Check for updates

View Article Online
View Journal

Chemical Science

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: B. Chandra, K. K. Singh and S. Sen Gupta, *Chem. Sci.*, 2017, DOI: 10.1039/C7SC02780J.

This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the author guidelines.

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard Terms & Conditions and the ethical guidelines, outlined in our author and reviewer resource centre, still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.

ROYAL SOCIETY OF CHEMISTRY

rsc.li/chemical-science

Please do not adjust margins

View Article Online
DOI: 10.1039/C7SC02780J

Open Access Article. Published on 04 September 2017. Downloaded on 05/09/2017 01:33:09.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Chemical Science Accepted Manuscript

Journal Name

ARTICLE

Selective Photocatalytic Hydroxylation and Epoxidation Reaction by an Iron Complex Using Water as the Oxygen Source

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

Bittu Chandra[#], Kundan K. Singh[#] and Sayam Sen Gupta*[a]

The iron complex, $[(bTAML)Fe^{III}\text{-}OH_2]^-$ (**1**), selectively catalyses the photocatalytic hydroxylation and epoxidation reactions of alkanes and alkenes respectively using water as the oxygen-atom source. Upon oxidation of unactivated alkanes, which included several substrates including natural products, hydroxylation was observed mostly at the 3° C-H bonds with 3°:2° selectivity up to ~100:1. When alkenes were used as substrates, epoxides were predominantly formed with high yields. In presence of $H_2{}^{18}O$, more than 90% of the ^{18}O-labelled oxygen atom was incorporated into the hydroxylated and epoxide product indicating water to be the primary oxygen source. Mechanistic studies indicate formation of an active $[\{(bTAML)Fe^{IV}\}_2\text{-}\mu\text{-oxo}]^{2-}$ (**2**) dimer from the starting complex **1** *via* PCET. The subsequent disproportionation of **2** upon addition of substrate, leading to formation of $Fe^V(O)$, renders the high selectivity observed in these reactions.

Introduction

Conversion of sunlight to chemical energy has been one of the grand challenges for chemists in the quest for a sustainable world.[1] The inspiration for such a process comes from photosynthesis, wherein sunlight is used to accomplish the energetically uphill water oxidation reaction.[2] During photosynthesis, a high-valent manganese-oxo cluster has been proposed to be the active intermediate for water oxidation.[3] Similarly, high-valent iron-oxo complexes have been shown to be the active intermediate for heme/non-heme enzymes and their model complexes which catalyse hydrocarbon oxidation using O_2 as the oxidant.[4] Combining these concepts, Inoue *et al.* first demonstrated that visible light can be utilized for the oxidation of organic substrates using water as the oxygen atom source.[5] Gray et al. have also developed a photochemical method to generate the intermediate "Compound I" and "Compound II" from peroxidases by using $[Ru^{II}(bpy)_3]^{2+}$ (bpy = 2,2'-bipyridine) as a photosensitizer and $[Co^{III}(NH_3)_5Cl]^{2+}$ as a mild one electron oxidant in aqueous medium.[6] Using these strategies, several photochemical oxygenation systems based on metal complexes (mostly Ru and Mn) as catalysts have been evolved. Examples include various Ru-Complexes[7,8] and Mn-Complexes such as Mn-Porphyrin[9], $[(R,R\text{-BQCN})Mn^{II}(OTf)_2]$ (BQCN = *N,N*'-dimethyl-*N,N*'-bis(8-quinolyl) cyclohexanediamine)[10a,b] and Mn(V)-Nitrido complex, $[Mn(N)(CN)_4]^{2-}$,[10c] that have been shown to be active catalysts for photocatalytic oxygenation reactions where water was used as the oxygen source. Although ruthenium and manganese based metal complexes have been explored for photochemical alcohol, olefin and sulfide oxidation reactions, they have not been shown to catalyse oxidation of unactivated C-H bonds.[7,8,9,10] The likely reason is that Ru-oxo and Mn-oxo intermediates, formed during these reactions, do not cleave unactivated C-H bonds with rates fast enough to function as catalysts for C-H bond oxidation reactions. In contrast, iron based metalloenzymes (sMMO,[11a,b] heme and non-heme enzymes[4,11c,d]) and their synthetic models[4b,c,e] exhibit excellent reactivity and selectivity towards hydrocarbon oxidation. However, for synthetic systems, very few examples are known where cheap and environmentally benign metal like iron has been used as a catalyst for photochemical oxidation reactions. Recently, photochemical generation of oxoiron(IV) have been demonstrated using $[Fe^{II}(N_4Py)]^{2+}$ [N_4Py = N,N-bis(2-pyridylmethyl)-N-bis(2-pyridyl)methylamine][12] and $[Fe^{II}(MePy_2tacn)]^{2+}$ [$MePy_2tacn$ = *N*-methyl-*N,N*-bis(2-picolyl)-1,4,7-triazacyclononane].[13] The complex $[Fe^{II}(MePy_2tacn)]^{2+}$, along with $[Ru^{II}(bpy)_3]^{2+}$ as a photosensitizer and sodium persulfate as a sacrificial oxidant under light irradiation has been shown to catalyse sulfoxidation reaction albeit with low yields. However, the photochemical hydroxylation of unactivated C-H bonds using $[Fe^{II}(MePy_2tacn)]^{2+}$ complex described above has not been reported. Mechanistic studies on iron catalysed hydroxylation reactions have revealed that in both chemical and biological systems, efficient and selective hydroxylation of unactivated C-H bonds have been mostly catalysed by reactive intermediates such as oxoiron(V) (synthetic systems),[14,15,19] the isoelectronic oxoiron(IV) radical cation (heme enzymes)[4a,11c,d] and the $[(\mu\text{-}O)_2Fe^{IV}{}_2]$ (methane monooxygenase[11a,b]). None of these intermediates were

