Catalytic reactions in a Co$_{12}$ cuboctahedral cage arising from guest encapsulation and cage-based redox activation†

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A Co$_{12}$ coordination cage with a cuboctahedral architecture, and incorporating a mixture of tritopic (face-capping) and ditopic (edge-bridging) ligands, shows strong guest binding of large aromatic fluorophores (fluorescein and its derivatives 6-carboxyfluorescein and Eosin-Y) with 1:1 binding constants in water in the range log $K = 6.7$–$7.9$: its large central cavity (>1000 Å$^3$) facilitates binding of much larger guests than was possible with the smaller Co$_8$ cage that we have reported previously. Guest binding is accompanied by catalysed reactions of bound guests because the high positive charge on the cage surface (24+) also attracts anions, allowing the organic guests and anionic reaction partners to be co-located, resulting for example in cage-catalysed hydrolysis of phosphate esters (the insecticides Me-paraoxon and Et-para-oxon) and conversion of diacetyl fluorescein to fluorescein. In addition, we demonstrate a new type of cage-based catalysis which relies on the redox activity of the Co(II)/Co(III) couple in the cage to activate the peroxymonosulfate (PMS) anion by converting it to the highly reactive SO$_4^{2-}$ radical ion, which bleaches cavity-bound fluorescein by complete oxidation. This is an example of an ‘advanced oxidation process’ in which the host cage not only brings the fluorescein and the PMS together via orthogonal hydrophobic and electrostatic interactions, but also provides redox activation of the PMS via a Co(II)/Co(III) couple, with the cage taking an active role in the catalytic process rather than acting simply as a passive reaction vessel.

Introduction

The enduring interest in the chemistry of self-assembled coordination cages is due in large part to their ability to act as catalysts for chemical transformations of guests bound in their central cavity. Binding of a potential substrate inside a cage cavity can be considered as an approximate model for binding of substrates at enzyme active sites, and the mechanisms by which reactions are accelerated have some obvious similarities between the two cases. Effects responsible for catalysed reactions of substrates bound in cages include conformational changes which bring a flexible substrate close to the conformation of a reaction transition state; electronic effects associated with the high charges which may be carried by multinuclear metal/ligand assemblies; and high local concentrations when two reaction partners are co-located in or around the cage.

Our recent work on cage-based catalysis has focussed on our octanuclear cubic [M$_4$L$_{12}$]$^{16+}$ system in which a ditopic bis(pyrazolyl-pyridine) bridging ligand spans each of the twelve edges of the assembly of eight M(II) ions which lie at the vertices. The cage has a cavity size (ca. 400 Å$^3$) which is ideal for accommodating a wide range of small organic guests; in its water-soluble forms, the hydrophobic effect ensures strong binding of such guests, with binding constants of up to 10$^6$ M$^{-1}$ for optimally-sized guests and the high positive charge allows the cage to accumulate anions around its surface very effectively. This last effect is the basis for its catalytic activity as the cage uses two orthogonal interactions to bring two reaction partners into close proximity, viz. (i) an organic substrate which binds in the cage cavity via the hydrophobic effect; and (ii) accumulation of anions around the cage surface via electrostatic/ion-pairing effects. The result is a high local concentration of ions around a cage-bound guest, leading to catalysed bimolecular reactions such as the Kemp elimination (reaction of benzisoxazole with hydroxide, or with a basic phenolate anion, phosphorus ester hydrolysis, or an aldol condensation.

Whilst this [Co$_4$L$_{12}$]$^{16+}$ cubic cage (hereafter abbreviated as Co$_8$) has provided many examples of cage-based catalysis it is of course size- and shape-limited in the guests that it can bind. We were therefore interested to see if we could extend...
cage-based catalysis to larger members of our coordination cage family which would be able to accommodate a wider range of guests in the central cavity, whilst maintaining the key characteristics that make catalysis possible (a hydrophobic interior cavity surface for organic guest binding; and a high positive charge which attracts anions to the cage surface). This is non-trivial as it requires solubility in water, requiring in some cases significant changes to ligand syntheses to introduce external solubilising substituents such as HO groups or PEG chains. Additionally, some of the larger cages that we have prepared exit in solution in slow equilibria between larger cages and smaller assemblies which prevents meaningful analysis of host/guest chemistry.

