



## Ambiphilicity of a mononuclear cobalt(III) superoxo complex†

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**Addition of HOTf to a mixture of Co<sup>III</sup>(BDPP)(O<sub>2</sub><sup>•</sup>) (1, H<sub>2</sub>BDPP = 2,6-bis((2-(S)-diphenylhydroxymethyl-1-pyrrolidinyl)methyl)pyridine) and Cp<sup>\*</sup><sub>2</sub>Fe produced H<sub>2</sub>O<sub>2</sub> in high yield implying formation of Co<sup>III</sup>(BDP-P)(OOH) (3), and reaction of Sc(OTf)<sub>3</sub> with the same mixture gave a peroxo-bridged Co<sup>III</sup>/Sc<sup>III</sup> 5. These findings demonstrate the ambiphilic property of Co<sup>III</sup>-superoxo 1.**

Metal-superoxo species are often believed to be the first intermediate following dioxygen (O<sub>2</sub>) association in the catalytic cycle of O<sub>2</sub> activating metalloenzymes.<sup>1</sup> Despite intensive work in the past, the chemistry of metal-superoxo complexes remains largely unexplored, and hence attracts significant attention from chemists and biochemists.<sup>2</sup> *Inter alia*, metal-superoxo intermediates can react with NO<sup>•</sup> or organic radicals to furnish metal-peroxynitrite<sup>3</sup> and -alkylperoxo<sup>4</sup> complexes *via* radical coupling. Furthermore, they exhibit considerable electrophilicity as indicated by their capability of performing hydrogen atom abstraction (HAA)<sup>5</sup> from weak C–H and O–H bonds and oxygen atom transfer<sup>6</sup> to triphenylphosphine or thiol anisoles. On the other hand, they can initiate deformylation processes when treated with 2-phenylpropionaldehyde, thereby revealing their nucleophilic character.<sup>7,8</sup> Besides the aforementioned well know activities, in a given elementary transformation metal-superoxo intermediates may function not only as an electrophile but also as a nucleophile. In fact, ambiphilicity

of metal-superoxo species has been postulated in a series of theoretical and experimental investigations including O<sub>2</sub> activation catalyzed by  $\alpha$ -ketoglutarate dependent dioxygenases,<sup>9</sup> and by Cu, Fe and Co model complexes.<sup>10</sup> Only recently has such ambiphilic property been experimentally confirmed.<sup>8</sup> In our continuing efforts devoted to investigating reactivity of metal-superoxo intermediates, some of us succeeded in preparing a range of homologous Fe<sup>III</sup>-, Co<sup>III</sup>- and Mn<sup>III</sup>-superoxo species by reacting O<sub>2</sub> with the corresponding divalent precursors.<sup>11</sup> It has been shown that these trivalent metal-superoxo complexes can convert into the metal-hydroperoxo complexes *via* HAA. In particular, the reaction of Mn<sup>III</sup>(BDP<sup>BPr</sup>P)(O<sub>2</sub><sup>•</sup>) (H<sub>2</sub>BDP<sup>BPr</sup>P = 2,6-bis((2-(S)-di(4-bromo)-phenylhydroxymethyl-1-pyrrolidinyl)methyl)pyridine) with trifluoroacetic acid (TFA) and Sc(OTf)<sub>3</sub> yields rare examples of Mn<sup>IV</sup>-hydroperoxo complexes, Mn<sup>IV</sup>(BDP<sup>BPr</sup>P)(OOH), and [Mn<sup>IV</sup>( $\mu$ -OO)Sc(OTf)<sub>2</sub>]<sub>n</sub><sup>(3-n)+</sup> as evidenced by the combined spectroscopic and computational studies (Scheme 1).<sup>8</sup> Obviously, these proton- and metal-coupled electron transfer processes provide the first experimental support for the proposed ambiphilicity of metal-superoxo species. In this regard, more examples are desired to fully understand how the ambiphilic property of metal-superoxo species affects their chemical reactivity. To this end, we examined the reaction of a Co<sup>III</sup>-superoxo complex, Co<sup>III</sup>(BDPP)(O<sub>2</sub><sup>•</sup>) (1, H<sub>2</sub>BDPP = 2,6-bis((2-(S)-diphenylhydroxymethyl-1-pyrrolidinyl)methyl)pyridine) with TFA and Sc(OTf)<sub>3</sub> together with external electron donors.