---

[a] *Dr. Sayam Sen Gupta*
Department of Chemical Sciences
Indian Institute of Science Education and Research Kolkata
Mohanpur, West Bengal, India-741246
E-mail:sayam.sengupta@iiserkol.ac.in

[#] *Both authors contributed equally to this work*

†Electronic Supplementary Information (ESI) available: materials, general instrumentation and additional figures, See DOI: 10.1039/x0xx00000x

Please do not adjust margins

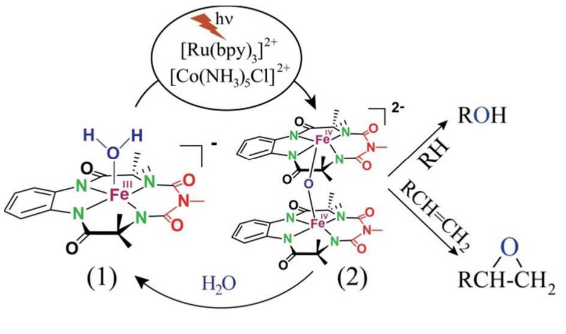
View Article Online
DOI: 10.1039/C7SC02780J

Open Access Article. Published on 04 September 2017. Downloaded on 05/09/2017 01:33:09.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

formed in the photochemical systems reported till date using $[Fe^{II}(N_4Py)]^{2+}$ and $[Fe^{II}(MePy_2tacn)]^{2+}$ complexes which explains the absence of iron catalysts catalysing photochemical C-H bond oxidation in the literature.

We focused our attention to peroxidase mimicking iron(III) complex of bTAML[14] (bTAML = biuret-modified tetraamidomacrocyclic ligand) synthesized in our laboratory where the highly electron donating tetraanionic N-donors are well-known to stabilize high valent iron-oxo species such as $[(bTAML)Fe^{V}(O)]^{-}$ and $[(bTAML)Fe^{IV}(O)]^{2-}$ (subsequently referred to as $Fe^{V}(O)$ and $Fe^{IV}(O)$ respectively).[15] Moreover, complex **1** in combination with chemical oxidants, catalyses the oxidation of unactivated alkanes, alkenes and alcohols selectively.[15b,17b,18,19] The high selectivity obtained has been attributed to the presence of oxoiron(V) and $[\{(bTAML)Fe^{IV}\}_2(\mu\text{-}O)]^{2-}$ (**2**) as active intermediates in these reactions. We have also shown that the oxidant $[Ru^{III}(bpy)_3]^{3+}$, generated either chemically or photochemically, is a competent oxidant to oxidize $[(bTAML)Fe^{III}(OH_2)]^{-}$ (**1**) complex in solution to the catalytically active $[\{(bTAML)Fe^{IV}\}_2(\mu\text{-}O)]^{2-}$ dimer (**2**).[16] We therefore hypothesized that complex **1** along with $[Ru^{II}(bpy)_3]^{2+}$ and $[Co^{III}(NH_3)_5Cl]^{2+}$, can be a competent system to catalyse the photochemical oxidation of synthetically challenging reactions such as selective hydroxylation of unactivated C-H bonds and epoxidation reactions. Development of such iron-based catalysts would become transformational in the goal to achieve green methods for selective oxidation of C-H bonds.

Herein, we report selective photocatalytic alkane hydroxylation and olefin epoxidation by employing $[Et_4N][(bTAML)Fe^{III}(OH_2)]$ (**1**) as a catalyst, $[Ru^{II}(bpy)_3]Cl_2$ as a photosensitizer, $[Co^{III}(NH_3)_5Cl]Cl_2$ as a mild one electron acceptor and water as the oxygen atom source. We also demonstrate that under the reaction conditions, intermediate **2** was generated and found to be the active oxidant (Scheme 1). To the best of our knowledge, this represents the first example for the use of iron-complex to catalyse photochemical selective oxidation of unactivated C-H bonds and C=C bonds using water as O-atom donor.



Scheme 1 Photocatalytic oxygenation of hydrocarbons.

Results and discussion

Photocatalytic Oxidation of Alkanes

All the photocatalytic hydroxylation reactions were performed by employing catalyst **1** (~3-7mol% loading), $[Ru^{II}(bpy)_3]Cl_2$ and $[Co^{III}(NH_3)_5Cl]Cl_2$ in acetonitrile-phosphate buffer solution mixture in presence of light (3W blue LED, 440nm) under argon atmosphere. Photocatalytic hydroxylation of alkanes having different unactivated 3° and activated 2° C-H bonds was attempted under optimized reaction conditions. Adamantane having twelve 2° and four 3° C-H bonds was used as a substrate probe to study the regioselectivity using the photocatalytic system. Upon completion of reaction, 1-adamantanol was formed in good yields (88%) and the 3°:2° selectivity for adamantane oxidation was calculated to be ~100:1 (Table 1; Entry 1). In case of cumene, which contains six 1° and one benzylic 3° C-H bonds, 3° hydroxylated product was formed as the major product (67% yield; Table 1, Entry 2). Next, *cis*-1,2-dimethylcyclohexane and *cis*-decalin were chosen as substrates to examine the stereoselectivity of this oxidation. Reaction of *cis*-1,2-dimethylcyclohexane and *cis*-decalin displayed primarily 3° hydroxylated product (99% and 96% yield respectively) with more than ~97% retention of configuration under the reaction condition (Table 1; Entry 3, 4). The high stereo-retention observed excluded the possibility of radical processes since *cis*-1,2-dimethylcyclohexane and *cis*-decalin are known to epimerize to the *trans* isomer if radical processes are operational. In cyclohexane derivatives, the stereochemical orientation of the 3° C-H bonds (axial or equatorial) determines the regioselective outcome of the reaction. For catalytic hydroxylation of *trans*-decalin, the reaction was comparatively slower with lower yield (60%) of the oxidized product (Table 1, Entry 5) in contrast to that of the *cis* isomer. Oxidation of *trans*-decalin also exhibits oxidation at the methylenic C-H bonds unlike its *cis* congener, resulting in the formation of both alcohol (99% retention of configuration) and ketone at a ratio of 3:2. The difference in reactivity between the *cis* and *trans* isomers can be attributed to the strain release in the transition state for the cis-isomers.[20] In short, the hydroxylated products formed after the reaction displayed very high regioselectivity of 3° over 2° C-H bonds (Table 1; Entry 3, 4, 6) where 3° hydroxylated products were formed predominantly. This result is consistent with similar oxidation reported by us using complex **1** and mCPBA as the oxidant.[19] Further the regioselective oxidation of 3° C-H bonds in natural product derivative of cedrol, cedryl acetate, was performed. Cedrol is a sesquiterpene alcohol found in essential oil, having a very rigid structure with five 3° C-H positions. The substrate was hydroxylated very selectively with good yield albeit low conversion (Table 1, Entry 6). In order to find the O-atom source in the product formed, oxidation reactions of *cis*-1,2-dimethylcyclohexane and adamantane were carried out in a mixture of CH_3CN and $H_2{}^{18}O$ (3:2 v/v). We observed >90% and >95% incorporation of ^{18}O-labelled oxygen

