Methyl Aryl Ketones in the Synthesis of Hexaazabicycloicosane Cage Complexes

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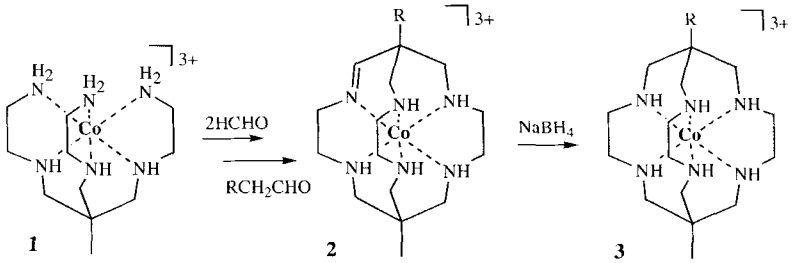
This paper is dedicated to Gottfried Huttner, a stimulating teacher, researcher and companion

Abstract: The template syntheses of various Co^{III}–hexaazaicosane-type cage complexes with aromatic substituents are described. The parent template, $[Co(sen)]^{3+}$ ion {sen = 4,4′,4″-ethylidynetris(3-azabutan-1-amine)}, paraformaldehyde, a methyl aryl ketone and a base were reacted in acetonitrile to give aroyl substituents attached to the fully saturated sarcophagine cage (1-aroyl-8-methyl-3,6,10,13,16,19-hexaazabicyclo[6.6.6]-icosane cobalt(III) ion) and aryl substituents attached to an analogous imine-type cage (2-aryl-8-methyl-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosa-2-ene cobalt(III) ion). Phenyl, napthyl, phenanthryl, anthracenyl and anthraquinonyl substituents have been bound to the cage simply by this route to give molecules that can act as intercalators in DNA or as photosensitizers attached to reversible redox-active metal centres and can couple an organic two-electron reagent with an inorganic one-electron reagent. An X-ray crystallographic analysis of a phenanthroyl cage complex has also been carried out. These substances and their progeny should be useful as biological probes and fluorescent indicators and for energy capture and conversion.

Keywords
cage compounds · cobalt · cyclic voltammetry · fluorescence spectroscopy · template synthesis

Introduction

The synthesis of bicycloicosane cage molecules containing six nitrogen donor atoms was originally achieved by reacting aqueous methanal with cobalt(III) amines to form intermediates bearing coordinated imines, which then condensed with ammonia or the conjugate base of nitromethane and more methanal to give the encapsulated products.[1, 2] Reaction of $[Co(sen)]^{3+}$ {Scheme 1, **1**; sen = 4,4′,4″-ethylidynetris(3-azabutan-1-amine)} with higher aldehydes and paraformaldehyde in acetonitrile proved to be a successful route for synthesizing cages with various apical substituents (Scheme 1, **2** and **3**), primarily because the mixed aldehyde synthesis can be controlled by adjusting aldehyde concentrations to regulate condensation rates.[3, 4] Subsequently it was also shown that when acetonitrile is used as the solvent, quite weak carbon acids such as *N*-alkylated γ-picoline and a pyruvate imine cobalt(III) complex may be used to produce functionalized carbon-capped cages.[5, 6]



1 2 3

Scheme 1. Reaction of $[Co(sen)]^{3+}$ with mixed aldehydes in acetonitrile.

The final saturated complexes described above have an approximately octahedral coordination geometry. Those with inequivalent apical substituents generally average C_3 symmetry, but this is lost if functional groups or substituents are incorporated into one or more of the strands. The cages are self-assembled with a high degree of stereospecificity. There are seven chiral centres in the parent saturated hexaaza complex, apart from conformers. Additional complications arise from the substituents, but if the starting template is one chiral form then the cage product consists of one isomer; this is the situation for the

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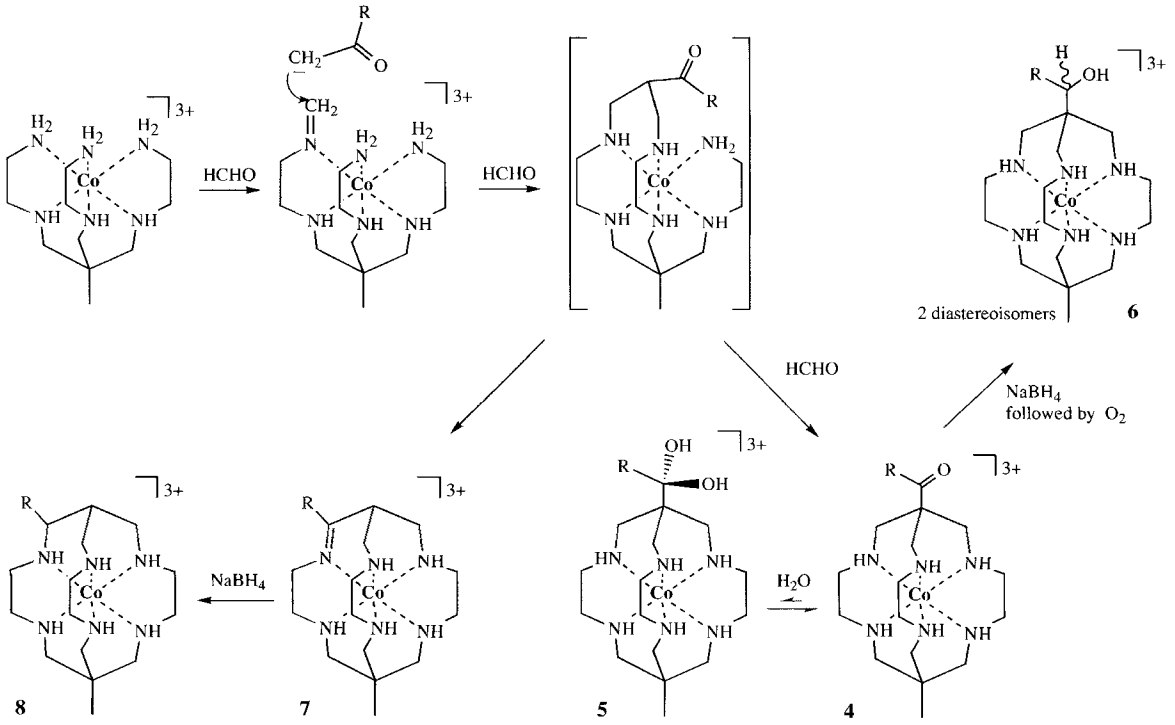
syntheses using the $[Co(sen)]^{3+}$ template at $\approx 20\,^{\circ}C$. Essentially, the initial configuration of the $Co(N-CH_2-CH_2-N)_3$ moiety in the starting material determines the same configuration for each chiral nitrogen centre.[1]

Some ketones contain methyl groups that are effective carbon acids,[7] and the carbonyl group in such compounds is also able to condense with a coordinated amine.[8] The success of earlier syntheses prompted us to investigate the use of various methyl ketones in template condensation reactions with $[Co(sen)]^{3+}$ and paraformaldehyde, and these pursuits have given rise to a series of cage complexes with aromatic and other substituents. In addition to providing linking functionalities, the substituents can also modulate certain physical properties of the complexes.[9] In some examples, aromatic substituents could act as photoactive centres[10, 11] and could also be used as intercalating agents to target DNA sites.[12] This paper describes the reactions of $[Co(sen)]^{3+}$, paraformaldehyde, and a series of methyl aryl ketones to produce cages with aryl groups attached to the apex or elsewhere in the cap. Some of the trivial nomenclature used for these molecules has been described in previous papers.[2-6, 9]

Results

Cage syntheses: The simplest ketone used in these reactions was acetophenone, in which the methyl group is weakly acidic ($pK_a = 19$).[13] It was reacted with $[Co(sen)]^{3+}$ and paraformaldehyde in acetonitrile to produce a mixture of yellow–orange complexes that separated into two bands during ion-exchange chromatography. The NMR spectra in D_2O of the residue from the first band indicated that two cage species were present, one (**4**, $R = C_6H_5$, Scheme 2) containing a ketone functional group (^{13}C NMR: $\delta \approx 204$), the other (**5**, $R = C_6H_5$) having a diol functional group (^{13}C NMR: $\delta \approx 97$).[14] Hydration of ketones to form diols has been observed previously in cobalt(III) complexes of keto acids[15, 16] and in the pyruvate-imine-capped cage.[6] This increased stability of the diol indicates the electron-withdrawing capacity of the cobalt(III) cage, at least in relation to the apical substituents. However, ketone hydrates are rarely stable in the solid state[17] and only the ketone form would be expected even if the complex was crystallized from aqueous solution. Accordingly spectra were obtained in $[D_6]$dimethylsulfoxide; these were consistent with a single cage species with average C_3 symmetry containing a ketone functional group as an apical substituent (**4**, $R = C_6H_5$). Such a complex arises from the sequential condensation of the methyl group of acetophenone with three methanimine groups formed by addition of three methanal molecules to $[Co(sen)]^{3+}$, as shown in Scheme 2. When the aroyl-substituted species was treated with $NaBH_4$, the carbonyl group was reduced to a secondary alcohol.[18] Two diastereoisomers (**6**, $R = C_6H_5$) arise from the reduction of the ketone, which generates a chiral centre in the resulting secondary alcohol. The ^1H NMR spectrum showed a signal for the proton attached to the methine carbon of the secondary alcohol at $\delta = 4.58$ but it did not reveal the diastereoisomers. The ^{13}C NMR spectrum, however, was consistent with an approximately equimolar mixture of two isomers, as all signals were doubled. There was no ketone or diol signal, and the signals at $\delta = 76.0$ and 75.7 were consistent with the presence of an alcohol.