Treating **1** with HOTf in THF at –90 °C gave a gray-green solution attributed to intermediate **2** having two weak absorption bands at 470 and 640 nm, which reached maxima when 1 equiv. of HOTf was added (the inset of Fig. 1). The existence of an isosbestic point at 590 suggested that no intermediate was formed in the course of conversion of **1** to **2** (Fig. 1). Conversely, complex **1** can be retrieved from deprotonation of **2** by 1 equiv. of 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) with a yield of 80% with respect to **1** (Fig. S1, ESI†). Moreover, complex **2** can be obtained from one-electron oxidation of the hydroperoxo complex Co<sup>III</sup>(BDP-P)(OOH) (**3**). Adding equimolar of tris(4-bromophenyl)ammoniumyl hexachloroantimonate, which is often referred to as magic blue, to a THF solution of **3** at –90 °C resulted in a gray-green solution, whose

<sup>a</sup> Department of Chemistry, National Taiwan Normal University, Taipei 11677, Taiwan. E-mail: wzlee@ntnu.edu.tw

<sup>b</sup> Universität Göttingen, Institut für Anorganische Chemie, D-37077 Göttingen, Germany. E-mail: franc.meyer@chemie.uni-goettingen.de

<sup>c</sup> Max-Planck-Institut für Chemische Energiekonversion, Mülheim an der Ruhr D-45470, Germany. E-mail: eckhard.bill@cec.mpg.de

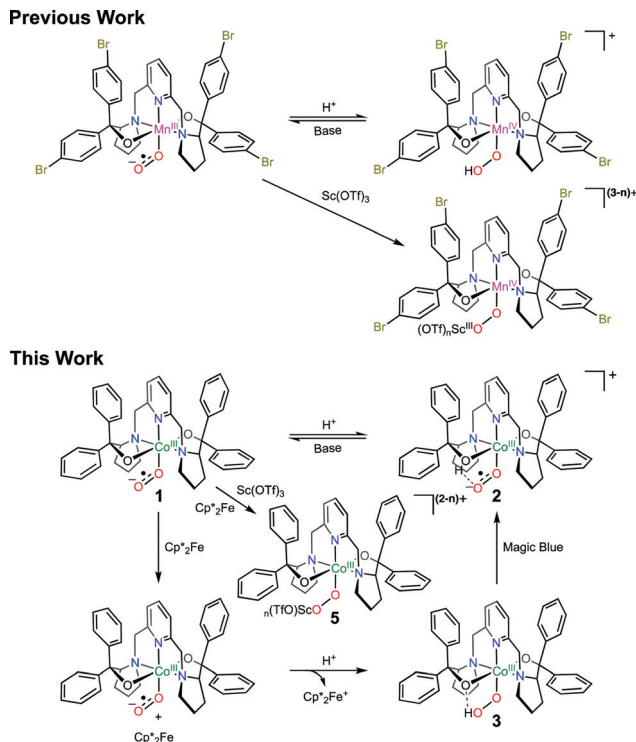
<sup>d</sup> State Key Laboratory of Catalysis, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023, China. E-mail: shengfa.ye@dicp.ac.cn

<sup>e</sup> Max-Planck-Institut für Kohlenforschung, Mülheim an der Ruhr, D-45470, Germany. E-mail: shengfa.ye@kofo.mpg.de