In this paper we introduce the cuboctahedral cage \( \text{Co}_{12} \) (Fig. 1) as a catalyst for reactions between hydrophobic substrates and anions in water, using a range of ester hydrolysis reactions as illustrations. Significantly, we also report extension of the range of cage-catalysed reactions to include some that require not just co-location of reaction partners around the cage, but redox activation of one of the reagents by the Co(II) ions in the cage. This is an additional degree of sophistication in the cage-based catalysed reactions, making the cages not just an inert container that holds components in close proximity to one another, but also an active participant in electron-transfer steps required for the catalytic cycle in a way that has been demonstrated in recent examples of photo-redox catalysis. This additional redox-based participation of the cage in catalytic processes will substantially extend the scope of reaction types that can be catalysed.

Results and discussion

The \( \text{Co}_{12} \) cage and its water solubilisation

As the candidate for extending our cage-based catalysis studies we have chosen the \( \text{M}_{12} \) cuboctahedral cage shown in Fig. 1. This is based on a mixture of two different types of ligand (edge-bridging, ditopic, \( \text{L}^\text{ph} \); and face-capping, tritopic, \( \text{L}^\text{mes} \)). A combination of four equivalents of \( \text{L}^\text{mes} \) and twelve equivalents of \( \text{L}^\text{ph} \) combine with twelve M(II) ions to form a cuboctahedral array \( [M_{12}(\text{L}^\text{ph})_{12}(\text{L}^\text{mes})_4]^{24+} \) in which four of the eight \( \text{M}_3 \) triangular faces are capped by an \( \text{L}^\text{mes} \) ligand, and the other four are edge-bridged, forming a set of (chiral) \( M_4(\text{L}^\text{ph})_4 \) cyclic helicates. Interestingly the four triangular cyclic helicate faces can vary their sense of helicity between ‘anticlockwise’ (A) and ‘clockwise’ (C) independently of one another, which means that the \( [M_{12}(\text{L}^\text{ph})_{12}(\text{L}^\text{mes})_4]^{24+} \) cage can exist as a mixture of three different diastereoisomers: (i) all four cyclic helicate faces homochiral (enantiomeric pair AAAA/CCCC, \( T^\text{symmetry} \)); (ii) three cyclic helicate faces of one chirality and one of the other (enantiomeric pair AACC/CCCA, \( C_3 \) symmetry); and finally (iii) two cyclic helicates of each chirality (AACC, \( S_2 \) symmetry, which has no enantiomer). The result is a set of three \( \text{M}_{12} \) cages of essentially the same size and with very similar arrangement of metal ions at the vertices, differing only in the chiralities of the cyclic helicate faces. Examples of all three diastereoisomers of this type of cuboctahedral cage have been individually structurally characterised in previous work. Separation of the three diastereoisomers in significant quantities beyond picking individual crystals was not possible given their essentially identical size/shape and identical charge. Importantly for the purposes of this work, the cavity volumes of the three diastereoisomers are very similar to one another (1036\( \pm \)112 Å\(^3\)) and substantially larger than the cavity of the \( \text{M}_{4} \) cubical cage (409 Å\(^3\)) so we expect fundamentally different host/guest chemistry. For the purposes of this work, therefore, the set of three similar diastereoisomers of the \( [\text{Co}_{12}(\text{L}^\text{ph})_{12}(\text{L}^\text{mes})_4]^{24+} \) cage is considered as a single species.

Initially therefore we combined \( \text{Co(BF}_4)_2 \), \( \text{L}^\text{ph} \) and \( \text{L}^\text{mes} \) in a 12:12:4 ratio in the previously-reported way\(^\text{11b} \) to obtain solid \( [\text{Co}_{12}(\text{L}^\text{ph})_{12}(\text{L}^\text{mes})_4]^{24+} \) (hereafter abbreviated as \( \text{Co}_{12} \)).