Chemical Science Accepted Manuscript

This journal is © The Royal Society of Chemistry 20xx

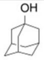
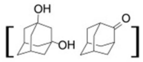
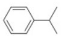
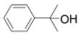
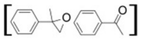
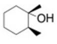
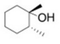
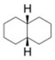
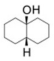
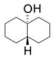
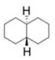
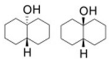
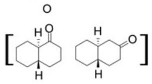
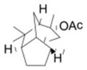
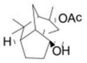
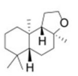
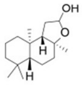
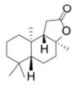
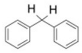
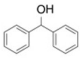
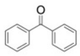
Please do not adjust margins

View Article Online
DOI: 10.1039/C7SC02780J

Open Access Article. Published on 04 September 2017. Downloaded on 05/09/2017 01:33:09.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

atom in 1-adamantanol (Fig. 2D) and (1*S*,2*R* or 1*R*,2*S*)-1,2-dimethylcyclohexanol (Fig. S1†) respectively which confirmed water as the O-atom source. This also precluded the involvement of O_2 based radical pathway during the reaction.

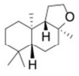
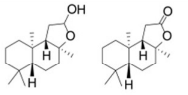
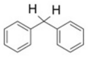
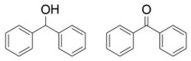
Table 1 Photocatalytic hydroxylation of different alkanes by **1** using water as the oxygen source.

Entry	Substrate	Products	(Other products)	Conversion (%)	Yield (%)[b]
1.				76	88
2.				50	67
3.				55	99 (60:1) (*cis* : *trans*)
4.[a]				99	96 (65:1) (*cis* : *trans*)
5.[a]				50	60 (20:1) (*trans* : *cis*)
6.[a]				37	97
7.				56	98 (7:12) (alcohol : ketone)
8.				60	94 (7:10) (alcohol : ketone)

Reaction conditions: **1** (1.0×10^{-4} M), $[Ru(bpy)_3]^{2+}$ (2.0×10^{-3} M), $[Co(NH_3)_5Cl]^{2+}$ (2.0×10^{-2} M) and substrate (3.0×10^{-3} M), acetonitrile-aqueous phosphate buffer (3:2 v/v, 10 mM, pH 10), photoirradiation with LED (3W, 440 nm), room temperature (27 °C), under argon, 40 mins. [a]Catalyst **1** (2.0×10^{-4} M). [b]Yields are based on substrate conversion (amount of side products indicated inside the parenthesis are not included); yields and conversions were estimated by GC.

Finally, the selective oxidation of substrates bearing activated methylenic and benzylic C-H bonds were explored. In case of the substrate ambroxide, oxidation at the α-ethereal C-H bond occurred predominantly among numerous other electronically and sterically accessible secondary and tertiary sites (Table 1; Entry 7). At lower substrate concentration, over-oxidized ketone was the major product formed (Table 1; Entry 7, 8). The alcohol to ketone product ratio increased with increasing substrate concentration (3 mM to 40 mM; Table 2) under the same reaction condition. Similar results were found when diphenylmethane was employed as substrate (Table 1; Entry 8). This formation of ketone was attributed to the over-oxidation of the hydroxylated product, which was first formed during the hydroxylation reaction (cyclohexanol oxidation has been shown to be 400 times faster than cyclohexane oxidation[18]). The incorporation of ~80% ^{18}O-labelled oxygen atom in the ketone product of ambroxide (Fig. S2†) also supports this hypothesis. The quantum yields for the photocatalytic oxidation of alkanes were determined using a standard actinometer (potassium ferrioxalate) and a maximum value of 12.2% was observed in case of *cis*-decalin hydroxylation (Table S1†).

Table 2 Effect of substrate concentration on photocatalytic hydroxylation of 2° C-H bond by **1** using water as the oxygen source.

Entry	Substrate	Products	Alcohol /Ketone (ratio) in different substrate concentration (mM)			
			3 mM	10 mM	20 mM	40 mM
1.			0.6	1.8	2.4	5.3
2.			0.7	1.5	3.5	6.1

Reaction conditions: **1** (1.0×10^{-4} M), $[Ru(bpy)_3]^{2+}$ (2.0×10^{-3} M), $[Co(NH_3)_5Cl]^{2+}$ (2.0×10^{-2} M); acetonitrile-aqueous phosphate buffer (3:2 v/v, 10 mM, pH 10), photoirradiation with LED (3W, 440 nm), room temperature (27 °C), under argon, 40 mins.