The ^1H and ^{13}C NMR spectra of the residue from the second band described above were consistent with those expected for a single cage complex formed by the addition of two methanal molecules to $[Co(sen)]^{3+}$, subsequent condensation of the two methanimines with the methyl group of acetophenone and final-



Scheme 2. Mechanism and products of the capping reaction of $[Co(sen)]^{3+}$.

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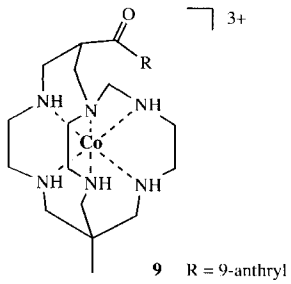
ly condensation of the ketone functional group with the third tripodal amine. The cage has a phenyl-substituted imine group in the cap (**7**, R = C_6H_5). It is asymmetric and formed stereospecifically, as shown by the 19 signals in the ^{13}C NMR spectrum, four of which arise from the phenyl substituent. The single signal at $\delta = 190.2$ is attributed to the imine carbon atom. Treatment of **7** with sodium borohydride at pH 8 yielded the orange, saturated species (**8**, R = C_6H_5). The reduction of the imine was stereospecific, as only one diastereoisomer was detected. As expected, this cage was also asymmetric; it showed 19 signals in the ^{13}C NMR spectrum, and the imine signal had vanished. Experiments simply with $[Co(sen)]^{3+}$ and acetophenone in acetonitrile under similar conditions did not produce any new species, so clearly methanal is required to connect the ketone to the tripod. The proposed mechanism for the synthesis of these cages is shown in Scheme 2. While the precise order of the condensations has not been determined, this mechanism is consistent with the data. Experiments using lesser amounts of methanal resulted in lower yields but no difference in the cage products.

The synthesis of two cages from a single capping reaction was observed previously in the reaction of $[Co(sen)]^{3+}$ with paraformaldehyde and ethanal.[3] An unsaturated species was formed by the initial addition of two methanal molecules to $[Co(sen)]^{3+}$ and the methyl group of ethanal, followed by condensation of the aldehyde group with the remaining coordinated amine. The second minor cage product with an apical formyl substituent arose from condensation of three methanal molecules with the tripodal amines and the aldehyde methyl group. The use of a methyl aryl ketone instead of ethanal is a route to a wide range of substituted cages because it is possible to vary the nature of the aryl group extensively. For example, 4′-nitroacetophenone, methyl 2-naphthyl ketone, 9-acetylanthracene, 2-acetylanthraquinone and 2-acetylphenanthrene were used in capping reactions analogous to that described above and usually two cage complexes were isolated from each reaction, a symmetric (C_3) form with an aroyl group at the apex and an unsymmetrical imine species with the aromatic substituent at the cap 2 position. The exception was the 9-acetylanthracene reaction, from which only the ketone-substituted species was isolated.

In all instances, the ^1H and ^{13}C NMR spectra and microanalyses confirmed the presence of the aromatic group and the overall structure of the complexes. All the imine-bearing cages yielded saturated products stereospecifically and in high yield when treated with $NaBH_4$. Reduction of the anthraquinone imine cage was not attempted, since anthraquinone itself is reduced by $NaBH_4$. Cages were prepared with 4-nitrophenyl, 2-naphthyl, 9-anthryl, 2-phenanthryl and 2-anthraquinonyl substituents at the cap 2 position or connected to the apex (1 position) as aroyl groups. All the ketonic cages in this group except the anthracene species showed ketone⇌diol equilibria in aqueous solution, but only an aroyl-substituted complex when the spectra were recorded in dimethylsulfoxide or acetone. They were all less water-soluble than their imine counterparts and eluted ahead of them from Sephadex ion exchange resin. The yield of the imine cage was greater than that of the ketonic derivative in most cases (5:3–5:2). As stated above, the reaction with 9-acetylanthracene produced only an aroyl form, possibly because the large 9-anthryl substituent inhibited the ketone–amine condensation necessary to form the imine species. Given the reaction concentrations used here, it seems likely that following the formation of a methylene imine and its condensation with the active methyl group, the intramolecular cyclization between the carbonyl group and a remaining tripodal amine is competitive with addition and subsequent condensation of a third methanal molecule to the tripod.

A second species isolated from the 9-acetylanthracene reaction contained an anthracene moiety, which was identified by NMR spectra. The ^{13}C NMR spectrum lacked an imine signal but contained a signal at $\delta = 207$ consistent with an anthryl ketone substituent and another signal at $\delta = 82$ characteristic of a methylene bridge, as also were doublets at $\delta = 5.29$ and 5.63 in the ^1H NMR spectrum.[19] These data are consistent with **9** (Scheme 3), which is formed from the addition of two coordinated methanimines to 9-acetylanthracene while a third methanimine has condensed with a secondary amine to form a methylene bridge.



9 R = 9-anthryl

Scheme 3. R = 9-anthryl.

A cage complex with an aminophenyl substituent at the cap 2 position was also prepared by reducing the nitrophenyl imine cage with tin and hydrochloric acid and then oxidizing the Co^{II} product with air.

X-ray analysis: The structure of the cage with a phenanthroyl substituent, $[Co(PhreCO,Me\text{-}sar)]Cl_3 \cdot 3.35H_2O$ (sar = 3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosane, sarcophagine), was established by X-ray crystallography; the crystal data are shown in Table 1. Atomic coordinates, bond lengths and valence angles have been deposited at the Cambridge Crystallographic Data Centre, along with the unit cell diagrams. An ORTEP plot of the complex cation (Figure 1) shows that the phenanthryl moiety is covalently attached to the apex of the cage through a carbonyl linking group; the caption gives some average bond lengths which are unexceptional for molecules of

Table 1. Crystal data for $[Co(PhreCO,Me\text{-}sar)]Cl_3 \cdot 3.35H_2O$.

formula	$C_{30}H_{48.70}Cl_3CoN_6O_{4.35}$
M_r	728.34
a, Å	9.998(3)
b, Å	12.795(3)
c, Å	15.809(3)
α, °	66.95(1)
β, °	74.72(2)
γ, °	69.51(2)
V, Å^3	1724.2(8)
Z	2
space group	$P\bar{1}$ (No. 2)
T, °C	23.0
λ, Å	0.71069 ($Mo_{K\alpha}$)
ρ_{calcd}, g cm^{-3}	1.403
$\mu(Mo_{K\alpha})$, cm^{-1}	7.74
$R(F_o)$, $R_w(F_o)$ [a]	0.036, 0.032

[a] $R(F_o) = \sum(||F_o| - |F_c||)/\sum|F_o|$, $R_w(F_o) = (\sum w(|F_o| - |F_c|)^2/\sum wF_o^2)^{1/2}$.

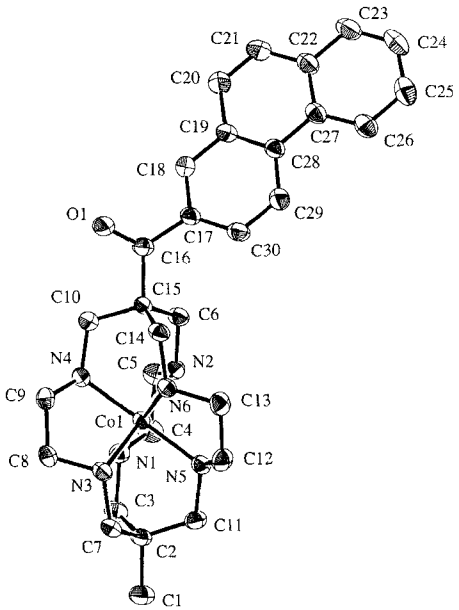


Figure 1. ORTEP diagram of the cation $[Co(PhreCO,Me\text{-}sar)]^{3+}$. Ellipsoids show 30% probability levels; H atoms have been omitted for clarity. Average bond lengths (Å): Co–N 1.967(3), C–N 1.490(10), C–C(en) 1.507(4), C–C(cap) 1.552(4), CH_3–C 1.534(4), C(O)–C(cap) 1.552(4), C(O)–C(aryl) 1.498(4). The cage and aryl bond lengths and angles are typical for entities of this kind.

