Chemical Science

EDGE ARTICLE

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Cite this: Chem. Sci., 2018, 9, 1989

Received 2nd November 2017 Accepted 12th January 2018

DOI: 10.1039/c7sc04732k

rsc.li/chemical-science

Introduction

Cytochrome c oxidase (CcO) is the terminal enzyme in the mitochondrial respiratory chain. CcO consumes most of the molecular oxygen (O₂) processed by living organisms by reducing it to water (H₂O).¹ The four-electron/four-proton reduction process $(O_2 + 4e^- + 4H^+ \rightarrow 2H_2O)$ takes place at the heme a_3 /Cu_B hetero-binuclear active centre of CcO (Fig. 1a).¹⁻⁵ For the catalytic O₂ reduction reaction, the reaction mechanism schematically depicted in Fig. 1b has been proposed.¹⁻³ In the catalytic cycle, the fully reduced heme a_3/Cu_B site (Fe^{II}/Cu^I, compound R) reacts with O2 to form an oxymyoglobin-like superoxo complex of heme a_3 (Fe^{III}-O₂^{-/}/Cu^I, compound A).^{3,6} Compound A is rapidly (~0.5 ms) converted to an oxoferryl intermediate (Fe^{IV}=O/Cu^{II}-OH, compound P) via O-O bond cleavage assisted by H atom injection from a vicinal tyrosine

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A water-soluble supramolecular complex that mimics the heme/copper hetero-binuclear site of cytochrome c oxidase[†]‡

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In mitochondria, cytochrome c oxidase (CcO) catalyses the reduction of oxygen (O_2) to water by using a heme/copper hetero-binuclear active site. Here we report a highly efficient supramolecular approach for the construction of a water-soluble biomimetic model for the active site of CcO. A tridentate copper(II) complex was fixed onto 5,10,15,20-tetrakis(4-sulfonatophenyl)porphinatoiron(III) (Fe^{III}TPPS) through supramolecular complexation between Fe^{III}TPPS and a per-O-methylated β -cyclodextrin dimer linked by a (2,2':6',2"-terpyridyl)copper(II) complex (Cu^{II}TerpyCD₂). The reduced Fe^{II}TPPS/Cu^ITerpyCD₂ complex reacted with O_2 in an aqueous solution at pH 7 and 25 °C to form a superoxo-type Fe^{III} $-O_2^{-/}$ Cu^{l} complex in a manner similar to CcO. The pH-dependent autoxidation of the O₂ complex suggests that water molecules gathered at the distal Cu site are possibly involved in the $Fe^{III} - O_2^{-}/Cu^{I}$ superoxo complex in an aqueous solution. Electrochemical analysis using a rotating disk electrode demonstrated the role of the FeTPPS/CuTerpyCD₂ hetero-binuclear structure in the catalytic O_2 reduction reaction.

a)

residue.³⁻⁶ Mechanistic investigations have suggested that one or more water molecules near the bound O₂ can facilitate the conversion of compound A to compound P.^{7,8}

To understand the reaction mechanism, synthetic heme/ copper models have been constructed using tetraarylporphinatoiron(II) (PFe^{II}) combined with Cu^I complexes $(Cu^{I}L_{n}, where L is a nitrogen donor ligand; n (coordination)$ number) = 3 or 4).^{4,5} However, upon oxygenation of the PFe^{II} / $Cu^{I}L_{n}$ model systems in anhydrous organic solvents, µ-peroxotype bridged structures, *i.e.*, $PFe^{III}-O_2-Cu^{II}L_n$ complexes, tend to form instead of compound A-like superoxo species.9-12 In native CcO, the μ -peroxo-type bridged structure has not been



R



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HEMISTRY

O2-

Α

OH

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[†] This paper is dedicated to (late) Professor Takashi Ogura.