Photocatalytic Oxidation of Alkenes

Epoxidation of various alkenes were also performed under optimized reaction conditions by employing catalyst **1** (2 mol% loading) (Fig. S3†). Analysis of the products indicated predominant formation of alkene oxides in moderate to high yields (79-84%) and only trace amount of the side-product aldehyde (~5-7% with respect to epoxide) was observed. At first, styrene was chosen as the substrate for photocatalytic epoxidation reaction where styrene oxide was obtained as the predominant product. Subsequently, different para substituted styrene derivatives such as 4-chlorostyrene and 4-methoxystyrene were investigated and their corresponding epoxides were obtained with yields up to 92% (Table 3; Entry 1, 2 & 3). The higher amount of epoxide formation for para-substituted electron donating group on styrene in comparison to electron withdrawing group supports the likely involvement of an electrophilic high-valent iron-oxo intermediate, as has been reported earlier by us.[17b] For *cis*-stilbene, a substrate which contains a sterically constrained double bond, a lower conversion of 58% and a moderate yield of 79% (Table 3; Entry 4). The *cis/trans* product ratio 19:2 was estimated by ^1H-NMR (Fig. S4†) (Note: additional stereo-scrambling in *cis*/*trans* ratio was observed in GC run). The substrate scope was further expanded to include cyclooctene and norbornene (Table 3; Entry 5 and 6) where 94% yield of cyclooctene oxide and 92% yield of *exo*-norbornene oxide indicate selectivity for C=C bond over C-H bonds. For the epoxidation of alkenes, a maximum quantum yield of 18.7% for 4-methoxystyrene was observed (Table S2†).

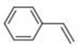
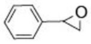
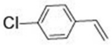
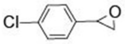
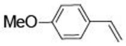
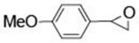
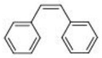
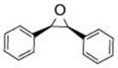
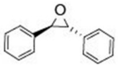
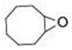
Chemical Science Accepted Manuscript

View Article Online
DOI: 10.1039/C7SC02780J

Open Access Article. Published on 04 September 2017. Downloaded on 05/09/2017 01:33:09.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Chemical Science Accepted Manuscript

Table 3 Photocatalytic epoxidation of different alkenes by **1** using water as the oxygen source.

Entry	Substrate	Product	Conversion (%)	Yield (%)
1.			72	90
2.			50	84
3.			95	92
4.		 	58	79
5.			51	94
6.			64	92

Reaction conditions: **1** (1.0×10^{-4} M), $[Ru(bpy)_3]^{2+}$ (2.0×10^{-3} M), $[Co(NH_3)_5Cl]^{2+}$ (2.0×10^{-2} M) and substrate (5.0×10^{-3} M), acetonitrile-aqueous phosphate buffer (3:2 v/v, 10 mM, pH 10), photoirradiation with LED (3W, 440 nm), room temperature (27 °C), under air, 40 mins.Yields are based on substrate conversion (the amount of side products are not included); yields and conversions were estimated by GC.

Mechanistic Insight

Since the operation of free radical oxidation was ruled out, involvement of high-valent iron-oxo intermediate during the reaction was investigated. Upon irradiation with blue LED light (λ_{max} = 440 nm) to the mixture of **1**, Ru^{2+} and Co^{3+} in 3:2 CH_3CN-phosphate buffer solution mixture, a broad absorption band in the region of 800-1000 nm was observed (Fig. 1; violet colour spectrum). This new species was assigned as the previously characterized dimer, $[\{(bTAML)Fe^{IV}\}_2(\mu\text{-}O)]^{2-}$ (**2**),[15b] which is consistent with the UV-vis spectrum of chemically synthesized dimer **2** (Fig. S5[†]). This intermediate species was not observed in the absence of any one of the components (catalyst, Ru^{2+}, Co^{3+} or light). Upon addition of substrate (alkenes or alkanes) to this solution, **2** reacted with substrate and regenerated the parental complex **1** (Fig. S6[†]), which would restart the catalytic cycle upon light irradiation with concomitant formation of oxygenated product (alcohol or epoxide).

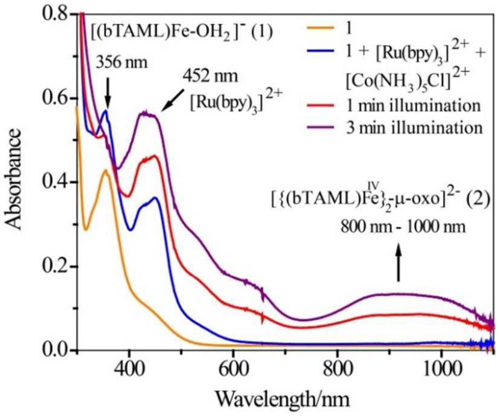


Fig. 1 UV-vis spectral scan of a photochemical reaction mixture of **1** (1.0×10^{-4} M), $[Ru^{II}(bpy)_3]^{2+}$ (2.0×10^{-5} M) and $[Co^{III}(NH_3)_5Cl]^{2+}$ (6.0×10^{-4} M) in acetonitrile-aqueous phosphate buffer (3:2) solvent.

We have demonstrated earlier that independently synthesized $[Ru^{III}(bpy)_3]^{3+}$ was competent to oxidize**1** to form the complex **2**.[16] We therefore propose that $[Ru^{III}(bpy)_3]^{3+}$, which is generated due to one electron transfer from the excited state of $[Ru^{II}(bpy)_3]^{2+}$ to the sacrificial oxidant $[Co^{III}(NH_3)_5Cl]^{2+}$, oxidizes **1** containing an axial H_2O ligand, to generate a putative $[(bTAML)Fe^{IV}\text{-}OH]^-$ species by one electron and one proton transfer process (PCET). This proposition is based on previous electrochemical studies reported by us.[15c,d] Under neutral or basic condition (pH 10 in this case), Fe^{IV}-OH species dimerizes immediately to form complex **2** as shown below.