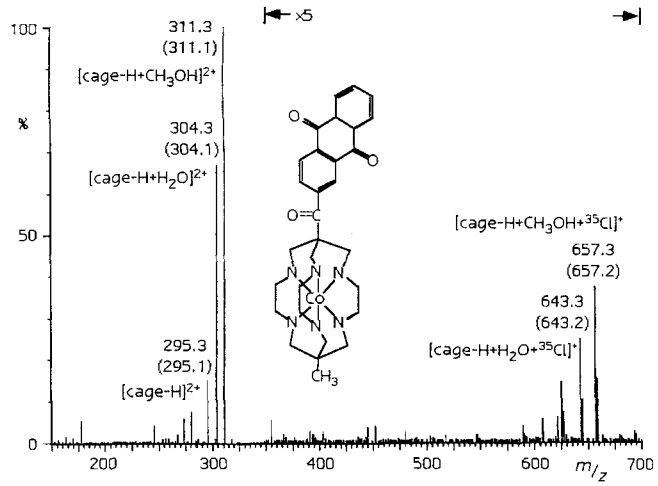


Figure 2. ESM spectrum of $[Co(AqCO,Me\text{-}sar)]^{3+}$ in aqueous methanol. $\Delta V = 50$ V (calcd m/z in brackets).

this kind. The complex adopts the lel_3 arrangement of its five-membered chelate rings, which has been the most commonly observed conformation for Co^{III}–sar-type cages.[20] The average Co–N bond length (1.967(3) Å) and twist angle (55.3(2)°) are typical for this type of molecule.[2] This is the second crystal structure determination of a Co^{III}–sar-type cage with an aromatic substituent attached to the cap. The structure of an analogous complex with a pyridine ring linked to the apex[21] did however exhibit the ob_3 conformation in the cage fragment. Both structures display extensive H-bonding between the anions and the coordinated amine H atoms but several lattice energy components, including hydrogen bonding, electrostatic effects on the packing and the nature of the charge distributions within the substituents, may determine which conformation is observed in the solid state. However both the pyridine- and the phenanthrene-substituted cage complexes in *aqueous* solutions appear to adopt largely the *lel* type conformations.

Mass spectrometry: Some of the complexes were also characterized by electrospray mass spectrometry (ESMS), a low-energy technique which has been useful in characterizing other cage molecules simply because at low skimmer voltages of 32–60 V the molecular ion is frequently the most abundant ion observed.[22] The complexes studied were the chloride salts of the following: $[Co(NpCO,Me\text{-}sar)]^{3+}$ (**4**, R = 2-naphthyl), $[Co(PhreCO,Me\text{-}sar)]^{3+}$ (**4**, R = 2-phenanthryl), $[Co(AqCO,Me\text{-}sar)]^{3+}$ (**4**, R = 2-anthraquinonyl), $[Co(2\text{-}H_3NPh,Me\text{-}sar)]^{4+}$ (**7**, R = 4-ammoniophenyl), and $[Co(2\text{-}Aq,Me\text{-}2\text{-}sarene)]^{3+}$ (**6**, R = 2-anthraquinonyl). The solvents used were aqueous acetonitrile and aqueous methanol. Representative ESM spectra (Figure 2) demonstrate simply and conclusively that the aromatic groups are covalently linked to the cobalt(III) cages; the combination of microanalysis, ^1H and ^{13}C NMR spectroscopy and ESMS is a powerful tool to help in the characterization of these molecules.

In the spectra uni-, di- and tripositive ions were clearly visible. Assignments were made based on the structures deduced from the analyses and NMR spectra; calculated and observed masses agreed to within the ESMS experimental uncertainty of ± 0.4 mass units. In all cases, an ion assigned as $[Co\ cage - H]^{2+}$ was visible and for four of the complexes it was the most abundant ion. The $[Co\ cage - H + CH_3OH]^{2+}$ ion was the most abundant ion for the anthraquinonoyl and phenanthroyl cobalt(III) cages. $[Co\ cage - H + {}^{35}Cl]^+$ and $[Co\ cage - H + {}^{37}Cl]^+$ ion pairs were also observed in all spectra. Ion triplets containing one cobalt(III) cage cation and two chloride counterions were only observed in the spectra obtained with low skimmer voltages, while ions such as $[Co\ cage - H + H_2O]^{2+}$ or $[Co\ cage - H + CH_3OH]^{2+}$ were only observed in the spectra of cage complexes with an aroyl group. This may indicate addition of methanol or water to the carbonyl centre to give the hemiketal or diol stabilized in the gas phase. At relatively low voltages (≤ 50 V) the bare complex and adducts consisting of the cation and one or more acetonitrile molecules were evident. At 90 V only the bare cation was observed and at high voltage (190 V) dissociation and fragment ions became evident.

Electronic spectroscopy: Unlike the unsubstituted cages[1, 2] only one of the ligand-field absorption bands (of origin $^1A_{1g} \rightarrow {}^1T_{1g}, O_h$) was observed, as the other was obscured by the tail of a charge-transfer absorption band from the ultraviolet region. The position of the band with parentage $^1A_{1g} \rightarrow {}^1T_{1g}$ was relatively little affected by the nature of the aromatic substituent: for the ketone and imine complexes it was observed at ≈ 470 nm, and for the saturated 2-substituted cages at ≈ 480 nm. Other studies have shown that the position of this d–d band for the sar-type cage complexes is altered significantly when substitution results in a conformational change from lel_3 to ob_3 or vice versa.[23] It is inferred therefore that the conformation in aqueous solution for these ions is largely the *lel* form.

The intensity of the band was not greatly affected by the nature of the aromatic substituents, only by their position in the

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cage frame; the molar absorption coefficient was $\approx 140\,M^{-1}cm^{-1}$ for the ketone complexes, $\approx 220\,M^{-1}cm^{-1}$ for the unsaturated cages and $\approx 200\,M^{-1}cm^{-1}$ for the saturated, cap-substituted forms. All these aromatic complexes absorbed strongly in the ultraviolet, and the absorbances due to the aromatic group were broadened and altered by the Co^{III} chromophore. The UV spectra of the phenanthrene ketone and imine cages and 2-acetylphenanthrene are shown as examples in Figure 3.

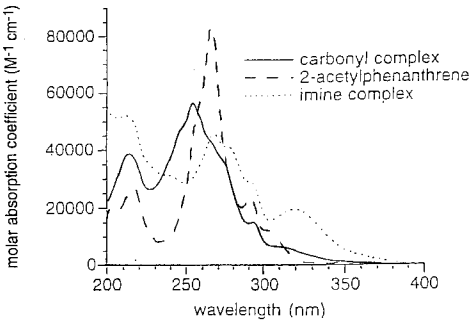

Figure 3. Ultraviolet absorption spectra of cage complexes with phenanthryl substituents: $[Co(PhreCO,Me\text{-}sar)]^{3+}$ —, $[Co(2\text{-}Phre,Me\text{-}sar\text{-}2\text{-}ene)]^{3+}$ ···. The 2-acetylphenanthrene spectrum (- - -) is shown for comparison.

Fluorescence studies: Emission and excitation spectra of several of the complexes were examined in aqueous solution. No emission was detected from the phenanthroyl Co^{III} cage complex or from its Co^{II} analogue, which was prepared by treating the former with zinc powder for 2 h. Phenanthrene-type emission was observed when the ketone group was reduced to an alcohol in solution with KBH_4 (the metal ion was concomitantly reduced to Co^{II}). This was also the case when the phenanthrene–imine cage was treated with KBH_4; the Co^{2+} ion was not lost from the cages during these processes. When the phenanthrene Co^{II} complexes were reoxidized to the Co^{III} species, some residual fluorescence was detected, but it was clearly efficiently quenched. No emission was detected from the anthracenoyl Co^{II} cage complex until after the ketone group and metal ion had been reduced in situ with KBH_4. The resulting anthracene alcohol Co^{II} form produced emission and excitation spectra. The fluorescent quantum yield of the Co^{II} cage was 0.004, but the fluorescence almost disappeared when a slightly acidic solution (pH 5) was oxidized to the Co^{III} species with oxygen. As with the analogous phenanthrene cages, the quenching was very efficient for the Co^{III} state. The fluorescence spectra from the anthracene alcohol cages are shown in Figure 4, and are similar to those obtained from other anthracene-substituted cages.[10, 11] A previous study has shown that anthracene-substituted cobalt^{III} cages only act as coupled photosensitizers and electron relays for H_2 production when the anthracene is well-separated from the metal centre by a linking group of approximately five atoms between the cage and the sensitizer.[11] It seems likely that the same situation will hold for the present molecules. These studies[10, 11] have also shown that the quenching mechanism is largely an energy transfer path. The fluorescent levels lie at higher energies but close enough to overlap with those of the Co^{III} ions at 570 nm. The marked reduction in the intensity of the Co^{II} absorption in this region limits the efficiency of the energy transfer in this oxidation state and the excited state is much longer lived.