[†] Electronic supplementary information (ESI) available. See DOI: 10.1039/c7sc04732k

experimentally identified, although it has been proposed as a transitional precursor of compound P.^{3,12,13} The structural differences between the native and model systems (superoxo vs. μ -peroxo)¹⁴ might be attributed to the influence of water.^{7,8,13} A model study by Naruta and co-workers demonstrated that the μ -peroxo complex (PFe^{III}-O₂-Cu^{II}L₃) formed at -70 °C was converted to the superoxo complex (PFe^{III}–O₂^{-/}Cu^IL₃) at -30 °C by the action of water molecules.15 In native CcO, highly ordered water molecules have been detected in the vicinity of heme a₃/Cu_B.^{7,16} A quantum chemical calculation suggested that a water molecule in the vicinity of $Cu_{\rm B}$ decreases the energy barrier of the transformation of compound A to compound P.8 In this context, a water-soluble $PFe^{II}/Cu^{I}L_{n}$ model compound would be useful to investigate the role of water on the reactivity of the Fe/Cu hetero-binuclear complex with O₂. However, very few heme/copper mimics functioning under aqueous conditions have been prepared so far, except for the system constructed in the engineered heme pocket of myoglobin.17,18

In this study, we describe an aqueous synthetic PFe/CuL₃ hetero-binuclear model system built on a porphyrin/ cyclodextrin supramolecular complex (Scheme 1). This system takes advantage of the very stable formation of a selfassembling 1:2complex of 5,10,15,20-tetrakis(4sulfonatophenyl)porphinatoiron (FeTPPS) with per-O-methylated β-cyclodextrins (CDs).¹⁹ We have previously studied the porphyrin/cyclodextrin complexes as simple biomimetic models of heme proteins that function under aqueous conditions,^{20–23} where the molecular cage of per-O-methylated β -CDs provided a microscopic hydrophobic environment for FeTPPS similar to the heme pocket of heme proteins.²⁴ Here, we have synthesised a per-O-methylated β -CD dimer linked by a Cu^{II}-



 $\label{eq:scheme1} \begin{array}{l} \mbox{Scheme1} & \mbox{Preparation of the supramolecular Fe}^{III}\mbox{TPPS}/\mbox{Cu}^{II}\mbox{TerpyCD}_2 \\ \mbox{complex}. \end{array}$

terpyridine complex ($Cu^{II}TerpyCD_2$, Scheme 1) to replicate the distal tridentate Cu_B site of CcO. The structural characterisation of the supramolecular FeTPPS/CuTerpyCD₂ complex and its reactivity towards O₂ are described.

Results and discussion

Synthesis of a water-soluble Fe^{III}/Cu^{II} hetero-binuclear complex

The synthetic route of a supramolecular Fe^{III}TPPS/Cu^{II}TerpyCD₂ complex is shown in Scheme 1 and experimental details are described in (ESI[‡]). Briefly, the terpyridyl ligand was inserted as a linker of the CD dimer (TerpyCD₂) by the reaction of 5,5″-bis(mercaptomethyl)-2,2′:6′,2″-terpyridine with 2,3-monoepoxyper-*O*-methylated β-CD (Epo-*O*Me-β-CD).²⁰ The addition of CuSO₄·5H₂O to TerpyCD₂ in an aqueous solution generated two absorption bands at 336 and 350 nm (Fig. 2a), which corresponded to the ligand to metal charge transfer bands of the terpyridyl-Cu^{II} 1 : 1 complex.²⁵ In the UV-vis titration, a biphasic spectral change was observed (Fig. 2a inset), indicating that the 1 : 2 complex of Cu²⁺ with TerpyCD₂ ($\lambda_{max} = 333$ nm) was first formed and then it was converted to the thermodynamically stable 1 : 1 complex upon further addition of Cu²⁺. The spectral



Fig. 2 Complexation of TerpyCD₂ with Cu²⁺ in aqueous solution. (a) UV-vis spectral change of TerpyCD₂ (33 μ M) upon stepwise addition of CuSO₄ in water at 25 °C. The inset shows changes in absorbances as a function of [CuSO₄]/[TerpyCD₂]. The biphasic titration curve indicates transient formation of the 1:2 complex before forming the thermodynamically stable 1:1 complex (Cu^{II}TerpyCD₂) during the titration. (b) Electrospray mass spectrum (positive mode) of the 1:1 mixture of TerpyCD₂ and CuSO₄ in H₂O. The inset shows the simulated isotope distribution patterns for the [Cu^{II}TerpyCD₂]²⁺ complex.