$$[Ru^{II}(bpy)_3]^{2+} \xrightarrow{h\nu} [Ru^{II}(bpy)_3]^{2+}*$$

$$[Ru^{II}(bpy)_3]^{2+}* + [Co^{III}(NH_3)_5Cl]^{2+} \longrightarrow [Ru^{III}(bpy)_3]^{3+} + [Co^{II}(NH_3)_5Cl]^{+}$$

$$[Ru^{III}(bpy)_3]^{3+} + \mathbf{1} \longrightarrow [(bTAML)Fe\text{-}OH]^- + [Ru^{II}(bpy)_3]^{2+}$$

$$[(bTAML)Fe\text{-}OH]^- + [(bTAML)Fe\text{-}OH]^- \longrightarrow \mathbf{2}$$

This is in contrast to $[(N_4Py)Fe^{II}]^{2+}$ and $[(MePy_2tacn)Fe^{II}]^{2+}$complexes where the Fe^{III}-OH species is oxidized by $[Ru^{III}(bpy)_3]^{3+}$ to form the corresponding $Fe^{IV}(O)$.[12,13] The reactivity of both the Fe^{IV} complexes, i.e. the $Fe^{IV}(O)$ and $[(\mu\text{-}O)Fe^{IV}_2]$ dimer (**2**) differ. While the high-valent $[(N_4Py)Fe^{IV}(O)]$ and $[(Me_2Pytacn)Fe^{IV}(O)]$ [$Me_2Pytacn$ = 1-(2-pyridylmethyl)-4,7-dimethyl-1,4,7-triazacyclononane] species are competent to cleave strong C-H bonds selectively, the low redox potential of Fe^{III}-OH formed prevents the subsequent “rebound” process, thus leading to free radical auto-oxidation.[22] In contrast, our investigations on the reactivity of the $[\{(bTAML)Fe^{IV}\}_2\text{-}\mu\text{-oxo}]^{2-}$ (**2**) with alkanes, alkenes and alcohols demonstrate that the dimer exists in equilibrium with the corresponding $Fe^{V}(O)$ and Fe^{III} (**1**). Such a proposal is based on our previously reported kinetic and mass spectral studies with **2**.[17b] Upon addition of substrate, the dimer (**2**) disproportionates into $Fe^{V}(O)$ and Fe^{III} (**1**), and the $Fe^{V}(O)$ intermediate remains the active oxidant. The primarily formation of the *cis*-hydroxylated product (Table 1; Entry 3) for reactions with *cis*-1,2-dimethylcyclohexane also supports our

This journal is © The Royal Society of Chemistry 20xx

View Article Online
DOI: 10.1039/C7SC02780J

Open Access Article. Published on 04 September 2017. Downloaded on 05/09/2017 01:33:09.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

reported mechanism that involves C-H bond abstraction by $Fe^{V}(O)$ and subsequent formation of hydroxylated product by a "rebound" mechanism.[15b] $H_2^{18}O$ labelling experiments with styrene and adamantane results in the formation of more than 90% ^{18}O-labelled epoxide and hydroxylated product respectively which clearly indicates water is the primary oxygen atom source (Fig. 2).

$$1 + [Ru(bpy)_3]^{2+} + [Co(NH_3)_5Cl]^{2+} + S \xrightarrow{H_2{}^{16}O\ /\ h\nu} S\text{-}^{16}O$$

$$1 + [Ru(bpy)_3]^{2+} + [Co(NH_3)_5Cl]^{2+} + S \xrightarrow{H_2{}^{18}O\ /\ h\nu} S\text{-}^{18}O$$

S = Substrate (alkanes or alkenes)

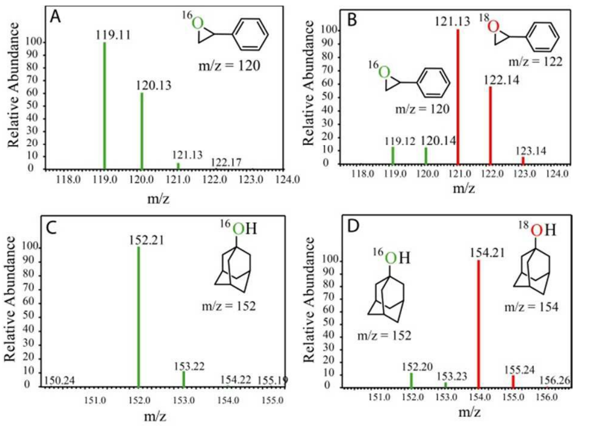
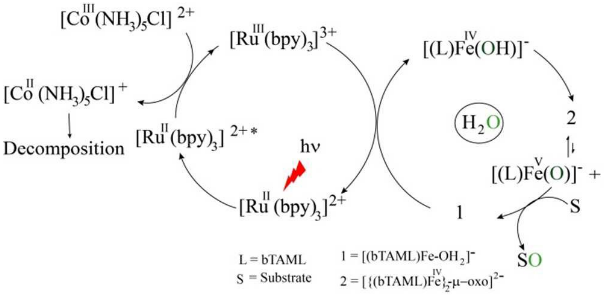


Fig. 2 GC-MS spectra of products after photochemical reaction with A) styrene in $H_2^{16}O$, B) styrene in $H_2^{18}O$,C) adamantane in $H_2^{16}O$, D) adamantane in $H_2^{18}O$.

