like acetonitrile (**3**) or water. The well-defined ligand coordination around the iron center and the facile replacement of the axial triflate anions prompted us to investigate the reactivity of this complex as a catalyst in the oxidation of alkanes with *tert*-butyl hydroperoxide (TBHP). In the course of this study we observed the formation of a purple-colored, transient species **4** and here we report the result of its independent synthesis (Scheme 1), spectroscopic characterization, and catalytic activity.



Scheme 1 Synthesis and structure of intermediate **4** in acetonitrile.

Addition of three equivalents of TBHP (solution in decane) to an acetonitrile solution of **2** results in the immediate formation of the purple species **4**, which has a characteristic UV-Vis absorption at $\lambda_{\text{max}} = 582 \text{ nm}$ ($\epsilon = 1334 \text{ M}^{-1} \text{ cm}^{-1}$, Fig. 1a) arising from a alkylperoxo-iron(III) LMCT band¹² and which is persistent for about 5 min at room temperature and for several hours at $-40 \text{ }^\circ\text{C}$.

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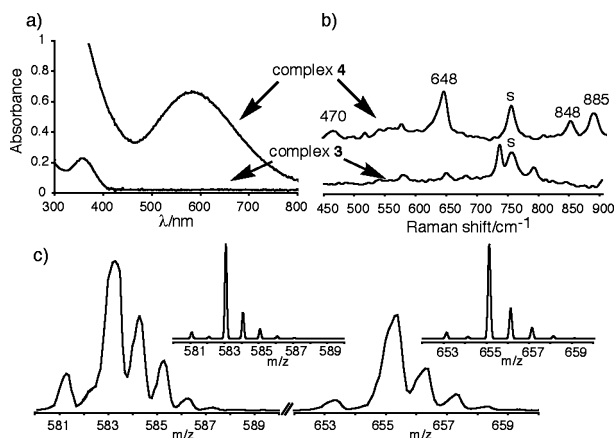


Fig. 1 Spectroscopic features of intermediate **4**; (a) UV-Vis spectra, (b) Raman spectra and (c) ESI-MS spectra.

The Raman spectrum of **4** shows four features at 885, 850, 648 and 470 cm^{-1} (Fig. 1b), which is characteristic of a high-spin iron(III) alkylperoxo complex.⁸ Based on the assignment of Lehnert *et al.*⁹ for terminal η^1 -alkylperoxo coordination, the two features above 800 cm^{-1} correspond to the O–O stretch that is strongly mixed with the C–C stretch vibration of the *t*Bu group. The band at 648 cm^{-1} is assigned to the Fe–O vibration and the feature around 470 cm^{-1} to a combined $\delta(\text{OCC})/\delta(\text{CCC})$ bending vibration of the *t*Bu group.

To gain more information about the ligand coordination in **4**, IR spectra were recorded in acetonitrile at -40°C 15 min after the addition of TBHP. Only a slight shift of the $\nu(\text{CO})$ of the prolinic ester moieties from 1684 cm^{-1} in **3** to 1670 cm^{-1} in **4** was observed, which points to the retention of coordination of both carbonyl groups of ligand **1** to the Fe(III) center (Fig. S2†). In addition, the observation of four sharp vibrations of the triflate anions indicates that they are no longer coordinated to iron in **4**.¹³

Positive electrospray ionization mass spectrometry on **4** showed four main ions at m/z 655, 583, 253 and 217. These mass values and their isotope patterns correspond to $\{[\text{Fe}^{\text{III}}(\text{OO}t\text{Bu})(\mathbf{1})](\text{OTf})\}^+$ ($m/z = 655$), $\{[\text{Fe}^{\text{III}}(\text{OH})(\mathbf{1})](\text{OTf})\}^+$ ($m/z = 583$), (Fig. 1c left and right, respectively) and $\{[\text{Fe}^{\text{III}}(\text{OO}t\text{Bu})(\mathbf{1})]\}^{+2}$ ($m/z = 253$) and $\{[\text{Fe}^{\text{III}}(\text{OH})(\mathbf{1})]\}^{+2}$ ($m/z = 217$). Ions with the stoichiometry $\{[\text{Fe}^{\text{III}}(\text{OO}t\text{Bu})(\text{OH})(\mathbf{1})]\}^+$ (m/z 523) and $\{[\text{Fe}^{\text{III}}(\text{OH})_2(\mathbf{1})]\}^+$ (m/z 451) are also present in the spectra, but with lower intensities (Fig. S3†). The observation of ions with one *t*BuOO[−] or HO[−] anion as well as of ions substituted with two of these anions, points to the formulation of the intermediate species **4** as $[\text{Fe}^{\text{III}}(\text{OO}t\text{Bu})(\text{X})(\mathbf{1})](\text{OTf})_y$ (X = OH₂, MeCN or HO[−] and $y = 1$ or 2) regardless of the TBHP solution (decane or water) used in its generation. The hydroxyl anions observed in the mass spectra of **4** can originate from fragmentation of either *t*BuOO[−] or of an aquo ligand^{8b} introduced by the oxidant solution or during ambient sample handling.