changes were completed at one equivalent of Cu^{2+} . The complexation between TerpyCD₂ and Cu^{2+} was also monitored by electrospray mass spectroscopy. In the 1 : 1 mixture of $CuSO_4$ and TerpyCD₂ in H₂O, the 1 : 1 complex ($Cu^{II}TerpyCD_2$) was observed at m/z 1577 and 1059 (Fig. 2b), which corresponds to $[Cu^{II}TerpyCD_2]^{2+}$ and $[(H_2O)Cu^{II}TerpyCD_2 + H]^{3+}$, respectively. The 1 : 2 complex was also detected as a small ion peak when the 1 : 2 mixture of $CuSO_4$ and TerpyCD₂ in H₂O was analysed by electrospray mass spectroscopy (data not shown).

The Cu^{II}TerpyCD₂ complex was then titrated with Fe^{III}TPPS (Fig. 3a). The Soret band of Fe^{III}TPPS shifted from 408 nm to 418 nm, indicating that a μ-oxo-dimer of Fe^{III}TPPS dissociated to the monomeric monohydroxo complex (Fe^{III}(OH⁻)TPPS)¹⁹ through interaction with Cu^{II}TerpyCD₂. The spectral changes were completed upon addition of one equivalent of $Cu^{II}TerpyCD_2$ to $Fe^{III}TPPS$, indicating a quantitative 1:1 complexation. The obtained complex was then analysed by electrospray mass spectroscopy. The two main ion peaks were detected at m/z 1385 and 2078 as tri- and di-anionic species, respectively (Fig. 3b). Considering total charges of the complexes, the peaks at m/z 1385 and 2078 were assigned to the μ -oxo and μ -hydroxo Fe^{III}TPPS/Cu^{II}TerpyCD₂ complexes, *i.e.*, [PFe^{III}-O-Cu^{II}CD₂]³⁻ and [PFe^{III}-(OH)-Cu^{II}CD₂]²⁻, respectively. The assignments were confirmed by isotope pattern simulations (Fig. 3b inset). Evidence of the µ-oxo (Fe^{III}-O-Cu^{II})





Characterisation of an O₂ adduct of the Fe^{II}/Cu^I complex

The Fe^{III}TPPS/Cu^{II}TerpyCD₂ complex was reduced with excess sodium dithionite (Na₂S₂O₄) to obtain the fully reduced [PFe^{II}/Cu^ICD₂]³⁻ complex in the deoxy state in an O₂-free solution (λ_{max} at 430, 554, and 601 nm, Fig. 5, black line). The dissolved O₂ in the solution was completely consumed by excess dithionite, and the redox potential of dithionite is negative



Fig. 3 Characterisation of the supramolecular Fe^{III}TPPS/Cu^{II}TerpyCD₂ complex. (a) UV-vis spectral changes of Fe^{III}TPPS (3 μ M) upon stepwise addition of Cu^{II}TerpyCD₂ in 0.05 M phosphate buffer at pH 7.0 and 25 °C. The inset shows the changes in absorbance at 418 nm as a function of the molar ratio ([Cu^{II}TerpyCD₂]/[Fe^{III}TPPS]). (b) Electrospray mass spectrum (negative mode) of the 1 : 1 mixture of Fe^{III}TPPS and Cu^{II}TerPyCD₂ in H₂O. The inset shows the simulated isotope distribution patterns for the μ -oxo- and μ -hydroxo-bridged Fe^{III}TPPS/Cu^{II}TerpyCD₂ complexes.

Fig. 4 Optimized molecular structures of the FeTPPS/CuTerpyCD₂ inclusion complexes in the Fe/Cu non-bridged and Fe/Cu oxobridged forms. The models are shown from both side and top views. Hydrogen atoms are omitted for clarity. Molecular mechanics calculations were carried out using CONFLEX/MM3 (extensive search) parameters in Scigress version 2.2.1 software program (Fujitsu).