High-resolution ES mass spectrometry confirmed formation of the cage with a characteristic sequence of signals associated with loss of different numbers of anions giving the species \( [\text{Co}_{12}(\text{L}^\text{ph})_{12}(\text{L}^\text{mes})_4]^{24+} \) for \( n = 4\rightarrow 9 \), Fig. S1–S4; with the correct fractional isotope spacings and isotopic patters in the high-resolution signals). In the \( ^1\text{H} \) NMR spectrum in CD\(_3\)CN (Fig. S5), the paramagnetism associated with use of high-spin
Co(n) ions acts as a convenient shift reagent, spreading out the signals over a 200 ppm chemical shift range.⁷ The spectrum is clearly highly complex due to the mixture of three diastereoisomers with different symmetries and cannot be assigned in detail: but we can identify in some parts of the spectrum a characteristic set of eight signals (subsets of 1, 3 and 4 signals with the same intensity within each subset) which arise from one chemical type of proton (e.g. a pyridyl H⁺ from L⁴mes) in the three diastereoisomers, as described earlier.¹¹ In the ¹H NMR spectrum for Co₁₂ in MeCN we can identify exactly this pattern between −10 and −23 ppm (Fig. S5, top panel) which, together with the mass spectrum, confirms formation of Co₁₂ with all three diastereoisomers present.

The complex formed beautiful crystals on recrystallisation from a variety of solvents which however failed to diffract X-rays significantly, even using synchrotron radiation, which is likely a consequence of co-crystallisation of the three diastereoisomers which will lead to extensive disorder in the organic ligand positions and (to a lesser extent) in the metal atom positions. Indeed the NMR spectrum of redisolved apparently 'single' crystals matched that of the bulk as-prepared material, showing the mixture of diastereoisomers to be present in the crystals. We note however that several other crystal structures of this M₁₂ cage family have been previously reported.¹¹

For control experiment purposes we also prepared the isostructural Zn₁₂ cage in exactly the same way; this complex too was characterised by high-resolution ES mass spectrometry (Fig. S7–S10†), showing the sequence [[Zn₁₂(L₃)₁₂(L⁴mes)₄] (BF₄)₄₋₋ (n = 4–9) with the expected isotope patterns and spacings for the individual species. The ¹H NMR spectrum of Zn₁₂ (Fig. S11†) is mostly unassignable due to the overlap of signals in the aromatic region associated with the mixture of diastereoisomers, but in the aliphatic region we can clearly see the singlets for the methyl protons of L⁴mes: a set of four of the same intensity for the S₁ isomer and a set of three of the same intensity for the C₁ isomer. We cannot see the additional signal arising from the T isomer (expected between 0 and 1 ppm) so we conclude that the Zn₁₂ complex consists of the S₁ and C₁ isomers: in the previously-reported Cd₁₂ species, the T isomer was by far the least abundant of the three.¹¹ A DOSY spectrum (Fig. S12†) confirms that a single species (ignoring the isomerism) is present in solution, and from the diffusion coefficient [log(D/m² s⁻¹) = −9.8] we can estimate from the Stokes–Einstein equation that the radius of the complex is ca. 12 Å, which is close to the crystallographically-observed average radius of ca. 14 Å and far larger than any species such as individual ligands or low-nuclearity complexes.

Having confirmed formation of Co₁₂ (and Zn₁₂ for control experiments) the next problem is water-solubilisation to allow the hydrophobic effect to be exploited for guest binding. Appending hydroxymethyl or PEG substituents to the ligands is possible but laborious,⁷⁺ TableRow 1 and we found that ligand substituents in the obvious positions (pyridyl C⁺) caused steric problems which prevented cage assembly – a problem which did not arise earlier in the M₄L₁₂ cube where the pyridyl C⁺ substituents do not clash.⁷⁻ We have also used anion metathesis, with the usual fluoroborate anions associated with the cage synthesis being replaced by chloride ions which rendered the [M₄L₁₂]⁺⁺⁺ cage highly water soluble.⁶ However similar anion-exchange experiments to convert Co₁₂ to its chloride salt did not lead to sufficiently high water solubility and also results in partial decomposition, possibly because chloride is a good competing ligand for Co(n) and the high positive charge on this cage will result in a high chloride ion concentration around the cage following anion metathesis.