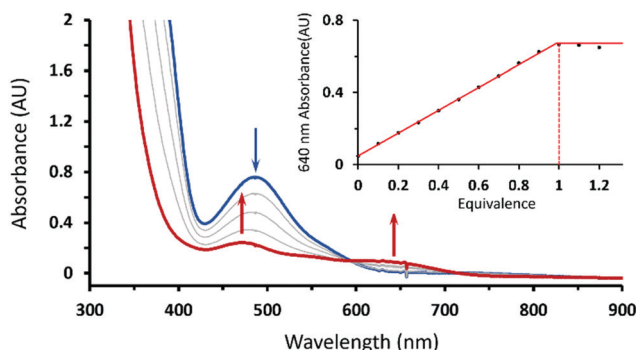
<sup>f</sup> Department of Medicinal and Applied Chemistry, Kaohsiung Medical University, Kaohsiung 807, Taiwan

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Scheme 1 Ambiphilicity of metal-superoxo complexes.

Fig. 1 UV-vis spectral changes of the reaction of **1** (1.0 mM, blue trace) with 1 equiv. of HOTf in THF at  $-90^\circ\text{C}$ . Inset: Titration curve of **1** with HOTf. X-axis: the equivalents of HOTf, Y-axis: the conversion ratio of the absorption peak at 640 nm.

absorption spectrum displayed the same signature features as those found for **2** (Fig. S2, ESI $^\dagger$ ).

To identify the exact nature of the resulting species **2**, we have undertaken detailed spectroscopic characterization and DFT calculations. The EPR measurement of **2** exhibited a spectrum similar to that of **1** ( $A_{\text{Co}} = 18\text{ G}$ ) except for a slightly larger  $^{59}\text{Co}$  hyperfine coupling constant ( $A_{\text{Co}} = 24\text{ G}$ ) seen in Fig. 2, thus indicating that **2** still consists of a  $\text{Co}^{\text{III}}$  center coupled with a radical ligand yielding an overall doublet ground state. The radical ligand thus would be a hydroperoxyl radical or a superoxo having a strong hydrogen bonding interaction with the protonated BDPP $^{2-}$  ligand (Scheme 1) as

Fig. 2 X-band EPR spectra of (A) **1** ( $g_1 = 2.098$ ,  $A_{\text{Co}} = 18\text{ G}$ ); (B) **1** with 1 equiv. of HOTf ( $g_1 = 2.066$ ,  $A_{\text{Co}} = 24\text{ G}$ ); (C) **1** with 1 equiv. of DOTf ( $g_1 = 2.064$ ,  $A_{\text{Co}} = 24\text{ G}$ ) and (D) **1** with 1 equiv. of  $\text{Sc}(\text{OTf})_3$  ( $g_1 = 2.066$ ,  $A_{\text{Co}} = 24\text{ G}$ ). Measurement condition:  $T = 77\text{ K}$ ,  $f_{\text{mw}} = 9.6\text{ GHz}$ .

suggested by the crystal structure of **3**. $^{11b}$  However, the EPR spectrum of the product generated by reacting **1** with deuterated triflate acid (DOTf) is almost identical to that of **2** without discernable line broadening, which essentially rules out the possibility of the radical ligand being a hydroperoxyl radical (Fig. 2C). Repeated attempts to obtain the O–O vibrational frequencies of **2** from resonance Raman measurements did not accomplish, largely because **2** has only weak chromophores in the usual UV-vis region (Fig. 1). Consequently, the intensity of the O–O stretching signal is too low to be readily detected.