Fig. 5 UV-vis spectra of the Fe^{III}TPPS/Cu^{II}TerpyCD₂ (green) and its reduced Fe^{II}TPPS/Cu^{II}TerpyCD₂ complexes in the deoxy (black), oxy (blue) and CO (red) forms in 0.05 M phosphate buffer at pH 7.0 and 25 °C. The inset shows the resonance Raman spectra of the Fe^{III}TPPS/Cu^{II}TerpyCD₂ complexes obtained by excitation at 405 nm under ¹⁶O₂ atmosphere (black), ¹⁸O₂ atmosphere (red), and the difference ¹⁶O₂–¹⁸O₂ (blue). Conditions: 0.05 M phosphate buffer at pH 7.0, 77 K (frozen solution).

enough to reduce both Fe^{III} and Cu^{II} to Fe^{II} and Cu^{I. 29,30} After the reduction, the solution was passed through a short gel-filtration column (Sephadex G-25) under aerobic conditions to remove excess $S_2O_4^{2-}$ and its oxidised products. The UV-vis spectrum of the resulting solution showed absorption maxima at 419 nm and 542 nm (Fig. 5, blue line); the Q-band was very different from that of the oxidised state (Fe^{III}TPPS/Cu^{II}TerpyCD₂, λ_{max} (Q-band) = 570 nm, green line) and similar to that of the O₂ complex of the previously reported Fe^{III}TPPS/CD dimer system.²⁰ Introduction of CO gas into the solution caused further spectral changes with absorption maxima at 418 nm and 535 nm (Fig. 5, red line). The sharp Soret band is characteristic of the CO-Fe^{II}TPPS complex,²⁰ indicating that a ligand exchange from O₂ to CO occurs in this system.

The O₂ complex was further characterized by EPR and resonance Raman (rR) spectroscopic analyses. The EPR spectrum of the O₂ adduct of Fe^{II}TPPS/Cu^ITerpyCD₂ measured at 77 K was completely silent (Fig. S4‡), which was consistent with the spectra of other O_2 complexes of the PFe^{II}/Cu^IL_n heterobinuclear systems.³¹⁻³³ The rR analysis at 77 K (frozen solution of the O2 adduct) using 405 nm excitation revealed a characteristic band at 578 cm⁻¹, which shifted to 551 cm⁻¹ under an ¹⁸O₂ atmosphere (Fig. 5 inset). The isotope shift ($\Delta \nu = 27 \text{ cm}^{-1}$) corresponds to the expected value for the $v_{\rm Fe-O}$ stretching mode.¹⁵ The wavenumber is quite similar to those of the PFe^{III}- $O_2^{-}/Cu^{I}L_n$ superoxo complexes in the previously reported native34 and synthetic model systems as listed in Table 1.14,15,35 Furthermore, the O–O bond stretching mode (ν_{O-O}) was not enhanced in this system. This is a relevant observation as the $v_{\rm O-O}$ band is often observed in the range of 750–900 cm⁻¹ in the PFe^{III}–O₂–Cu^{II}L_n μ -peroxo complexes, but not in the case of the Fe^{III}–O₂^{-/}Cu^IL_n superoxo complexes (Table 1).^{14,15,35–37} Based on the rR data, the configuration of the present O2-adduct of Fe^{II}TPPS/Cu^ITerpyCD₂ is assigned as the superoxo-type PFe^{III}-

Table 1 The Fe–O and O–O stretching frequencies ($\nu_{\text{Fe}-\text{O}}/\text{cm}^{-1}$, $\nu_{\text{O}-\text{O}}/\text{cm}^{-1}$) in the O₂ complexes of native CcO and synthetic PFe/CuL_n compounds