We found however that we could successfully water-solubilise Co₁₂ for catalysis in two different ways which did not require anion-exchange or complex synthetic chemistry associated with incorporation of ligand substituents. These are (i) inclusion of 1% dmso in the aqueous solvent;⁶ and (ii) more unusually, use of a non-ionic surfactant. Use of a small amount of dmso in the aqueous solvent (dmso/water 1 : 99, v/v) provided sufficient solubility for many spectroscopic and catalysis measurements with Co₁₂ as we report below. The non-ionic surfactant polysorbate-20 (also known as Tween-20) also proved to be effective. Tween-20 contains a water-soluble branched poly-oxethylene terminus functionalised with a lauryl ester chain which provides a hydrophobic terminus. As such one of the applications of Tween-20 is to render watersoluble a range of hydrophobic species, including drug molecules for formulation purposes¹² and hydrophobic membrane proteins during extraction following cell lysis,¹³ and it turned out to be very effective at allowing Co₁₂ to be water-solubilised to a surprisingly high (mM range) concentration. Addition of solid Co₁₂ to commercial Tween-20, followed by overnight stirring, sonication, dilution with water, and filtration through a 2-micron filter afforded a clear aqueous solution whose con-

† In the T-symmetry isomer all such protons are equivalent, giving a single signal for all twelve of them. In the C₃-symmetry isomer there are four inequivalent environments (with equal likelihood) for each proton, and in the S₃-symmetry isomer there are three inequivalent environments (with equal likelihood) for each such proton. The result is a set of eight signals, being sets of 1 + 3 + 4 for the three diastereoisomers, and if the assembly of the four triangular helicate faces in the cuboctahedron is purely statistical with no preference for any one diastereoisomer, all eight signals should be of equal intensity (see ref. 11b). Any bias towards one diastereoisomer and away from the others will result in a very characteristic set of closely-spaced 1 + 3 + 4 signals for each chemical environment of proton.

§ We could also achieve significant water solubility using 10% MeCN in water, a solvent mixture that allowed greater solubility than 1% dmso in water, and we used 10% MeCN in water for some of the NMR and MS experiments to confirm stability of the cages in water. Notably this gave cleaner ES mass spectra than did 1% dmso in water, as the presence of dmso results in greater fragmentation and adduct formation at the high temperatures required for solvent evaporation under MS conditions (compare Fig. S1/S3, and S7/S9†). For the catalysis experiments however we used either Tween-20 or 1% dmso in water to achieve water solubility, to maximise the amount of water present and hence the hydrophobic effect responsible for guest binding. We note that a small admixture of dmso to facilitate water solubility has not caused any stability problems with other members of this cage family based on Co(n) tris(pyrazolyl-pyridine) metal complex units, see for example ref. 6g.
Guest binding in Co12 in water

Initial studies on guest binding focussed on the set of four guests shown in Scheme 1: these are fluorescein (FLU), 6-carboxyfluorescein (6FLU), Eosin-Y (EY) and hydroxypyrene-tris-sulfonate (HPTS). All of these are fluorescent so we could monitor guest uptake into Co12 by following fluorescence quenching as portions of TW20⊂Co12 were added to a fixed concentration (1 µM) of the potential guest in aqueous solution. Binding is clearly strong (Fig. 2): fitting the curve for quenching of FLU (a dianion under the prevailing conditions) for example, to a 1 : 1 binding isotherm, afforded a log \( K \) value of 6.7. A Job plot based on the fluorescence titration data confirmed 1 : 1 binding, and an electrospray mass spectrum of a Co12/FLU mixture showed a set of strong signals associated with the 1 : 1 Co12-FLU adduct associated with varying numbers of anions (Fig. S13†). This behaviour is notably different from what we observed for the interaction of FLU with the smaller Co8 cage, which is too small to accommodate FLU inside the cavity: in that case external surface binding occurred with up to five FLU units interacting with the Co8 cage exterior according to the Job plot, and a much smaller binding constant.8 In contrast, with Co12 as the host, we are clearly seeing (a) much stronger binding of fluorescein and (b) this binding is in a 1 : 1 ratio as shown by both a Job plot and an electrospray mass spectrum, all of which is consistent with cavity-based binding of the single FLU guest.