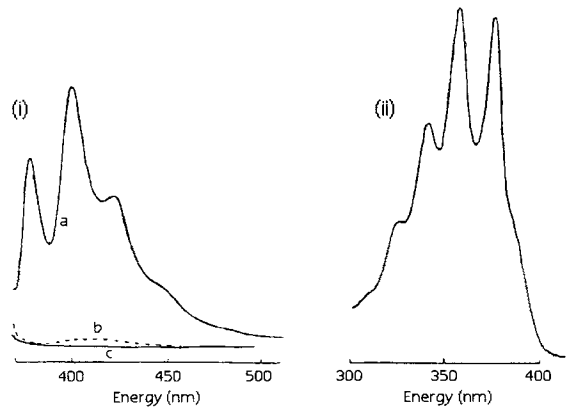

Figure 4. i) Emission spectrum of $[Co(AntCO,Me\text{-}sar)]^{3+}$ in aqueous solution a) after reduction with KBH_4, b) after reduction with KBH_4 and purging with oxygen; c) untreated solution. ii) Excitation spectrum of $[Co(AntCO,Me\text{-}sar)]^{3+}$ in aqueous solution after reduction with KBH_4.

Electrochemistry: The electrochemistry of the cage complexes was studied using cyclic voltammetry; some results are listed in Table 2. Some aromatic species exhibited weak adsorption phenomena in the oxidation wave with glassy carbon, gold and platinum electrodes and were not studied further. The nature of the aromatic substituents for the most part did not greatly affect the $Co^{III/II}$ reduction potentials. The anthraquinone–imine complex, however, showed a two-electron wave due to reduction of the anthraquinone group at -0.23 V (vs SHE) (Figure 5) and a one-electron wave at ≈ -0.5 V (vs SHE) due to the $Co^{III/II}$ couple in 0.1 M sodium acetate solution. Reduction of the metal centre would therefore lead to reduction of the quinone by intramolecular electron transfer. In 0.1 M trifluoroacetic acid, the $Co^{III/II}$ potential did not change much (0.05 V) but the anthraquinone/anthraquinol potential changed substantially to 0.12 V, that is, $\Delta E \approx 0.35$ V. This effect is probably related to protonation at the oxygen sites. Reduction of the protonated ligand would be expected at a more positive potential. The CV

Table 2. Cyclic voltammetry data for some aromatic-substituted cages (glassy carbon working electrode, saturated calomel reference electrode, scan rate 20 mVs^{-1}, 25 °C).

Cage complex	$E_{1/2}$ vs SHE (V)	ΔE_p (mV)
$[Co(PhCO,8\text{-}Me\text{-}sar)]^{3+}$ [a]	−0.38	118
$[Co(NpCO,Me\text{-}sar)]^{3+}$ [b]	−0.39	101
$[Co(AntCO,Me\text{-}sar)]^{3+}$ [b]	−0.37	63
$[Co(AntCO,Me\text{-}sar)]^{3+}$ [f,g]	−0.35	65
$[Co(2\text{-}Np,Me\text{-}sar\text{-}2\text{-}ene)]^{3+}$ [b]	−0.45	71
$[Co(2\text{-}Phre,Me\text{-}sar\text{-}2\text{-}ene)]^{3+}$ [b]	−0.45	84
$[Co(2\text{-}Aq,Me\text{-}sar\text{-}2\text{-}ene)]^{3+}$ [b]	−0.50 [c]	74
	−0.23 [d]	68
$[Co(2\text{-}Aq,Me\text{-}sar\text{-}2\text{-}ene)]^{3+}$ [f,g]	−0.45 [c]	70
	0.12 [d]	46
$[Co(2\text{-}NO_2Ph,Me\text{-}sar\text{-}2\text{-}ene)]^{3+}$ [b,g]	−0.49 [e]	68

[a] Supporting electrolyte 0.1 M $NaClO_4$. [b] Supporting electrolyte 0.1 M $NaCH_3COO$. [c] $Co^{II/III}$ couple. [d] Owing to anthraquinone reduction. [e] Two couples observed, only $Co^{II/III}$ couple reported. [f] HMDE, supporting electrolyte 0.1 M CF_3COOH. [g] Scan rate 100 mVs^{-1}.

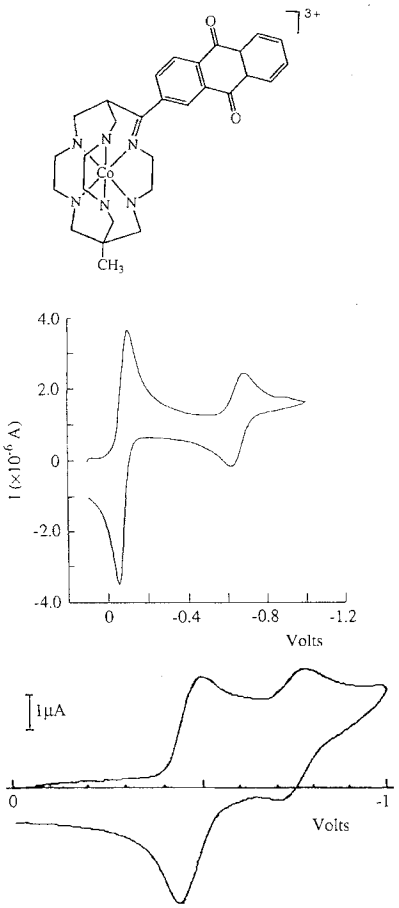

Figure 5. Cyclic voltammogram of $[Co(2\text{-}Aq.Me\text{-}sar\text{-}2\text{-}ene)]^{3+}$ in 0.1 M CF_3CO_2H (top) and in 0.1 M $NaOOCCH_3$ (bottom); scan rate 100 mVs^{-1}, HMDE working electrode, 25 °C, SCE reference.

plot from sodium acetate solution could superficially indicate some coupling between the two systems, except for the fact that the $Co^{III/II}$ potential barely changes with pH. Also, modelling of the observed CV by overlap of independent cyclic voltammograms for each couple indicates they are essentially independent.[24] The single-electron reduction of the anthraquinone was not observed (even at scan rates up to 1 Vs^{-1}), and clearly the radical product does not have a more negative potential than that of $Co^{III/II}$, otherwise the system would have been more closely coupled. On a faster timescale than our equipment offers, it might be interesting to observe the behaviour of the quinone radical.

The reduction potentials of the imine cages were less positive than those of the analogous ketone-substituted species. The electrochemistry of the anthroyl and the anthraquinone imine complexes was also measured in 0.1 M CF_3COOH using a hanging mercury drop electrode; under those conditions the reduction potentials were slightly more positive.

The data presented here show that the reduction potential of the anthraquinone moiety is more positive than any of the $Co^{III/II}$ couples in the complexes with aromatic substituents. Hence the opportunity now exists to place an electron donor (for example anthracene in its excited state linked to the cage by a longer spacer group[11]) and an electron acceptor (anthraquinone) at opposite ends of a cobalt(III) cage. After photolysis, charge separation could be achieved in a cascade, mediated by the metal ion in the centre of the cage complex. Experiments of this kind are in train with both Co and Zn complexes.

Conclusion

Methyl aryl ketones have proved to be effective reagents in the synthesis of hexaazabicycloicosane cobalt^{III} cage complexes bearing aromatic substituents. When the solvent is acetonitrile, the methyl groups in these ketones are sufficiently acidic to act as nucleophiles in the syntheses. The resulting cage complexes exhibit the same stability and other properties associated with the cobalt(III) centre that have been observed in the simpler analogues,[2] and they also have the ability to participate in reactions centred on the aromatic substituent, such as photochemical reactions in the case of phenanthrene- and anthracene-substituted cages and DNA intercalation in some instances.[12]

Experimental Section

The NMR spectra were recorded with a Varian Gemini 300 spectrometer; the solvents were D_2O, $[D_6]Me_2CO$ and $[D_6]Me_2SO$. The internal reference was dioxane (^1H NMR: $\delta = 3.70$ and ^{13}C NMR: $\delta = 67.4$ vs. $SiMe_4$). Peak assignments were made by means of DEPT spectra and by analogy with complexes containing similar chromophores. IR spectra were recorded with a Perkin–Elmer 683 spectrometer with KBr disks. Electronic spectra were obtained with a Hewlett–Packard 8450 spectrophotometer from aqueous solutions. Electrospray mass spectra (ESMS) were obtained with a Fisons/VG Biotech Quatro mass spectrometer from aqueous acetonitrile solutions. The solvent stream was aqueous methanol. Ion exchange chromatography was performed with analytical grade Dowex 50WX2 (200–400 mesh) and SP-Sephadex C-25 cation exchange resins, and evaporations were carried out with a Büchi rotary evaporator at ≈20 Torr in a water bath at less than 50 °C. Cyclic voltammetry was performed on a BAS 100 electrochemical analyser under nitrogen in 0.10 M $NaClO_4$ solutions with a glassy carbon working electrode, a platinum wire auxiliary electrode and a saturated calomel reference electrode at 25 °C. The scan rate was either 20 or 100 mVs^{-1}.