	$\nu_{\rm Fe-O}/{\rm cm}^{-1} {}^{16}{\rm O}_2$ (${}^{18}{\rm O}_2$)	$\nu_{\rm O-O}/{\rm cm}^{-1}$ ¹⁶ O ₂ (¹⁸ O ₂)	Medium
Superoxo group			
CcO (beef heart) ^{<i>a</i>}	572 (548)	_	H ₂ O, pH 7.4
CcO (bovine heart) ^b	571 (545)	_	H ₂ O, pH 7.2
Fe/Cu[NMePr] ^c	570 (544)	_	CH_2Cl_2
FeCuArOH ^d	575 (549)	_	DMF
[(L ^{N4-OH})Cu/	574 (548)	_	CH ₃ CN/THF
Fe(TMPIm)] ^e			
FeTPPS/	578 (551)	_	H ₂ O, pH 7.0
CuTerpyCD ₂ ^f			
μ-Peroxo group			
LS-4DCHIm ^g	585, 591 (564)	876, 863 (820)	MeTHF
[L ^{OH} Fe/Cu] ^h	_	799 (752)	CH ₃ CN/
			toluene
[(L ^{N4-OH})Cu/ Fe(TMPIm)] ^e	611 (584)	787, 803 (751)	CH ₃ CN/THF
^{<i>a</i>} Ref. 34. ^{<i>b</i>} Ref. 6. ^{<i>c</i>} 1 ^{<i>h</i>} Ref. 36.	Ref. 14. ^d Ref. 35.	^e Ref. 15. ^f This w	ork. ^g Ref. 37.

 $O_2^{-}/Cu^{I}L_3$ complex (Fig. 6), which is the same coordination mode as in compound A of native CcO.^{3,14,38}

The superoxo PFe^{III}-O₂^{-/}Cu^ICD₂ complex was gradually converted to another state when the solution was allowed to stand at pH 7 and 25 °C under aerobic conditions (Fig. 7). The absorption spectra showed several isosbestic points and the final spectrum (shown as a green line in Fig. 7) was coincident to that of the oxidised Fe^{III}TPPS/Cu^{II}TerpyCD₂ complex (Fig. 5). EPR spectral changes also support oxidation of the superoxo $PFe^{III}-O_2^{-}/Cu^{I}CD_2$ species to the $Fe^{III}TPPS/Cu^{II}TerpyCD_2$ complex (Fig. S4^{\ddagger}). The first-order rate constants (k_{obs}) for the conversion were determined from the absorbance change at various pH conditions. Interestingly, the superoxo complex was more rapidly converted at lower pH (Fig. 7 inset). The linear pH/ $\log k_{obs}$ dependency at pH 7-10 (slope = -0.11) suggests that the conversion is partially accelerated by a proton-coupled process.³⁹ Collman *et al.* have reported that the rate of the O₂ reduction catalysed by their PFe/CuLn model complex is pHdependent and increases at lower pH.40 We have previously reported that the autoxidation rate of the O_2 complex in the PFe^{II}/ CD dimer system without any distal functions is independent of pH in the neutral pH region (7-10), whereas it is accelerated at



Fig. 6 Oxygenation of the Fe^{II}TPPS/Cu^ITerpyCD₂ complex to form a superoxo $PFe^{III}-O_2^{-}/Cu^{I}CD_2$ complex.



Fig. 7 Spontaneous conversion of the superoxo ($PFe^{III}-O_2^{-}/Cu^{I}CD_2$) complex in 0.05 M phosphate buffer at pH 7.0 and 25 °C. The spectrum was recorded at 15 s intervals. The inset shows the logarithmic first-order rate constants (k_{obs}) for the conversion as a function of the pH of the solution.

pH below 6 and above 10.²⁴ Therefore, the pH-rate dependency at the neutral pH region suggests that the water molecules gathered at the distal Cu site promote the conversion of the $PFe^{III}-O_2^{-}/Cu^{I}CD_2$ complex to the oxidised $PFe^{III}-(OH)-Cu^{II}CD_2$ complex.