The binding constant (log \( K = 6.7 \)) with FLU is already much larger than we have observed with virtually all other cage/guest complexes using Co8,8 which can be ascribed to a combination of (i) the higher hydrophobic surface area of fluorescein compared to the smaller guests that can fit inside the Co8 cage, and (ii) an electrostatic contribution associated with the 2− charge on fluorescein and the 24+ charge on Co12. We found no evidence for further association of larger numbers of FLU guests associated with external surface binding which could still in principle be possible: if it does occur, it is clearly much weaker than the cavity binding.

The related guests 6CFLU and EY bind even more strongly (log \( K \) values of 7.0 and 7.9 respectively, with 1 : 1 Co12 : guest binding according to Job plots – see Fig. 2, inset, for an example), which we ascribe to the higher negative charge (of 6CFLU, 3−) and higher hydrophobicity (of EY) respectively, compared to FLU.6b HPTS – a trianion – binds too strongly for a binding constant to be determined under these conditions but clearly behaves differently: the very rapid quenching (≈1 equivalent of Co12 is needed to completely quench the HPTS fluorescence) implies that binding is not just cavity-based but there is also a surface interaction whereby one Co12 binds and quenches multiple equivalents of HPTS around its exterior, in a manner analogous to the Co8/FLU system.6b

Co12-catalysed phosphotriester hydrolysis

To examine the ability of TW20⊂Co12 to act as a catalyst using the same mechanism as we observed with the cubic Co8 cage (co-location of hydrophobic substrate and anions using orthogonal interactions)6c we examined the catalysed hydrolysis of the phosphotriesters methyl- and ethyl-paraoxon (4-O2NC6H4O=P(−O)(OR))2, with R = Me or Et respectively, which are potent acetylcholinesterase-inhibiting insecticides,
and contain 4-nitrophenolate as the leaving group from the hydrolysis reaction, allowing facile monitoring of hydrolysis reaction rates by UV/Vis spectroscopy.

Under a range of catalyst and substrate concentration conditions (using fixed pH 8, borate buffer, see Fig. 3 and SI16†) we obtained second-order rate constants for the cage-catalysed hydrolysis of these paraoxons of ca. 0.5 M⁻¹ s⁻¹ for methyl-paraoxon and 0.4 M⁻¹ s⁻¹ for ethyl-paraoxon which are 1–2 orders of magnitude faster than we observed using Co₈ as the catalyst under similar conditions.⁵⁶ Exactly similar behaviour (with slightly smaller rate accelerations) was observed using 1% dmso in water as the solvent rather than the aqueous Tween-20 surfactant (see ESI†).

In our earlier work using Co₈ we found that the cage-catalysed hydrolysis of methyl-paraoxon occurred at the external surface of the cage, as the substrate did not bind in the Co₈ cavity for steric reasons. Nonetheless the hydrophobicity of the exterior surface allowed methyl-paraoxon to associate with it in aqueous solution, and the 16+ charge on the cage attracted hydroxide ions, so the cage surface still served as a medium to attract and co-locate the two reaction partners around the exterior surface, even if the resulting catalysis did not benefit from the substrate lying inside the cavity. With TW20⊂Co₁₂ as the catalyst the much (2.5×) larger cage cavity will allow methyl- and ethyl-paraoxon to bind inside it, surrounded by hydroxide ions that are also attracted by the 24+ surface charge, resulting in the catalysed hydrolysis of both substrates that we observe at a rate higher than was previously observed for an external surface-based reaction. From these observations we can expect that the larger cavity of Co₁₂ will facilitate catalysed reactions of hydrophobic cavity-binding guests with anions with a much wider range of substrates compared to Co₈.