Proposed Photocatalytic Reaction Cycle

Finally, on the basis of product analysis, UV-vis spectroscopy, ^{18}O-labelling experiments, mass analysis and previously reported observations, we propose the following catalytic cycle for photochemical oxygenation reaction (Scheme 2). In water, Fe^{III}-bTAML (**1**) upon irradiation with light (3W blue LED, 440nm) in presence of photosensitizer $[Ru^{II}(bpy)_3]^{2+}$ and electron acceptor $[Co^{III}(NH_3)_5Cl]^{2+}$ gets oxidized to $[(bTAML)Fe^{IV}\text{-}OH]^{-}$ which immediately gets converted into dimer **2**. Upon addition of substrate, the dimer disproportionates to the $Fe^{V}(O)$ and Fe^{III} (**1**). For hydroxylation reaction, the mechanism likely involves a C-H bond abstraction followed by a rebound process to generate the corresponding alcohol. For epoxidation reactions, formation of a radical intermediate upon electrophilic attack of the $Fe^{V}(O)$ onto the alkene followed by a fast ring closing step is expected.[17b]

Before concluding, one important point is worth noting. Irradiation with visible and UV light has been shown to alter the reactivity of intermediates such as $[(corrole)Fe^{IV}\}_2\text{-}\mu\text{-}oxo]$, $[Fe^{IV}(O)(MePy_2tacn)]^{2+}$ and cofacial bis-porphyrin-diiron(III)-μ-oxo complexes as has been reported by Newcomb et al.[21b], Lloret-Fillol et al.[13] and Nocera et al.[21a] respectively. For Fe^{IV} intermediates, light was shown to disproportionate $[(corrole)Fe^{IV}\}_2\text{-}\mu\text{-}oxo]$ to form the corresponding $[(corrole)Fe^{V}(O)]$ hence increasing its reactivity. For the corresponding $[Fe^{IV}(O)(MePy_2tacn)]^{2+}$, the increase in reactivity was explained due to the formation of an excited state *via* spin change. Such possibility of rate enhancements in the reactivity of **2** due to the presence of light clearly exists and is currently being investigated.



Scheme 2 Proposed reaction mechanism.

Conclusions

In conclusion, we have demonstrated the first example of an iron-complex catalysed photocatalytic hydroxylation and epoxidation reaction with variety of substrates using water as the oxygen source. The $[\{(bTAML)Fe^{IV}\}_2(\mu\text{-}O)]^{2-}$ (**2**) dimer, produced by oxidative activation of water molecule, remains the active oxidant and results in hydroxylation or epoxidation with such high selectivity. ^{18}O-labelling experiments support a metal based selective and controlled oxygenation of substrates having C-H and C=C bonds. Although the reactivity of this photochemical system is lower as compared to the Fe^{III}-bTAML/NaOCl system and the use of $[Co(NH_3)_5Cl]^{2+}$ as the electron acceptor is not optimal, we believe that conjugating complex **1** to a light harvesting system can increase its efficiency many-fold. Such work is being attempted currently in our laboratory.

Experimental Section

General Procedure for the Photocatalytic Hydroxylation Reactions

The photocatalytic oxidation of alkanes were carried out under argon atmosphere in acetonitrile and phosphate buffer (pH 10, 10 mM) (3:2 v/v) mixed solvent. The reaction solution (1.0 mL) containing catalyst **1** (1.0×10^{-4}M) $[Ru(bpy)_3]Cl_2.6H_2O$ (2.0×10^{-3}M), $[Co(NH_3)_5Cl]Cl_2$ (2.0×10^{-2}M) and substrate (3.0×10^{-3} M) was irradiated with a blue LED light source (3W, 440 nm) and stirred for 40 mins at room temperature. The temperature was kept constant by using a water circulating system during the whole reaction. The final reaction mixture was extracted with dichloromethane (five times with 2 mL of dichloromethane each time) and dried over Na_2SO_4. After concentrating the reaction solution by purging with nitrogen gas, product was identified and quantified by GC-MS. Control experiments were performed at the same condition as mentioned above.

General Procedure for the Photocatalytic Epoxidation Reactions

Chemical Science Accepted Manuscript

View Article Online
DOI: 10.1039/C7SC02780J

Open Access Article. Published on 04 September 2017. Downloaded on 05/09/2017 01:33:09.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

The photocatalytic epoxidation of alkenes were carried out in acetonitrile and phosphate buffer (pH 10, 10 mM) (3:2 v/v) mixed solvent. The reaction solution (1.0 mL) containing catalyst **1** (1.0×10^{-4} M) $[Ru(bpy)_3]Cl_2.6H_2O$ (2.0×10^{-3} M), $[Co(NH_3)_5Cl]Cl_2$ (2.0×10^{-2} M) and substrate (5.0×10^{-3} M) was irradiated with a blue LED light source (3W, 440 nm) and stirred for 40 min at room temperature (27^{o}C). The temperature was kept constant by using a water circulating system during the whole reaction. After 40 mins, reaction mixture was extracted with dichloromethane (five times with 2 mL of dichloromethane each time) and dried over Na_2SO_4. After concentrating the reaction solution by purging with nitrogen gas, product was identified and quantified using GC-MS.

^{18}O-labelling Experiment

The ^{18}O-labelling experiments were carried out for the photochemical oxidation of styrene, adamantane, *cis*-1,2-dimethylcyclohexane and ambroxide. A mixture of acetonitrile and $H_2{}^{18}O$ (3:2 v/v) solution containing catalyst **1** (1.0×10^{-4} M), $[Ru(bpy)_3]Cl_2.6H_2O$ (2.0×10^{-3} M), $[Co(NH_3)_5Cl]Cl_2$ (2.0×10^{-2} M) and substrates (styrene, adamantane, *cis*-1,2-dimethylcyclohexane and ambroxide) (5.0×10^{-3} M) were stirred and irradiated with light (3W Blue LED, 440 nm) for 40 mins at room temperature. The resulted solution was extracted with dichloromethane and products were analyzed by GC-MS.

UV-vis Experiment

The photochemical generation of $[\{(bTAML)Fe^{IV}\}_2\text{-}\mu\text{-oxo}]^{2-}$ (**2**) was observed in UV-vis spectroscopy. A solution mixture of acetonitrile and phosphate buffer (3:2) containing catalyst (1.0×10^{-4} M), $[Ru(bpy)_3]Cl_2.6H_2O$ (2.0×10^{-5} M) and $[Co(NH_3)_5Cl]Cl_2$ (6.0×10^{-4} M) were taken in to a 1.0 cm (path length) quartz cuvette and spectra was recorded at 0, 1 and 3 mins of photoirradiation with a blue LED light source (3W, 440 nm). The chemical formation of $[\{(bTAML)Fe^{IV}\}_2\text{-}\mu\text{-oxo}]^{2-}$ (**2**) was also examined from changes in the absorption spectra of solution mixture of acetonitrile and phosphate buffer (3:2 v/v) containing catalyst (**1**) and NaOCl (0.5 equivalent) (Fig. S5†).