The quantum chemical study on native CcO^8 proposes that a water molecule coordinating to the distal copper ion facilitates the conversion of compound A to compound P through the formation of the hydroperoxo Fe^{III}-OOH intermediate that has not been experimentally detected. Thus, the involvement of a water molecule in the present PFe^{III}-O₂^{-/}Cu^ICD₂ complex is likely to occur. In addition, molecular modelling suggests that a water molecule bound to the distal copper ion can induce protonation of the superoxo complex (Fig. 8a), where the methoxy groups of the CD dimer are suitable to provide two hydrogen bonding sites to the water. The pH-dependent decomposition of the superoxo complex, as shown in Fig. 7, might be explained by the acid-base equilibrium of the water molecule (Fig. 8b), where the proton-donation to the superoxo complex is likely to induce the O-O bond cleavage as proposed in CcO^8 and/or the proton-assisted autoxidation reaction similar to myoglobin.41,42

The O₂ binding in the present complex was practically irreversible; the O₂ complex of Fe^{II}TPPS/Cu^ITerpyCD₂ was never converted to its Fe^{II}/Cu^I deoxy complex, even when the O₂ complex once formed was dissolved in a deoxygenated buffer (Fig. S5[‡]). In contrast, the deoxy complex was observed in the Fe^{II}TPPS/TerpyCD₂ complex without copper under the same experimental conditions.43 This result indicates that the O2 bound to PFe^{II} is tightly held by the distal Cu^IL₃ complex, as previously demonstrated by the Fe/Cu superoxo complex.14 The tight O_2 binding was also confirmed by observing ligand exchange with CO. The ligand exchange occurred slowly over \sim 30 min when the Fe/Cu superoxo complex was dissolved in a CO saturated buffer (Fig. S5[‡]), whereas it occurred instantaneously in the absence of distal Cu complex or in the absence of O₂ (Fig. S5[‡]). The ligand exchange of O₂ with CO also rapidly occurs in the previous Fe^{II}TPPS/CD dimer systems.^{20,24} The



Fig. 8 The superoxo $PFe^{III}-O_2^{-}/Cu^ICD_2$ complex with a water molecule. (a) The molecular model constructed using CONFLEX/MM3 (extensive search) parameters in Scigress version 2.2.1 software program (Fujitsu). Hydrogen atoms, except for water, are omitted for clarity. (b) The possible acid–base equilibrium of the water, where the proton-donation to the superoxo $PFe^{III}-O_2^{-}$ moiety is likely to occur at low pH.

significantly slow ligand exchange of $PFe^{II}-O_2^{-}/Cu^{I}L_3$ with CO caused by distal Cu complex might be related to the lower CO/ O₂ affinity ratio of native CcO (0.1) in comparison to that of myoglobin (20–50) or haemoglobin (200–250).⁴⁴

Electrochemical analysis for the O2 reduction

To evaluate the CcO-like function of this system, we monitored the electrocatalytic O₂ reduction reaction.⁴⁵⁻⁴⁷ The cyclic voltammogram (CV) of the Fe^{III}TPPS/Cu^{II}TerpyCD₂ complex immobilized on a glassy carbon electrode showed a reversible redox couple at $E_{1/2} = -0.21$ V (vs. Ag/AgCl) in a deoxygenated buffer solution (under Ar, Fig. 9a, black line). The result is similar to those of the previously reported PFe/CuL_n heterobinuclear systems; the Fe^{III}/Fe^{II} and Cu^{II}/Cu^I redox waves appear at the same potentials.^{31,46} In an air-saturated buffer, the CV of the Fe^{III}TPPS/Cu^{II}TerpyCD₂ complex showed a large catalytic current below -0.25 V because of O₂ reduction (Fig. 9a, blue line). A comparison of the CVs of the Fe^{III}TPPS/ Cu^{II}TerpyCD₂ complex with those of the reference samples, *i.e.*, Fe^{III}TPPS and Fe^{III}TPPS/TerpyCD₂ (Fig. 9b), clearly indicates the effect of the Fe/Cu hetero-binuclear structure in the O2 reduction; the Fe^{III}TPPS/Cu^{II}TerpyCD₂ complex showed a very large catalytic current starting from a lower onset potential ($\Delta E_{onset} =$ -40 mV). The O₂ reduction process was then studied by linear sweep voltammetry (LSV) using a rotating disk electrode (RDE, Fig. 9c). The LSVs of the Fe^{III}TPPS/Cu^{II}TerpyCD₂ and Fe^{III}TPPS/ TerpyCD₂ complexes showed diffusion limited catalytic O₂reduction currents below -1.0 V vs. Ag/AgCl. In the case of FeTPPS without the CD dimer, the current was never saturated in LSV due to a slow reaction rate of the iron porphyrin with O₂