EPR spectra of frozen solutions of **4** show a mixture of high-spin Fe(III) species with $S = 5/2$ (Fig. S4†). The major feature at $g = 7.7$, 4.26 and 2.01 with $E/D = 0.07$ represents a high-spin Fe(III) center with a small distortion from axial symmetry. Regrettably, we were not able to calculate the E/D value for the other minor high-spin features or to simulate these features with sufficient accuracy.

The UV-Vis, Raman and EPR spectroscopic features of intermediate **4** correspond well with the spectroscopic data reported for other high-spin iron(III) alkylperoxo species.⁸ Additionally, the $\nu(\text{CO})$ around 1670 cm^{-1} in the IR spectrum of **4** and the detection of the doubly substituted ions $([\text{Fe}(\text{OH})(\text{OO}t\text{Bu})\text{L}]^+)$ and $([\text{Fe}(\text{OH})_2\text{L}]^+)$ by ESI-MS indicate the retention of the seven-coordinate geometry around the iron center and the planar coordination mode of ligand **1** as in **2** with two ligands in the axial positions of the pbp, *i.e.* one *t*BuOO[−] anion and a second ligand X (X = OH₂, HO[−], or MeCN). The pentagonal coordination of the ligand donor atoms corroborates with the formation of a single diastereoisomer with the same $R_N R_N S_C S_C$ configuration as in diastereopure **2**.

The additional high-spin Fe(III) features as detected by EPR spectroscopy most probably originate from other seven-coordinate complexes with different axial ligands (a shoulder at 1684 cm^{-1} in the IR spectra). The observation of a mixture of species by EPR, whereas these additional species were not observed in the UV-Vis and Raman spectra, indicates that these species are formed in relatively low concentrations. The presence or absence of O₂ during the generation of species **4** did not influence its spectroscopic characteristics.

During the decay of **4** we did not spectroscopically observe the formation of high-valent iron oxo-intermediates. Isolation of the iron complex after reaction with oxidant, demetalation (with 30% aqueous NH₃), and ¹H NMR analysis of the organic component demonstrated that ligand **1** stays intact, *i.e.* no racemisation or oxidation occurred. All our attempts to crystallize the transient purple species from acetonitrile solution failed. Attempts to crystallize **4** from CH₂Cl₂, in which it is stable for several days below -40°C , resulted in the crystallization of the decomposition product $[\text{Fe}(\mathbf{1})(\text{OH})_2](\text{OTf})_2$ ¹⁴ which further corroborates the structural integrity of the Fe-coordination mode upon generation and deterioration of **4**, and the robustness of chiral ligand **1**.

Complex **2** in acetonitrile, *i.e.* complex **3**, catalyzes the oxidation of hydrocarbons in the presence of TBHP with reasonably high TON's after 1 h (4.2–9.5) and with high oxidant consumption (42–94%) in the case of cyclohexane, adamantane, and ethylbenzene. However, for sterically hindered 1,2-dimethylcyclohexane a much lower TON (1.7) was found. Data for the oxidation of different alkanes with a combination of **2** and TBHP/decane are summarized in Table 1.¹⁵ Large excesses of substrate were used to minimize over-oxidation of alcohols to ketones (ratio **2** : substrate : oxidant = 1 : 500 : 10). The alcohol to ketone ratio (A/K) obtained in the oxidation of both cyclohexane and ethylbenzene is <1. A normalized 3°/2° ratio of 12.3 was obtained in the oxidation of adamantane. In the oxidation of *cis*-1,2-dimethylcyclohexane, the stereo-retained product, (*S,S* & *R,R*)-1,2-ol formed in addition to the product with loss of the original stereochemistry, (*R,S* & *S,R*)-1,2-ol. In the oxidation of ethylbenzene, a 6.5% enantiomeric excess was obtained for one of the reaction products, 1-phenyl ethanol.