Acknowledgements

S.S.G. acknowledges SERB, New Delhi (Grant no EMR/2014/00016) and IISER-Kolkata (“Start-up Grant”) for funding. K.K.S. and B.C. acknowledge UGC-New Delhi for fellowship.

Notes and references

1 (a) N. S. Lewis and D. G. Nocera, *Proc. Natl. Acad. Sci. U. S. A.*, 2006, **103**, 15729-15735; (b) A. Magnuson, M. Anderlund, O. Johansson, P. Lindblad, R. Lomoth, T. Polivka, S. Ott, K. Stensjö, S. Styring, V. Sundström and L. Hamarström, *Acc. Chem. Res.*, 2009, **42**, 1899-1909.

2 (a) B. Loll, J. Kern, W. Saenger, A. Zouni and J. Biesiadka, *Nature*, 2005, **438**, 1040-1044; (b) J. P. McEvoy and G. W. Brudvig, *Chem. Rev.*, 2006, **106**, 4455-4483; (c) J. Barber, *Chem. Soc. Rev.*, 2009, **38**, 185-196.

3 (a) K. N. Ferreira, T. M. Iverson, K. Maghlaoui, J. Barber and S. Iwata, *Science*, 2004, **303**, 1831-1838; (b) J. Yano, J. Kern, K. Sauer, M. J. Latimer, Y. Pushkar, J. Biesiadka, B. Loll, W. Saenger, J. Messinger, A. Zouni and V. K. Yachandra, *Science*, 2006, **314**, 821-825.

4 (a) B. Meunier, S. P. de Visser and S. Shaik, *Chem. Rev.,* 2004, **104**, 3947-3980; (b) M. Costas, M. P. Mehn, M. P. Jensen and L. Que, Jr., *Chem. Rev.,* 2004, **104**, 939-986; (c) C. Krebs, D. G. Fujimori, C. T. Walsh and J. M. Bollinger, Jr., *Acc. Chem. Res.,* 2007, **40**, 484-492; (d) W. Nam, *Acc. Chem. Res.* 2007, **40**, 522-531; (e) L. Que, Jr. and W. B. Tolman, *Nature*, 2008, **455**, 333-340; (g) L. Shu, J. C. Nesheim, K. Kauffmann, E. Munck, J. D. Lipscomb and L. Que, Jr., *Science*, 1997, **275**, 515-518; (h) M. Costas, J. -U. Rohde, A. Stubna, R. Y. N. Ho, L. Quaroni, E. Munck and L. Que, Jr., *J. Am. Chem. Soc.,* 2001, **123**, 12931-12932.

5 H. Inoue, M. Sumitani, A. Sekita and M. Hida, *J. Chem. Soc., Chem. Commun.*, 1987, 1681-1682.

6 (a) D. W. Low, J. R Winkler and H. B. Gray, *J. Am. Chem. Soc.,* 1996, **118**, 117-120; (b) J. Berglund, T. Pascher, J. R. Winkler and H. B. Gray, *J. Am. Chem. Soc.,* 1997, **119**, 2464-2469.

7 (a) S. Funyu, T. Isobe, S. Takagi, D. A. Tryk and H. Inoue, *J. Am. Chem. Soc.,* 2003, **125**, 5734-5740; (b) F. Li, M. Yu, Y. Jiang, F. Huang, Y. Li, B. Zhanga and L. Sun, *Chem. Commun.,* 2011, **47**, 8949-8951; (c) D. Kalita, B. Radaram, B. Brooks, P. P. Kannam and X. Zhao, *ChemCatChem.*, 2011, **3**, 571-573; (d) P. Guillo, O. Hamelin, P. Batat, G. Jonusauskas, N. D. McClenaghan and S. Ménage, *Inorg. Chem.*, 2012, **51**, 2222-2230; (e) D. Chao and W. F. Fu, *Chem. Commun.,* 2013, **49**, 3872-3874; (f) T. V. Pho, M. V. Sheridan, Z. A. Morseth, B. D. Sherman,T. J. Meyer, J. M. Papanikolas, K. S. Schanze and J. R. Reynolds, *ACS Appl. Mater. Interfaces,* 2016, **8**, 9125-9133; (g) L. Bai, F. Li, Y. Wang, H. Li, X. Jianga and L. Sun, *Chem. Commun.,* 2016, **52**, 9711-9714.

8 S. Ohzu, T. Ishizuka, Y. Hirai, S. Fukuzumi, and T. Kojima, *Chem.- Eur. J.,* 2013, **19**, 1563-1567.

9 (a) S. Fukuzumi, T. Kishi, H. Kotani, Y.-M. Lee and W. Nam, *Nat. Chem.,* 2011, **3**, 38-41; (b) S. Fukuzumi, T. Mizuno and T. Ojiri, *Chem. Eur. J.,* 2012, **18**, 15794-15804.

10 (a) X. Wu, X. Yang, Y. M. Lee, W. Nam and L. Sun, *Chem. Commun.,* 2015, **51**, 4013-4016; (b) D. Shen, C. Saracini, Y.-M. Lee, W. Sun, S. Fukuzumi and W. Nam, *J. Am. Chem. Soc.*, 2016, **138**, 15857-15860; (c) G. Chen, L. Chen, L. Ma, H.-K. Kwong and T.-C. Lau, *Chem. Commun.*, 2016, **52**, 9271-9274.