Syntheses: *Caution*! Perchlorate salts are potentially explosive!

2-Acetylanthraquinone: 2-Acetylanthraquinone was prepared by oxidation of 2-ethyl anthraquinone.[25] After recrystallization the product was purified by silica gel chromatography with dichloromethane as eluant.

General method of cage synthesis with methyl aryl ketones: $[Co(sen)]Cl_3$[26] (1.0 g), paraformaldehyde (0.30 g), $NaClO_4$ (3 g) and a methyl aryl ketone were stirred in acetonitrile (20 mL) for 10 min and triethylamine (1 mL) was added. The suspension was stirred in a stoppered flask for 4 h, acidified with acetic acid, diluted with water and filtered, and the filtrate chromatographed on SP-Sephadex. Elution of the column with 0.2 M K_2SO_4 generally produced two main orange bands (F_1 and F_2) which, after desalting on Dowex resin, were initially isolated as their crude chloride salts by rotary evaporation.

Phenyl-substituted cage complexes: The ketone used was acetophenone (1 mL).

1-Benzoyl-8-methyl-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosane cobalt(III) triperchlorate hydrate ($[Co(PhCO,Me\text{-}sar)](ClO_4)_3 \cdot H_2O$): The residue from the first band (F_1, 0.20 g, 27%) was taken up in minimum water and recrystallized as the perchlorate salt by addition of conc. $HClO_4$. ^1H NMR ($[D_6]Me_2SO$): $\delta = 0.99$ (CH_3), 2.5–3.6 (complex methylene envelope), 6.60, 6.72 (br, NH), 7.70, 7.80, 7.87 (m, arom.); ^{13}C NMR ($[D_6]Me_2SO$): $\delta = 20.4$ (CH_3), 41.3 (C_q–CH_3), 50.2, 52.2, 52.4, 57.3 (CH_2N), 53.8 (C_q–C=O), 128.2 (2C), 128.9 (2C), 132.9, 136.8 (arom.), 199.8 (C=O); anal. calcd (found) for $Co_1C_{22}H_{40}N_6O_{14}Cl_3$: C 33.97 (33.6), H 5.18 (5.2), N 10.80 (10.6), Cl 13.67 (14.3), Co 7.58 (7.6)%.

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8-Methyl-1-(phenylhydroxymethyl)-3,6,10,13,16,19-hexaazabicyclo[6.6.6]-icosane cobalt(III) trichloride ([Co(PhCH(OH),Me-sar)]·Cl_3, two diastereoisomers unresolved): [Co(PhCO,Me-sar)]$(ClO_4)_3\cdot H_2O$ (0.5 g) was dissolved in aqueous $NaHCO_3$ and treated with excess $NaBH_4$ for one hour. The solution was neutralized with acetic acid, diluted with water and chromatographed on Sephadex (during this process the product was oxidized in air to the Co^{III} cage). The column was washed with water then eluted with 3 M HCl to remove the orange–yellow title products. ^{1}H NMR (D_2O): δ = 0.85 (3H, CH_3), 2.30 3.28 (complex methylene envelope), 4.58 (1H, C*H*(OH)), 6.74 (6H, NH), 7.29 (m), 7.41 (m, 5H, arom.); ^{13}C NMR (D_2O): δ = 20.2 & 20.3 (CH_3), 42.8 & 42.9 (CH_3–*C*q), 51.4 & 51.5 (CH(OH)–*C*q), 52.0 & 52.1, 55.6 (4C), 55.6 & 55.7 (CH_2–N), 75.7 & 76.0 (CH(OH)), 128.5 & 128.6, 129.5 (2C), 129.6 & 129.7, 138.8 & 138.9 (arom.).

8-Methyl-2-phenyl-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosa-2-ene cobalt(III) sesqui(tetrachlorozincate) sesquihydrate ([Co(2-Ph,Me-sar-2-ene)]-$(ZnCl_4)_{1.5}\cdot 1.5H_2O$): The residue from the second band (F_2, 0.47 g, 46%) was crystallized as the tetrachlorozincate salt. ^{1}H NMR (D_2O): δ = 0.99 (CH_3), 2.5–4.8 (complex methylene envelope), 7.57 (m, arom.); ^{13}C NMR (D_2O): δ = 20.8 (CH_3), 41.5 (C_q–CH_3), 48.0, 48.9, 52.4, 52.6, 55.1, 55.2, 55.4, 55.6, 56.5, 57.9, 58.5 (CH_2–N), 50.7 (C_q–H), 129.1 (2C), 130.1 (2C), 132.7, 134.2 (arom.), 190.2 (C=N); anal. calcd (found) for $Co_2C_{42}H_{78}N_{12}O_3Cl_{12}Zn_3$: C 32.79 (32.8), H 5.11 (4.9), N 10.92 (10.8), Cl 27.65 (27.8), Co 7.66 (7.9)%.

8-Methyl-2-phenyl-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosane cobalt(III) chloride tetrachlorozincate ([Co(2-Ph,Me-sar]ClZnCl_4): [Co(2-Ph,Me-sar-2-ene)]$(ZnCl_4)_{1.5}\cdot 1.5H_2O$ (0.39 g) was dissolved in $NaHCO_3$ solution and treated with excess $NaBH_4$ for 5 min. The pH of the solution was adjusted to $\approx$3 with acetic acid, and the solution was chromatographed on Dowex. The column was washed with water and eluted with 6 M HCl. The product complex was isolated by rotary evaporation of the solvent and crystallized as the chloride–tetrachlorozincate salt (0.30 g, 80%). ^{1}H NMR (D_2O): δ = 0.91 (CH_3), 2.3–4.0 (complex methylene envelope), 7.51 (m, arom.); ^{13}C NMR (D_2O): δ = 20.3 (CH_3), 44.0 (C_q–CH_3), 48.1, 54.2, 54.4, 55.0, 55.2, 55.2, 55.4, 55.7, 56.2, 57.9, 58.5 (CH_2–N), 54.7 (C_q–H), 67.3 (*C*H(C_6H_5)), 127.5 (2C), 130.3 (2C), 130.4, 135.8 (arom.); anal. calcd (found) for $Co_1C_{21}H_{38}N_6Cl_5Zn_1$: C 37.30 (37.2), H 5.66 (5.9), N 12.43 (12.3), Cl 26.22 (26.4), Co 8.72 (8.7)%.

Nitrophenyl-substituted cage complexes: The ketone was 4′-nitroacetophenone (0.5 g).

8-Methyl-1-(4-nitrobenzoyl)-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosane cobalt(III) trichloride trihydrate ([Co(NO_2PhCO,Me-sar)]$Cl_3\cdot 3H_2O$): The first fraction (F_1, 0.41 g, 30%) was recrystallized from water. Anal. calcd (found) for $[Co(C_{22}H_{37}N_7O_3]Cl_3\cdot 2.5H_2O$: C 40.16 (40.4), H 6.43 (6.6), N 14.91 (15.0), Cl 16.16 (16.3)%. The chloride salt was converted to the triflate salt to record the NMR spectra. ^{1}H NMR ([D_6]acetone): δ = 1.20 (3H, CH_3), 2.82–3.96 (complex methylene envelope), 6.57 (br, NH), 6.71 (br, NH), 8.04 (d, 2H, arom.), 8.46 (d, 3H, arom.); ^{13}C NMR ([D_6]acetone): δ = 19.4 (CH_3), 42.6 (C_q–CH_3), 51.7, 55.0, 55.1, 55.2 (CH_2–N), 58.8 (C_q–C=O), 114.4, 118.6, 122.8, 127.1 ($CF_3SO_3^-$), 123.9, 128.9, 143.4, 149.7 (arom.), 199.6 (C=O); UV/Vis (water): λ_{max} (ε_{max}) = 466 (137), 247 (21400), 216 nm (17300 $dm^3cm^{-1}mol^{-1}$).

8-Methyl-2-(4-nitrophenyl)-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosa-2-ene cobalt(III) trichloride trihydrate ([Co(2-NO_2Ph,Me-sar-2-ene)]$Cl_3\cdot 3H_2O$): The second fraction (F_2, 0.96 g, 70%) was recrystallized as the chloride salt. Anal. calcd (found) for $[Co(C_{22}H_{37}N_7O_3]Cl_3\cdot 2.5H_2O$: C 40.16 (40.4), H 6.43 (6.6), N 14.91 (15.0), Cl 16.16 (16.3)%; ^{1}H NMR (D_2O): δ = 1.02 (3H, CH_3), 2.59–3.65 (complex methylene envelope), 7.87 (d, 2H, arom.), 8.44 (d, 2H, arom.); ^{13}C NMR (D_2O): δ = 20.8 (CH_3), 41.7 (CH_3C_q), 47.9, 48.6, 52.7, 52.8, 55.0, 55.3, 55.7, 56.4, 58.3 (N–CH_2), 50.5 (CH), 125.29, 130.30, 138.22, 150.52 (arom.), 188.7 (C=N); UV/Vis (water): λ_{max} (ε_{max}) = 468 (217), 296 sh (9980), 266 nm (20300 $dm^3cm^{-1}mol^{-1}$).