Much lower yields of the oxidation products were found when these oxidations were performed under Ar (Table 1) and in the presence of radical traps like acetone, CCl₄, or 2,6-di-*tert*-butyl-4-methylphenol (Table S5†). The A/K ratio in cyclohexane oxidation remained lower than one also when the reaction was performed in acetone or in the presence of radical traps. Only a small amount of 1-chloro-adamantane was detected in GC-MS,

Table 1 Oxidation of alkanes catalyzed by complex **2** with TBHP–decane^a

Substrate	Product	TON ^b	Conv. oxidant	Remarks
Cyclohexane ^{c,d}	Cyclohexanol	1.6 (0.5)	42% (5%)	A/K = 0.6 (0.5)
	Cyclohexanone	2.6 (n.o.)		
Adamantane ^c	Adamant-1-ol	6.9 (0.6)	85% (6%)	3°/2° = 12.6 (1.8)
	Adamant-2-ol	1.1 (n.o.)		
	Adamant-2-one	0.5 (n.o.)		
	(R,R & S,S)-1,2-ol	1.2		
<i>cis</i> -1,2-Dimethylcyclohexane	(R,S & S,R)-1,2-ol	0.5	17%	RC ^e = 41%
	1-Phenyl ethanol	4		
Ethylbenzene	Acetophenone	5.4		A/K = 0.74

^a Reaction conditions: 0.5 mL of 70 mM *t*BuOOH (5–6 M decane solution) solution in MeCN was added slowly over 30 min to a stirred solution of 2.8 mL MeCN containing **2** (3.5 μmol) and substrate (1.75 mmol) at ambient temperature, stirring was continued for another 30 min; ratio of cat : oxidant : substrate = 1 : 10 : 500. The reported values are the average of two independent runs. ^b Moles of product/moles of catalyst. ^c The values in parentheses were obtained under Ar, n.o. = not observed. ^d Cyclohexyl *tert*-butylperoxide was only observed in GC-MS when 150 eq of oxidant were used (results not shown). ^e Retention of configuration (RC) of 3°-ol = 100 × [(RR + SS) – (RS + SR)]/(3°-ol).

while no cyclohexylchloride or cyclohexyl *tert*-butylperoxide was observed under similar conditions in the oxidation of cyclohexane.

The low A/K ratios, observed for cyclohexane and ethylbenzene indicate that O-centered alkylperoxy radicals,^{7c,7d,16} which can disproportionate into products *via* Haber–Weiss reactions^{17a} and Russell termination steps,^{17b} most likely participate in the oxidation process. The formation of the 1,2-ol product with the loss of the stereochemistry in the oxidation of *cis*-1,2-dimethylcyclohexane can be explained by the formation of substrate alkyl radicals with a lifetime sufficiently long to allow epimerization at the radical site. These observations together with the significant decrease of the oxidation products in the presence of radical traps imply that alkyl radicals are to a certain extent involved in the oxidation of the alkanes with **2** and TBHP.¹⁶ On the other hand, the normalized 3°/2° ratio (12.3) for adamantane oxidation is significantly larger than that found for Gif-type oxidations (2.7) or oxidations attributed to HO• (2) or *t*BuOO• (6–10) radicals,^{7c,18} and is in the range of oxidations with PhIO catalyzed by P450 mimics¹⁹ and close to the values obtained with [Fe^{II}(TPA)(MeCN)₂]/H₂O₂.²⁰ The high 3°/2° ratio indicates that an oxidant more selective than HO• or *t*BuO• is involved.

In conclusion, we have demonstrated by several spectroscopic techniques the formation of a diastereopure, mononuclear, high-spin iron(III) alkylperoxo complex with seven-coordinate geometry which is unique for Fe(III) alkylperoxo complexes.^{7,8} Complex **2** shows catalytic activity in the oxidation of non-activated alkanes with high TON's and the possibility that a metal-based oxidant is involved in the oxidation cannot be excluded in view of the high 3°/2° ratio for the oxidation of adamantane, even though O-radicals and C-radicals are apparently generated during these reactions.

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- Complex **4** is also formed when an aqueous solution of TBHP (70%) is added to an acetonitrile solution of **2** with $\lambda_{\text{max}} = 568 \text{ nm}$ ($\epsilon = 1046 \text{ M}^{-1} \text{ cm}^{-1}$, Fig. S1†) showing essentially identical ESI-MS spectra.
- For detailed analysis of the IR vibrations of coordinated and uncoordinated triflate anions to the iron, see ref. 11.
- The synthesis and X-ray structural determination of [Fe(1)(OH)₂]₂(OTf)₂ was reported earlier by us, see ref. 11.

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