11 (a) A. C. Rosenzweig, C. A. Frederick, S. J. Lippard and P. Nordlund, *Nature*, 1993, **336**, 537-543; (b) R. L. Lieberman and A. C. Rosenzweig, *Nature*, 2005, **434**, 177-182; (c) I.G. Denisov, T.M. Makris, S.G. Sligar and I. Schlichting, *Chem. Rev.*, 2005, **105**, 2253-2278; (d) J. Rittle and M.T. Green, *Science*,2010, **330**, 933-937.

12 H. Kotani, T. Suenobu, Y. -M. Lee, W. Nam and S. Fukuzumi, *J. Am. Chem. Soc.,* 2011, **133**, 3249-3251.

13 A. Company, G. Sabenya, M. Gonza´lez-Be´jar, L. Go´mez, M. Cle´mancey, G. Blondin, A. J. Jasniewski, M. Puri, W. R. Browne, J. Latour, L. Que, Jr., M. Costas, J. Pe´rez-Prieto and J. Lloret-Fillol, *J. Am. Chem. Soc.*, 2014, **136**, 4624-4633.

14 (a) S. Sen Gupta, M. Stadler, C. A. Noser, A. Ghosh, B. Steinhoff, D. Lenoir, C. P. Horwitz, K.-W. Schraman and T. J. Collins, *Science,* 2002, **296**, 326-328; (b) T. J. Collins, *Acc. Chem. Res.*, 2002, **35**, 782-790; (c) T. J. Collins, *Acc. Chem. Res.*, 1994, **27**, 279-285; (d) B. C. Ellis, C. T. Tran, M. A. Denardo, A. Fischer, A. D. Ryabov and T. J. Collins, *J. Am. Chem. Soc.*, 2009, **131**, 18052-18053; (e) C. Panda, M. Ghosh, T. Panda, R. Banerjee and S. Sen Gupta, *Chem. Commun.,* 2011, **47**, 8016-8018.

15 (a) F. T. de Oliveira, A. Chanda, D. Banerjee, X. Shan, S. Mondal, L. Que, Jr., E. L. Bominaar, E. Münck and T. J. Collins, *Science,* 2007, **315**, 835-838; (b) M. Ghosh, K. K. Singh, C. Panda, A. Weitz, M. P. Hendrich, T. J. Collins, B. B. Dhar and S. Sen Gupta, *J. Am. Chem.*

Chemical Science Accepted Manuscript

View Article Online
DOI: 10.1039/C7SC02780J

Open Access Article. Published on 04 September 2017. Downloaded on 05/09/2017 01:33:09.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Soc., 2014, **136**, 9524-9527; (c) S. Pattanayak, A. Rana, A. J. Jasniewski, K. K. Singh, A. Weitz, M. Hendrich, L. Que Jr., A. Dey and S. Sen Gupta, 2017, *Inorg. Chem.*, 2017, **56**, 6352−6361; (d) S. Pattanayak, D. R. Chowduri, B. Garai, K. K. Singh, A. Paul, B. B. Dhar and S. Sen. Gupta, *Chem. Eur. J.*, 2017, **23**, 3414-3424.

16 C. Panda, J. Debgupta, D. Diaz Diaz, K. K. Singh, S. Sen Gupta and B. B. Dhar, *J. Am. Chem. Soc.*, 2014, **136**, 12273-12282.

17 (a) K. K. Singh, M. k. Tiwari, M Ghosh, C. Panda, A. Weitz, M. P. Hendrich, B. B. Dhar, K. Vanka, and S. Sen Gupta, *Inorg. Chem.*,2015, **54**, 1535-1542; (b) K. K. Singh, M. k. Tiwari, B. B. Dhar, K. Vanka and S. Sen Gupta, *Inorg. Chem.*, 2015, **54**, 6112-6121.

18 M. Ghosh, Y. L. K. Nikhil, B. B. Dhar and S. Sen Gupta*, Inorg. Chem.*, 2015, **54**, 11792-11798.

19 S. Jana, M. Ghosh, M. Ambule and S. Sen Gupta, *Org. Lett*. 2017, **19**, 746−749.

20 K. Chen, A. Eschenmoser and P. S. Baran, *Angew. Chem. Int. Ed*., 2009, **48**, 9705-9708.

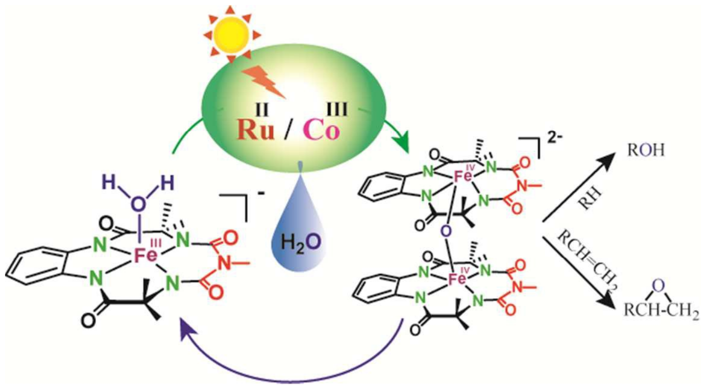
21 (a) J. Rosenthal, J. Bachman, J. L. Dempsey, A. J. Esswein, T. G. Gray, J. M. Hodgkiss, D. R. Manke, T. D. Luckett, B. J. Pistorio, A. S. Veige and D. G. Nocera, *Coord. Chem. Rev.,* 2005, **249**, 1316–1326; (b) D. N. Harischandra, G. Lowery, R. Zhang and M. Newcomb, *Org. Lett*., 2009, **11**, 2089-2092.

22 K.-B. Cho, H. Hirao, S. Shaik and W. Nam, *Chem. Soc. Rev*., 2016, **45**, 1197-1210.

Chemical Science Accepted Manuscript

View Article Online
DOI: 10.1039/C7SC02780J

TOC: Selective photocatalytic hydroxylation and epoxidation reaction by an iron complex using water as the oxygen source.



Open Access Article. Published on 04 September 2017. Downloaded on 05/09/2017 01:33:09.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.

Chemical Science Accepted Manuscript