8-Methyl-2-(4-nitrophenyl)-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosane-cobalt(III) triperchlorate trihydrate ([Co(2-NO_2Ph,Me-sar)]$(ClO_4)_3\cdot 3H_2O$): [Co(2-NO_2Ph,Me-sar-2-ene)]Cl_3 was reduced with aqueous sodium borohydride as described above. There was some accompanying reduction of the nitro group (< 5%) and the resulting ammoniophenyl-substituted cage easily separated on Dowex resin with 3 M HCl. The major product was dissolved in the minimum volume of water and precipitated by dropwise addition of concentrated sodium perchlorate solution. Anal. calcd (found) for $[Co(N_7C_{21}H_{37}O_2)](ClO_4)_3\cdot 3H_2O$: C 30.35 (30.2), H 5.22 (5.2), N 11.80 (11.9), Cl 12.80 (13.1)%; ^{1}H NMR (D_2O): δ = 0.98 (3H, CH_3), 2.4–4.3 (complex methylene envelope), 7.85 (d, 2H, arom.), 8.26 (d, 2H, arom.); ^{13}C NMR (D_2O): δ = 20.4 (CH_3), 42.5, 44.0, 48.1, 54.2, 54.4, 54.4, 55.3, 55.6, 56.1, 56.5, 67.1, 67.2 (N–CH_2, N–CH, CH_3–C_q, HC_{apex}), 125.2, 129.1, 142.9, 148.6 (arom.); UV/Vis (water): λ_{max} (ε_{max}) = 482 (214), 259 (28264), 215 nm (21794 $dm^3cm^{-1}mol^{-1}$).

2-(4-Aminophenyl)-8-methyl-3,6,10,13,16,19-hexaazabicyclo[6.6.6] icosane cobalt(III) trichloride hydrate ([Co(2-(4-H_2NPh),Me-sar)]$Cl_3\cdot xH_2O$): [Co(2-NO_2Ph,Me-sar)]Cl_3 (0.755 g) and Sn (4.5 g) were placed in a round-bottomed flask (50 mL) equipped with a reflux condenser and conc. HCl (10 mL) was added slowly with stirring. The mixture was stirred for one hour on a water bath, cooled to $\approx$20 °C, diluted with water to 1 L and filtered to remove the unreacted tin. The filtrate was sorbed onto Dowex and eluted with 3 M HCl. The complex was recrystallized from water and ethanol. Yield 0.74 g, 98%. ^{1}H NMR (D_2O): δ = 0.96 (3H, CH_3), 2.3–4.1 (complex methylene envelope), 7.54 (d, 2H, arom.), 7.76 (d, 2H, arom.); ^{13}C NMR (D_2O): δ = 20.3 (CH_3), 42.4, 43.8, 48.1, 54.2, 54.3, 54.5, 55.1, 55.2, 55.5, 55.9, 56.3 (H–C_{apex}, CH_3–C_q, N–CH_2), 66.9 (N–CH), 124.9, 129.5, 131.5, 136.9 (arom.); UV/Vis (water): λ_{max} (ε_{max}) = 481 (227), 244 nm (34992 $dm^3cm^{-1}mol^{-1}$); low-resolution ESMS [*m*/*z* obs (calcd) (%) assignment where cage = $[^{59}Co^{14}N_7{}^{12}C_{21}{}^1H_{39}]^{3+}$ (50 V)]: 223.5 (223.6) (100%) [cage – H]$^{2+}$, 446.3 (446.2) (20%) [cage – 2H]$^+$, 482.2 (482.2) (45%) [cage – H + ^{37}Cl]$^+$. The presence of an aromatic amine was confirmed by diazotization of a small sample.

2-Naphthalene-substituted cages: The ketone used was 2′-acetonaphthone (0.50 g). The synthesis was as described except that fractions eluted from Sephadex were desalted on Dowex with 6 M HCl/ethanol.

8-Methyl-1-(2-naphthoyl)-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosane cobalt(III) trichloride trihydrate ([Co(NpCO,Me-sar)]$Cl_3\cdot 3H_2O$): The first fraction (F_1, 0.48 g, 34%) was recrystallized from hot water. Anal. calcd (found) for $[Co(C_{26}H_{40}N_6O]Cl_3\cdot 3H_2O$: C 45.26 (45.2), H 7.01 (6.9), N 12.18 (12.0), Cl 15.41 (15.4)%. The chloride salt was converted to the triflate to record the NMR spectra. ^{1}H NMR ([D_6]acetone): δ = 1.19 (3H, CH_3), 2.82–4.04 (complex methylene envelope), 6.57 (HN), 6.72 (HN), 7.81 (m, 3H, arom.), 8.14 (m, 3H, arom.), 8.48 (1H, arom.); ^{13}C NMR ([D_6]acetone): δ = 19.5 (CH_3), 42.4 (CH_3–C_q), 52.2, 52.4, 54.9, 55.0, 55.1 (N–CH_2), 59.1 (C_q–C=O), 114.3, 118.6, 122.8, 127.0 ($CF_3SO_3^-$), 124.3, 127.4, 127.9, 128.7, 128.9, 129.0, 129.6, 132.3, 134.4, 135.0 (arom.), 198.7 (C=O); UV/Vis (water): λ_{max} (ε_{max}) = 468 (134), 251 (31100), 223 nm (51800 $dm^3cm^{-1}mol^{-1}$); low-resolution ESMS [*m*/*z* obs (calcd) assignment where cage = $[^{59}Co^{14}N_6{}^{12}C_{26}{}^1H_{40}{}^{16}O]^{3+}$ (32 V)]: 255.2 (255.1) [cage – H]$^{2+}$, 264.2 (264.1) [cage – H + H_2O]$^{2+}$, 275.7 (275.6) [cage – H + CH_3CN]$^{2+}$, 545.5 (545.2) [cage – H + ^{35}Cl]$^+$, 546.9 (547.2) [cage – H + ^{37}Cl]$^+$, 581.3 (581.2) [cage + 2 ^{35}Cl]$^+$, 583.2 (583.2) [cage + ^{35}Cl + ^{37}Cl]$^+$, 591.4 (591.3) [cage – 2H + 2CH_3CN]$^+$, 599.2 (599.2) [cage + H_2O + 2 ^{35}Cl]$^+$.

8-Methyl-2-(2-naphthyl)-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosa-2-ene cobalt(III) triperchlorate sesquihydrate ([Co(2-Np,Me-sar-2-ene)]$(ClO_4)_3\cdot 1.5H_2O$): The second fraction (F_2, 0.75 g, 54%) was recrystallized from water as the perchlorate salt with conc. sodium perchlorate solution. Anal. calcd (found) for $[Co(C_{25}H_{38}N_6)](ClO_4)_3\cdot 1.5H_2O$: C 37.21 (37.3), H 5.12 (5.0), N 10.42 (10.4), Cl 13.18 (12.9)%; ^{1}H NMR (D_2O): δ = 1.00 (3H, CH_3), 2.56–4.69 (complex methylene envelope), 7.58 (d, 1H, arom.), 7.60 (m, 2H, arom.), 8.04 (m, 3H, arom.), 8.17 (1H, arom.); ^{13}C NMR (D_2O): δ = 20.8 (CH_3), 41.5 (C_q–CH_3), 50.7 (H–C_{apex}), 48.1, 49.1, 52.2, 52.4, 50.0, 55.1, 55.4, 55.6, 56.5, 57.9, 58.7 (HN–CH_2), 124.5, 128.7, 128.8, 129.9, 129.9, 130.1, 130.3, 130.8, 132.8, 135.6 (arom.), 190.1 (C=N); UV/Vis (water): λ_{max} (ε_{max}) = 470 (229), 308 (15300), 258 (40700), 212 nm (45800 $dm^3cm^{-1}mol^{-1}$).

8-Methyl-2-(2-naphthyl)-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosane-cobalt(III) trichloride trihydrate ([Co(2-Np,Me-sar)]$Cl_3\cdot 3H_2O$): [Co(Np,Me-sar-2-ene)]$(ClO_4)_3$ was reduced with aqueous sodium borohydride as described above and desalted on Dowex to give the chloride salt. Anal. calcd

(found) for $[Co(C_{25}H_{40}N_6]Cl_3\cdot 3H_2O$: C 46.63 (46.4), H 7.20 (7.5), N 13.05 (12.9), Cl 16.52 (16.5)%; ^{1}H NMR (D_2O): $\delta = 0.91$ (3H, CH_3), 2.15–3.86 (complex methylene envelope), 7.28 (d, 1H, arom.), 7.48 (q, 2H, arom.), 7.78 (t, 2H, arom.), 7.90 (d, 1H, arom.), 8.09 (1H, arom.); ^{13}C NMR (D_2O): $\delta = 21.3$ (CH_3), 43.4 (C_q–CH_3), 44.9, 45.0, 48.8, 54.9, 55.0, 55.1, 55.3, 55.4, 56.3, 56.4, 57.0, 57.4 (N–CH_2, C_{apex}), 68.6 (NC(H)Np), 126.5, 126.6, 129.2, 129.3, 129.6, 130.0, 131.2 (arom.), 134.0, 134.4, 134.5 (C_q, arom.); UV/Vis (water): λ_{max} (ε_{max}) = 482 (199), 245 (24995), 223 nm (96960 $dm^3cm^{-1}mol^{-1}$).