Co₁₂-catalysed carboxylate ester hydrolysis

Another illustration of a cage-catalysed reaction involving an ester substrate and hydroxide ions as the reaction partner is provided by the hydrolysis of diacetyl fluorescein (DAF; see Scheme 2) to fluorescein which can be readily followed by monitoring the grow-in of the absorption band for the fluorescein dianion as the reaction proceeds.⁵⁶

Under conditions where DAF shows no significant hydrolysis over several hours (0.25 mM DAF, 50 mM PBS buffer at pH 7) the presence of Co₁₂ results in appearance of the fluorescein absorption band at a rate which increases linearly with Co₁₂ concentration (Fig. 4): dividing the initial rate constant by the Co₁₂ concentration gives a second order rate constant for the cage-catalysed hydrolysis of DAF of 0.24 M⁻¹ s⁻¹. This is between one and two orders of magnitude greater than the catalysis of DAF hydrolysis by the smaller cage Co₈ under similar conditions.⁵⁶ in that case DAF cannot bind inside the cavity and the reaction occurs at the external surface of the cage with the substrate held by hydrophobic interactions in the hydroxide-rich region around the cationic surface. With Co₁₂ in contrast the improvement in catalytic rate enhancement compared to Co₈ implies that DAF is binding inside the cage cavity, surrounded by the layer of surface-bound hydroxide ions, and we have observed before how encapsulation of guests can result in much higher catalysed reaction rates.⁵⁶

Co₁₂-catalysed oxidation of dyes using peroxymonosulfate: an ‘advanced oxidation process’ involving cage-based redox activation

We demonstrate here a quite different example of a cage-catalysed reaction which requires not only the co-location of two reaction partners [the dye fluorescein, and the powerful anionic oxidant peroxy-monosulfate (PMS)] but also participation of the Co(n) ions in the cage in a redox cycle. PMS is of great interest as a powerful oxidant for destroying toxins and organic impurities as part of waste-water treatment where it

Fig. 3 Catalysed hydrolysis (pH 8, 298 K) of the phosphate esters (a) Me-paraoxon (0.45 mM) and (b) Et-paraoxon (0.49 mM) monitored by UV/Vis absorbance of the accumulating 4-nitrophenolate ion at 400 nm. The green, black, red and blue traces correspond to addition of 0, 1, 4 and 8 mol% of Co₁₂ (used as the TW20⊂Co₁₂ solution).

Fig. 4 Catalysed hydrolysis of DAF by Co₁₂ in 99 : 1 water/dmso at the indicated catalyst concentrations: 0.25 mM DAF, 50 mM PBS buffer, pH 7, 298 K.
has emerged as a desirable alternative to H₂O₂ and other sources of more conventional ‘reactive oxygen species’ such as \( \cdot \)O₂ and HO in so-called ‘advanced oxidation processes’. Importantly, despite its strong thermodynamic oxidising ability, direct reaction of PMS with the contaminants that it is intended to destroy is kinetically slow, and in practice PMS requires activation by any of a wide range of methods that cleaves the peroxide O-O bond to generate the \( \text{SO}_4^{2-} \) radical anion which is the species that is predominantly responsible for rapid oxidation of organic contaminants in water, ultimately to innocuous CO₂ and H₂O.¹⁴

A common method to activate PMS is a redox reaction with a low oxidation state metal ion, with Co(II) being reportedly particularly effective,¹⁴b according to eqn (1).

\[
\text{Co}^{3+} + \text{HSO}_5^- \rightarrow \text{Co}^{3+} + \text{SO}_4^{2-} + \text{HO}^-
\]  

(1)

Given that Co₁₂ can encapsulate fluorescein in the cavity, and the high positive charge of Co₁₂ means that it should also have the ability to accumulate anions in the same way as Co₈ does (as the ester hydrolysis catalytic studies reported above confirm), we can expect that fluorescein and PMS will be colocalised in and around molecules of Co₁₂. In addition, the Co(II) ions in the cage can, if necessary, provide the necessary activation of PMS via a Co(II)/Co(III) couple, with the resulting \( \text{SO}_4^{2-} \) again being held close to the Co₁₂ cage (and its encapsulated substrate) by the 24+ charge on the cage.