DFT calculations also suggested the O donor of the BDPP $^{2-}$  ligand to be the favored protonation site of **1**, consistent with experiment. Even when the starting geometry contained a OOH ligand in which the distal H atom forms a hydrogen bond with the BDPP $^{2-}$  ligand, the geometry optimizations invariably shifted the H atom back to the O atom of BDPP $^{2-}$  and eventually converged to **A** (Fig. 3). We also tested the initial geometry without the hydrogen bond by tilting the H atom upward. The computations indeed yielded a  $\text{Co}^{\text{III}}$  center bound to a hydroperoxyl radical ligand (**C**), but **C** lies  $23.2\text{ kcal mol}^{-1}$  higher in energy above **A** (Fig. 3). Moreover, formation of a hydrogen bond between the superoxo motif and the proton of the OH group of the protonated BDPP $^{2-}$  ligand stabilized **A** by  $10.4\text{ kcal mol}^{-1}$  relative to **B** (Fig. 3). Thus, **A** is best deemed as the most appropriate model for **2**.

Alternatively, to transform **1** into the corresponding peroxy product, we then added 1 equiv. of decamethylferrocene ( $\text{Cp}^*_2\text{Fe}$ ) or sodium naphthalenide ( $\text{NaC}_{10}\text{H}_8$ ) to THF solutions of **1** at  $-90^\circ\text{C}$ , but UV-vis measurements suggested that no reactions occurred (Fig. S3 and S4, ESI $^\dagger$ ). Taken together, neither proton nor electron donors alone can realize the superoxo-to-peroxy conversion for **1**.

Interestingly, upon treating a mixture containing equimolar **1** and  $\text{Cp}^*_2\text{Fe}$  with 1 equiv. of HOTf, the color of the reaction solution gradually changed from gray-green to dark green then orange; meanwhile, characteristic features of decamethylferrocenium ( $\text{Cp}^*_2\text{Fe}^+$ ) emerged suggesting that  $\text{Co}^{\text{III}}$ -superoxo **1** was reduced in the presence of both HOTf and  $\text{Cp}^*_2\text{Fe}$  (Fig. 4A).





Fig. 3 Computed models for **2**.

During this process, we did not observe the formation of  $\text{Co}^{\text{III}}$ -hydroperoxo **3**. Instead, the reaction produced 19% of  $\text{H}_2\text{O}_2$  with respect to **1**, as determined by iodometric titration (Fig. S5, ESI<sup>†</sup>). When 2 equiv. of HOTf was added, 42% of  $\text{H}_2\text{O}_2$  was furnished (Fig. S6, ESI<sup>†</sup>). Thus, we reasoned that the aforementioned reaction indeed generates **3**; however, once formed, **3** further reacted with HOTf to produce  $\text{H}_2\text{O}_2$ . On the other hand,

treating **2** with 1 equiv. of  $\text{Cp}^*_2\text{Fe}$  (Fig. 4B) also generated 23% of  $\text{H}_2\text{O}_2$  (Fig. S7, ESI<sup>†</sup>). Therefore, all experimental findings revealed that transformation of **1** to **3** proceeds *via* concerted proton coupled electron transfer, which clearly demonstrated the ambiphilicity of **1**.

Reaction of **1** with  $\text{Sc}(\text{OTf})_3$  in THF at  $-90^\circ\text{C}$  generated a product, which showed nearly identical absorption and EPR spectra to those of **2** (Fig. S8 (ESI<sup>†</sup>) and Fig. 2D). On the basis of these observations, we tentatively suggest that the reaction furnished a  $\text{Co}^{\text{III}}$ -superoxo- $\cdots\text{Sc}^{\text{III}}$  species,  $[\text{Co}(\text{BDPP})(\text{O}_2^{\bullet-})\cdots\text{Sc}(\text{OTf})_n]^{(3-n)+}$  (**4**). Furthermore, addition of  $\text{Sc}(\text{OTf})_3$  to the mixture of **1** and  $\text{Cp}^*_2\text{Fe}$  in THF at  $-90^\circ\text{C}$  afforded a  $\text{Co}^{\text{III}}$ -peroxo- $\text{Sc}^{\text{III}}$  complex,  $[\text{Co}(\text{BDPP})(\mu\text{-OO})\text{Sc}(\text{OTf})_n]^{(2-n)+}$  (**5**), as depicted in Scheme 1 (Fig. S9, ESI<sup>†</sup>). Addition of 2 equiv. of HOTf to the THF solution of **5** produced 76%  $\text{H}_2\text{O}_2$  as quantified by iodometric titration experiments (Fig. S10, ESI<sup>†</sup>). Formation of  $\text{H}_2\text{O}_2$  thus strongly supports the identity of peroxo-bridged binuclear **5**. These findings further reinforce the ambiphilic property of **1**.