2-Phenanthrene-substituted cages: The ketone used was 2-acetylphenanthrene (0.7 g). The reaction mixture from the synthesis described above was diluted, filtered, and the filtrate chromatographed on Dowex. Elution with 3M HCl removed some partially capped species. Conc. HCl/EtOH separated the cage species, which were evaporated to dryness, dissolved in water and sorbed onto Sephadex. Two fractions (F_1 and F_2) were eluted with 0.2M K_2SO_4 and desalted with conc. HCl/ethanol.

8-Methyl-1-(2-phenanthroyl)-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosane cobalt(III) trichloride trihydrate ([Co(PhreCO,Me-sar)]$Cl_3\cdot 3H_2O$): The first fraction (F_1, 0.43 g, 27%) was recrystallized from hot water as the chloride salt. Anal. calcd (found) for $[Co(C_{30}H_{42}N_6O)]Cl_3\cdot 3H_2O$: C 49.90 (49.5), H 6.70 (6.5), N 11.64 (11.4), Cl 14.73 (14.7)%. The complex was converted to the triflate salt to record the NMR spectra in $[D_6]Me_2SO$. ^{1}H NMR ($[D_6]Me_2SO$): $\delta = 0.85$ (3H, CH_3), 2.50–3.60 (complex methylene envelope), 6.51 (br, 3H, NH), 6.66 (br, 3H, NH), 7.78, 8.01, 8.35, 8.95 (centres of multiplets of arom. H); ^{13}C NMR ($[D_6]Me_2SO$): $\delta = 20.4$ (CH_3), 41.3 (Cq–CH_3), 50.3, 52.3, 52.5, 53.8 (CH_2N), 57.6 (Cq–C=O), 118.7, 123.0, 123.8, 125.4, 127.2, 128.3, 129.0, 129.1 (2C), 131.0, 132.3, 132.6, 135.0 (arom.), 200.0 (C=O); UV/Vis: λ_{max} (ε_{max}) = 468 (144), 293 (15200), 254 (56500), 214 nm (38800 $dm^3cm^{-1}mol^{-1}$); low-resolution ESMS [*m/z* obs (calcd) assignment where cage = $[^{59}Co^{14}N_6{}^{12}C_{30}{}^{1}H_{42}{}^{16}O]^{3+}$ and cage* = $[^{59}Co^{14}N_6{}^{12}C_{29}{}^{13}C^{1}H_{42}{}^{16}O]^{3+}$ (60 V)]: 280.3 (280.1) [cage – H]$^{2+}$, 289.4 (289.1) [cage – H + H_2O]$^{2+}$, 296.4 (296.1) [cage – H + CH_3OH]$^{2+}$, 559.4 (559.3) [cage – 2H]$^+$, 560.4 (560.3) [cage* – 2H]$^+$, 591.4 (591.3) [cage – 2H + CH_3OH]$^+$, 595.3 (595.2) [cage – H + ^{35}Cl]$^+$, 596.2 (596.2) [cage* – H + ^{35}Cl]$^+$, 597.4 (597.2) [cage – H + ^{37}Cl]$^+$, 613.4 (613.2) [cage – H + ^{35}Cl + H_2O]$^+$, 627.4 (627.3) [cage – H + ^{35}Cl + CH_3OH]$^+$, 628.4 (628.3) [cage* – H + ^{35}Cl + CH_3OH]$^+$, 629.4 (629.3) [cage – H + ^{37}Cl + CH_3OH]$^+$.

8-Methyl-2-(2-phenanthryl)-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosa-2-ene cobalt(III) trinitrate sesquihydrate ([Co(2-Phre,Me-sar-2-ene)]$(NO_3)_3\cdot 1.5H_2O$): The second fraction (F_2, 0.71 g, 48%) was recrystallized from water as the nitrate salt. Anal. calcd (found) for $[Co(C_{29}H_{40}N_6)](NO_3)_3\cdot 1.5H_2O$: C 46.77 (46.9), H 5.82 (5.8), N 16.93 (16.9)%; ^{1}H NMR spectrum (D_2O): $\delta = 1.00$ (3H, CH_3), 2.21–3.72 (complex methylene envelope), 7.20–7.39 (m, 6H, arom.), 7.78 (1H, arom.), 7.85 (1H, arom.), 7.92 (d, 1H, arom.); ^{13}C NMR (D_2O): $\delta = 20.8$ (CH_3), 41.7 (CH_3–C_q), 50.6 (N–*C*H(Phre)), 47.8, 48.7, 53.1, 55.3, 55.7, 56.3, 58.1 (N–CH_2 & H–C_{apex}), 123.8, 124.4, 125.3, 127.2, 127.9, 129.0, 129.1, 129.9, 130.1, 131.5, 132.6, 133.0 (arom.), 188.8 (C=N); UV/Vis (water): λ_{max} (ε_{max}) = 466 (247), 319 (19700), 291 sh (31100), 277 sh (46100), 268 (51800), 241 (33800), 211 nm (52100 $dm^3cm^{-1}mol^{-1}$).

8-Methyl-2-(2-phenanthryl)-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosane cobalt(III) trichloride trihydrate ([Co(2-Phre,Me-sar)]$Cl_3\cdot 3H_2O$): [Co(2-Phre,Me-sar-2-ene)]$Cl_3\cdot 3H_2O$ was reduced with aqueous sodium borohydride as described above. The crude chloride salt was recrystallized from water. Anal. calcd (found) for $[Co(C_{29}H_{48}N_6)]Cl_3\cdot 3H_2O$: C 50.19 (50.3), H 6.97 (6.6), N 12.11 (12.1)%; ^{1}H NMR (D_2O): $\delta = 0.90$ (3H, CH_3), 2.28–3.45 (complex methylene envelope), 7.43 (d, 1H, arom.), 7.68–7.96 (m, 6H, arom.), 8.58 (m, 2H, arom.); ^{13}C NMR (D_2O): $\delta = 20.3$ (CH_3), 42.4, 43.2 (*C*–CH_3, C_{apex}H), 47.8, 53.7, 54.5, 54.6, 54.8, 55.2, 55.4, 55.5, 55.6 (2C), 56.1 (CH_2–N), 66.3 (*C*H(phre)), 123.8, 124.9, 125.5, 126.4, 127.5, 128.3, 128.5, 128.8, 129.6, 130.0, 130.5, 132.4, 132.8, 133.7 (phenanthrene C).

9-Anthracene-substituted cage: The ketone used was 9-acetylanthracene (0.7 g) and the synthesis was as described above. After dilution, the reaction solution was filtered and the filtrate chromatographed on Dowex. Elution with 3M HCl removed some incompletely reacted species; the cage and then one other complex were removed with conc. HCl/ethanol. The latter two species were isolated by rotary evaporation of solvent and sorbed onto Sephadex. One fraction (F_1) was eluted with 0.2M K_2SO_4 and a second one (F_2) with 0.5M K_2SO_4; they were isolated as their crude chloride salts after desalting on Dowex.

1-(9-Anthracenoyl)-8-methyl-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosane cobalt(III) trichloride hydrate ([Co(AntCO,Me-sar)]$Cl_3\cdot 2.5H_2O$): The first fraction (F_1, 1.06 g, 68%) was recrystallized from hot water as the chloride salt. Anal. calcd (found) for $[CoN_6C_{30}H_{42}O]Cl_3\cdot 2.5H_2O$: C 50.53 (50.6), H 6.64 (6.4), N 11.78 (11.5)%. The complex was converted to its acetate salt to record the NMR spectra. ^{1}H NMR (D_2O): $\delta = 0.85$ (3H, CH_3), 1.92 (9H, $CH_3CO_2^-$), 2.21–3.39 (complex methylene envelope), 7.40 (m, 4H, arom.), 7.53 (m, 2H, arom.), 7.69 (m, 2H, arom.), 8.08 (1H, arom.); ^{13}C NMR (D_2O): $\delta = 20.2$ (CH_3), 24.0 ($CH_3CO_2^-$), 42.6 (CH_3–C_q), 53.0, 55.5 (N–CH_2), 60.8 (C_q–C=O), 123.9, 126.8, 127.2, 127.3, 129.2, 130.1, 130.7, 131.0, 131.5 (arom.), 182.6 ($CH_3CO_2^-$), 209.3 (C=O); UV/Vis (water): λ_{max} (ε_{max}) = 466 (153), 389 (6050), 369 (6850), 352 (5280), 335 sh (3480), 319 sh (2130), 253 (52100), 247 sh (41800), 216 nm (10400 $dm^3cm^{-1}mol^{-1}$).