In the absence of Tw₂₀Co₁₂, an aqueous solution of fluorescein (7.5 µM) also containing 45 equivalents of PMS showed no significant degradation of fluorescein as shown by the invariance of its UV/Vis absorption spectrum over time. In the presence of 10 mol% of Co₁₂, however the fluorescein absorption at 490 nm was quickly bleached (Fig. 5, red trace; vs. 75% bleaching by the end of the experiment. This sensitivity of the reaction to MeOH, but not to \( t\)-BuOH, confirms that \( \text{SO}_4^{2-} \) radicals (but not hydroxyl radicals) are involved, which in turn confirms that redox activation of PMS by Co(II) ions is required before the reaction can occur.

Thus, Co₁₂ in water could in principle accelerate the destruction of fluorescein by PMS in two ways. Firstly, colocalisation of the two reaction partners, either inside the cavity or around its exterior surface, could provide the catalysis following the example provided by the Kemp elimination and other reactions catalysed by Co₈. Moreover, the presence of Co(II) ions in the cage provides redox activation of the PMS by converting it to the more reactive species \( \text{SO}_4^{2-} \) according to eqn (1).¹⁴b Some control experiments clarify these issues.

Firstly, replacement of Co₁₂ as catalyst by the isostructural cuboctahedral cage Zn₁₂, whilst keeping all other conditions the same, completely stopped the degradation of fluorescein (Fig. 5, black trace). Co-location of fluorescein and PMS in and around the M₁₂ cage cavity alone is an insufficient condition for catalysis: the redox-based activation of the PMS to generate \( \text{SO}_4^{2-} \) is also required, as the quenching experiments with MeOH/\( t\)-BuOH showed. Use of Co(BF₄)₂ as activator was ineffective, with a mixture of fluorescein/PMS/Co(BF₄)₂ showing no degradation of fluorescein (Fig. 5, purple trace). However the Co²⁺/Co³⁺ couple in water is highly positive - around +1.8 V -

Fig. 5 Destruction of fluorescein by oxidation with peroxy-monosulphate under different sets of conditions, showing the importance of both cage-based encapsulation (red and blue lines vs. green and purple) and the importance of having Co(II) ions in the cage superstructure as redox agents for activation of peroxymonosulfate (red vs. black lines).
meaning that aqueous Co$^{2+}$ ions are poor reducing agents: a better comparison is with a Co(n) complex in an N$_6$ coordination environment similar to that which occurs in this cage family, with a much lower redox potential, that would make it a more effective activation agent for PMS according to eqn (1).

Accordingly the final control experiment was to investigate bleaching of fluorescein in a mixture of fluorescein/PMS/[Co(phen)$_3$]$^{2+}$ (phen = 1,10-phenanthroline)$^{18}$ in which the N$_6$-coordinated Co(n) ions are present at the same total concentration as in Co$_{12}$, i.e. the concentration of mononuclear [Co(phen)$_3$]$^{2+}$ is 12 times the molar concentration that was used for Co$_{12}$. The [Co(phen)$_3$]$^{2+/3+}$ redox potential has been reported as +0.62 V vs. NHE (−0.02 V vs. ferrocene/ferrocenium, Fe/Fe$^+$)$^{18a}$ and in a separate paper as −0.04 V vs. Fe/Fe$^+$$^{18b}$ This is much less positive than for Co(BF$_4$)$_2$ and is also lower than the Co$^{3+}$/Co$^{2+}$ couple of Co$_{12}$ for which we observed an electrochemically irreversible oxidation (presumably due to a forbidden spin-state change associated with the Co$^{5+}$/Co$^{3+}$ interconversion) at +0.62 V vs. Fe/Fe$^+$ in MeCN (Fig. S19†), making [Co(phen)$_3$]$^{2+}$ an even better reducing agent for activation of PMS than is Co$_{12}$. Despite this, in the presence of [Co(phen)$_3$]$^{2+}$ but in the absence of Co$_{12}$ (i.e. with redox activation of PMS available, but without cage-based encapsulation of components) we observed only slow degradation of fluorescein, to the extent of about 10% reduction in absorbance of PMS available, but without cage-based encapsulation of components in an inert reaction vessel, offering substantial promise for use of the cages in redox- and photo-redox catalysis processes.