In comparison with the similar reaction found for  $\text{Mn}^{\text{III}}$  ( $\text{BDP}^{\text{BP}}(\text{O}_2^{\bullet-})$ ) (Scheme 1), the difference can be readily attributed to the much higher oxidation potential of  $\text{Co}^{\text{III}}$  to  $\text{Co}^{\text{IV}}$  than that of  $\text{Mn}^{\text{III}}$  to  $\text{Mn}^{\text{IV}}$ , which can ultimately be rooted back to the distinct effective nuclear charge of low spin  $\text{Co}^{\text{III}}$  compared to high spin  $\text{Mn}^{\text{III}}$  centers. Therefore, formation of an otherwise hydroperoxo O–H bond does not provide a sufficient driving force to trigger an electron transfer from the  $\text{Co}^{\text{III}}$  center to the superoxo ligand. Consequently, the superoxo motif is not electron rich enough to accommodate the incoming proton from HOTf and protonation of the supporting  $\text{BDPP}^{2-}$  ligand is preferred. Therefore, to effect surperoxo-to-peroxo conversion for **1**, an external electron source has to be provided in addition to Brønsted or Lewis acids.

In conclusion, treatment of  $\text{Co}^{\text{III}}$ -superoxo **1** with HOTf and  $\text{Sc}(\text{OTf})_3$  afforded the ligand-protonated  $\text{Co}^{\text{III}}$ -superoxo **2** with a hydrogen bond formed between the  $\text{O}_2^{\bullet-}$  motif and the protonated  $\text{BDPP}^{2-}$  ligand and a superoxo-bridged binuclear  $\text{Co}^{\text{III}}/\text{Sc}^{\text{III}}$  **4**, and  $\text{Co}^{\text{III}}$ -superoxo **1** can be regenerated from deprotonation of **2** by DBU. However, addition of 2 equiv. of HOTf into the reaction mixture of **1** and  $\text{Cp}^*_2\text{Fe}$  produced 42% of  $\text{H}_2\text{O}_2$  suggesting the formation of  $\text{Co}^{\text{III}}$ -hydroperoxo **3**, and the reaction of  $\text{Sc}(\text{OTf})_3$  with **1** in the presence of  $\text{Cp}^*_2\text{Fe}$  gave a peroxo-bridged binuclear  $\text{Co}^{\text{III}}/\text{Sc}^{\text{III}}$  **5**. These findings provided strong experimental support for the ambiphilic property of  $\text{Co}^{\text{III}}$ -superoxo **1**. Interestingly, the ligand-protonated  $\text{Co}^{\text{III}}$ -superoxo **2** can be prepared from one-electron oxidation of  $\text{Co}^{\text{III}}$ -hydroperoxo **3**. The unveiled results underline the critical property of ambiphilicity for metal-superoxo species and direct us to design further investigation strategies towards better understanding  $\text{O}_2$  activation processes carried out by metalloenzymes and related catalysts.

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Fig. 4 UV-vis spectral changes of addition of (A) 1 equiv. of HOTf into a solution of **1** (1.0 mM) in the presence of 1 equiv. of  $\text{Cp}^*_2\text{Fe}$  and (B) 1 equiv. of  $\text{Cp}^*_2\text{Fe}$  into a solution of **2** (1.0 mM) in THF at  $-90^\circ\text{C}$ .



## Conflicts of interest

There are no conflicts to declare.

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