Fig. 9 (a, b) CV of the FeTPPS/CuTerpyCD₂ complex and its reference samples absorbed on the glassy carbon electrode with Nafion (5 wt% dispersion, 10 μ L) in pH 7 phosphate buffer at a scan rate of 0.1 V s⁻¹ using Ag/AgCl and Pt wire as the reference counter electrodes, respectively. (c) LSV data for the FeTPPS/CuTerpyCD₂ complex (10 nmol) coated with Nafion (5 wt% dispersion, 10 μ L) on a glassy carbon electrode in air saturated pH 7.0 phosphate buffer at a scan rate of 10 mV s⁻¹ at multiple rotations using Ag/AgCl and a Pt wire as the reference and counter electrodes, respectively. (d) Koutecky–Levich plots for the FeTPPS/CuTerpyCD₂ and FeTPPS/TerpyCD₂ complexes at the potentials of –1.0, –1.1 and –1.2 V to determine the average number of electrons (*n*) used for the O₂ reduction reaction.

on the disk electrode (Fig. S6[‡]). The saturated currents observed in the Fe^{III}TPPS/Cu^{II}TerpyCD₂ and Fe^{III}TPPS/TerpyCD₂ complexes at various rotation rates were analysed using the Koutecky–Levich equation to determine the average number of electrons (*n*) used in the O₂ reduction (Fig. 9d).⁴⁸ A significant increase in the *n* value was observed for the Fe/Cu heterobinuclear complex ($n = 3.03 \pm 0.01$) compared to the control sample without copper ($n = 1.63 \pm 0.03$).⁴⁹ Therefore, we conclude that the terpyridyl Cu complex associated with FeTPPS in our model system facilitates the catalytic O₂ reduction as an electron source, as proposed in the mechanism of native CcO³ and as proven using the synthetic model systems.^{5,45,48}

Conclusions

In conclusion, we have synthesized a water-soluble biomimetic model complex for the heme a_3/Cu_B hetero-binuclear active centre of C_cO by utilizing a supramolecular complexation, and characterised its reactivity with O₂. To the best of our knowledge, this is the first example of a totally synthetic C_cO model that works in a completely aqueous solution. In common with compound A of native C_cO, we have identified the PFe^{III}–O₂^{-/} Cu^ICD₂ superoxo complex as the O₂ adduct in our model system in aqueous solution, whereas the PFe^{III}–O₂–Cu^{II}L_n µ-peroxo complexes tend to form in the other synthetic model systems in anhydrous organic solvents. The pH-dependent conversion of the PFe^{III}–O₂^{-/}(Cu^ICD₂ superoxo complex to its oxidised µ-hydroxo PFe^{III}–(OH)–Cu^{II}CD₂ complex suggested the

involvement of water molecules in the formation of the superoxo complex in aqueous solution. We believe that our aqueous model system will help to clarify the long-standing arguments with regard to the native and synthetic model systems in CcO chemistry.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgements

We thank (late) Prof. Takashi Ogura (University of Hyogo) for the use of rR instruments and helpful discussion. This work was financially supported by MEXT/JSPS KAKENHI (Grant No. 15H02569, 16K13092, 17H02208), the MEXT-Supported Program for the Strategic Research Foundation at Private Universities (2015–2019), the Naito Foundation, Iketani Science and Technology Foundation, and Suntory Foundation for Life Sciences. JW and TH thank financial support from the bilateral France–Japan ANR-JST program TMOL"Molecular Technology" project "MECANO" AI\R.1 4.JTIC.OOO2.O 1.

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