These experiments confirm that the effective oxidative destruction of fluorescein using Co$_{12}$ as catalyst arises from a combination of three factors. These are the ability of Co$_{12}$ to (i) bind fluorescein strongly in water inside its cavity; (ii) accumulate anionic reaction partners around its positively-charged surface, bringing PMS anions close to the fluorescein substrate; and (iii) provide redox activation of the PMS using the Co(n) ions in the cage superstructure which facilitate its conversion to reactive SO$_4$$^{−}$ radicals. Removal of either the redox activation provided by the Co(n) ions in the cage (control experiment using Zn$_{12}$) or the cage-based co-encapsulation of reactants (control experiment using [Co(phen)$_3$]$^{2+}$ for activation) stops the effective oxidation catalysis provided by Co$_{12}$/PMS system. Finally we note that using the alternative method of water-solubilisation of Co$_{12}$ (addition of 1% dmso as co-solvent) also provided a clear catalysis of the fluorescein oxidation reaction by PMS (Fig. 5, blue trace) although the effect is less strong than when using Tween-20, an observation which mirrors what we observed (above) for cage-catalysed phospho-ester hydrolysis when the water/Tween-20 reaction medium afforded slightly better catalysis than water/dmso (99:1).

Conclusions

In conclusion we have demonstrated that the Co$_{12}$ cage can be solubilised in water (either using a neutral surfactant or by inclusion of 1% dmso in the solvent), permitting a range of guest binding and reactivity studies that rely on the hydrophobic effect. In aqueous solution Co$_{12}$ binds a range of organic fluorophores (fluorescein and analogues) very strongly ($K \approx 10^7$ M$^{−1}$) in the central cavity. The ability of the Co$_{12}$ cage to co-locate hydrophobic organic substrates and anions using two orthogonal interactions results in catalysed hydrolysis destruction of two phosphate-ester based insecticides and also of diacetyl fluorescein which incorporates two carboxylic ester groups. In both cases the second order rate constants for the catalysed reactions are significantly (1−2 orders of magnitude) larger than we previously observed using the smaller cage Co$_8$, which is suggestive of cavity-based catalysis in the larger cavity of Co$_{12}$ compared to exterior surface-based catalysis using Co$_8$.

In addition, Co$_{12}$ exhibits a new type of cage-catalysed reaction, specifically the destruction of fluorescein by PMS as a model for the ‘advanced oxidation process’ reactions that are studied to remove organic pollutants from water using peroxymonosulfate. This involves not just the ability of the Co$_{12}$ cage to bring the organic substrate and the anionic reaction partners into close proximity, but also requires redox activation of PMS (initial conversion to SO$_4$$^{−}$ radicals) using the Co(n) ions in the cage – which is therefore an active redox partner in the reaction as well as acting to co-locate the substrates in and around the cage cavity. This type of direct participation of redox-active ions in the cage superstructure in catalysed reactions, which means that the cage is no longer just acting as an inert reaction vessel, offers substantial promise for use of the cages in redox- and photo-redox catalysis processes.

Author contributions

X. Z.: cage synthesis, guest binding and catalysis studies, data analysis. B. S.: NMR and MS studies. M. D. W.: project supervision and manuscript preparation.

Conflicts of interest

There are no conflicts to declare.

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