3-(9-Anthracenoyl)-10-methyl-1,5,8,12,15,19-hexaazabicyclo[8.6.4]icosane cobalt(III) trichloride (9): F_2 was desalted (conc. HCl/ethanol) and the residue after rotary evaporation was extracted with warm ethanol. The extract was filtered and the filtrate diluted with water and chromatographed on Dowex. The column was washed with acetone and eluted with ethanol/conc. HCl. The product was isolated by rotary evaporation of the solvent and was recrystallized from water as the chloride salt. ^{1}H NMR (D_2O): $\delta = 1.00$ (CH_3), 2.23–4.16 (complex methylene envelope), 5.29, 5.63 (dd, $J = 12$ Hz, N–CH_2–N), 7.08, 7.21, 7.38, 7.54, 7.67 (m, arom.); ^{13}C NMR (D_2O): $\delta = 19.8$ (CH_3), 47.8 (Cq), 45.4, 48.6, 50.4, 51.5, 52.3, 52.5, 53.3, 54.8, 56.9, 63.1, 64.7 (CH_2–C=O, C CH_2 NH), 82.3 (N–CH_2–N), 124.2, 126.6, 128.0, 128.9, 129.6, 130.0, 130.9, 132.5 (anthryl carbons), 207.3 (C=O). This complex decomposes in $NaBH_4$ solution and it was not characterized further.

2-Anthraquinone-substituted cages: The ketone used was 2-acetylanthraquinone (0.7 g, 3 mmol). The reaction mixture from the synthesis described above was diluted and filtered, and the filtrate chromatographed on Dowex. Elution with 3M HCl removed some partially capped species. Conc. HCl/EtOH removed the cage species, which were evaporated to dryness, dissolved in water and sorbed onto Sephadex. Two fractions (F_1 and F_2) were eluted with 0.2M K_2SO_4 and were desalted with conc. HCl/ethanol.

1-(2-Anthraquinonoyl)-8-methyl-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosane cobalt(III) trichloride hydrate ([Co(AqCO,Me-sar)]$Cl_3\cdot 2.5H_2O$): The first cage (F_1, 0.252 g, 17%) was recrystallized from hot water as the chloride salt. Anal. calcd (found) for $[CoC_{30}H_{40}N_6O_3]Cl_3\cdot 2.5H_2O$: C 48.49 (48.3), H 6.10 (6.0), N 11.31 (11.2)%. The complex was converted to the triflate salt to record the NMR spectra. ^{1}H NMR ($[D_6]$acetone): $\delta = 1.19$ (3H, CH_3), 2.80–4.09 (complex methylene envelope), 6.59 (br, 3H, HN), 7.74 (3H, NH), 8.08–8.47 (7H, arom.); ^{13}C NMR ($[D_6]$acetone): $\delta = 19.4$ (CH_3), 42.7 ($CqCH_3$), 51.8, 55.0, 55.2, 55.3 (N–CH_2), 58.9 (C_qC=O), 126.1, 127.3, 127.5, 132.2, 133.6, 133.9, 135.9, 143.0 (arom.), 181.9 (C=O, anthraquinone), 200.0 (C=O); IR: $\tilde{\nu}_{max} = 1680$ cm^{-1} (C=O stretch); UV/Vis (water): λ_{max} (ε_{max}) = 468 (143), 333 (5090), 277 sh (15000), 256 (54800), 206 nm (32800 $dm^3cm^{-1}mol^{-1}$); low-resolution ESMS [*m/z* obs (calcd) assignment where cage = $[^{59}Co^{14}N_6{}^{12}C_{30}{}^{1}H_{40}{}^{16}O_3]^{3+}$ (60 V)]: 295.3 (295.1) [cage – H]$^{2+}$, 304.3 (304.1) [cage – H + H_2O]$^{2+}$, 311.3 (311.1) [cage – H + CH_3OH]$^{2+}$, 589.3 (589.2) [cage – 2H]$^+$, 607.3 (607.2) [cage – 2H + H_2O]$^+$, 621.3 (621.3) [cage – 2H + CH_3OH]$^+$, 625.3 (625.2) [cage – H + ^{35}Cl]$^+$, 627.3 (627.2) [cage – H + ^{37}Cl]$^+$, 643.3 (643.2) [cage – H + ^{35}Cl + H_2O]$^+$, 645.3 (645.2) [cage – H + ^{37}Cl + H_2O]$^+$, 657.3 (657.2) [cage – H + ^{35}Cl + CH_3OH]$^+$, 659.3 (659.2) [cage – H + ^{37}Cl + CH_3OH]$^+$.

2-(2-Anthraquinonyl)-8-methyl-3,6,10,13,16,19-hexaazabicyclo[6.6.6]icosa-2-ene cobalt(III) chloride diperchlorate hydrate ([Co(2-Aq,Me-sar-2-ene)]-Cl$(ClO_4)_2\cdot 4.5H_2O$): The second cage (F_2, 0.620 g, 40%) was recrystallized from water as the chloride–diperchlorate with aqueous sodium perchlorate solution. Anal. calcd (found) for $[Co(N_6C_{29}H_{38}O_2)](ClO_4)_2Cl\cdot 4.5H_2O$: C 39.71 (39.6), H 5.40 (5.1), N 9.58 (9.6), Cl 12.13 (11.8)%. ^{1}H NMR (D_2O): $\delta = 1.09$ (3H, CH_3), 2.65–4.11 (complex methylene envelope), 7.46–7.95, (m, 7H, arom.); ^{13}C NMR (D_2O): $\delta = 20.8$ (CH_3), 41.9 (C_qCH_3), 50.5 (H–C_{apex}), 48.7, 53.0, 55.0, 55.2, 55.4, 55.9, 56.5, 58.2, 58.2, 58.3, 58.3 (N–

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CH_2), 127.0, 127.9, 128.8, 134.5, 134.6, 135.0, 136.4 (CH, arom.), 132.4, 132.5, 133.4, 138.1 (C_q, arom.), 182.6, 182.8 (C=O, anthraquinone), 188.0 (C=N); IR: $\tilde{\nu}_{max} = 1675\,cm^{-1}$ (C=O stretch); UV/Vis: λ_{max} (ε_{max}) = 468 (230), 331 (8400), 261 (58000), 223 nm (31900 $dm^3 cm^{-1} mol^{-1}$); low-resolution ESMS [*m*/*z* obs (calcd) assignment where cage = $[^{59}Co^{14}N_6{}^{12}C_{29}{}^{1}H_{38}{}^{16}O_2]^{3+}$, cage* = $[^{59}Co^{14}N_6{}^{12}C_{28}{}^{13}C_1{}^{1}H_{38}{}^{16}O_2]^{3+}$, cage** = $[^{59}Co^{14}N_6{}^{12}C_{27}{}^{13}C_2{}^{1}H_{38}{}^{16}O_2]^{3+}$, 60 V]: 280.3 (280.1) [cage − H]$^{2+}$, 559.3 (559.2) [cage − 2H]$^{+}$, 595.3 (595.2) [cage − H + ^{35}Cl]$^{+}$, 597.3 (597.2) [cage − H + ^{37}Cl]$^{+}$; ESMS (water): 187.4 (187.1) [cage]$^{3+}$, 187.7 (187.4) [cage*]$^{3+}$, 188.0 (187.7) [cage**]$^{3+}$, 193.3 (193.1) [cage + H_2O]$^{3+}$.

The ^{1}H NMR spectra in D_2O were recorded for all the ketone-substituted cages to establish the hydration of the carbonyl group.

X-ray crystallography: Crystals were obtained from a 6 M HCl/EtOH solution of [Co(PhreCO,Me-sar)]Cl_3 by slow evaporation at room temperature.

Data collection and reduction: A yellow plate crystal of $C_{30}H_{48.70}Cl_3CoN_6O_{4.35}$ was attached to a quartz fibre and mounted on a Rigaku AFC6S diffractometer equipped with a graphite monochromator. The diameter of the incident beam collimator was 0.5 mm, the crystal to detector distance was 200 mm, and the detector aperture was 8.0 × 4.0 mm (horizontal × vertical). Lattice parameters were determined with $Mo_{K\alpha}$ radiation by least-squares refinement of the setting angles of 25 reflections in the range $32 < 2\theta < 36°$. The data were collected at a temperature of 23(1) °C by the $\omega - 2\theta$ scan technique to a maximum value of 50.1°. Scans of $(1.40 + 0.34\tan\theta)°$ in ω were made at a speed of 2.0 ° min^{-1} in ω (weak reflections were measured with up to 4 scans) with background counts for one sixth of the scan time on each side of every scan. Three representative reflections measured at intervals of 150 reflections showed no significant decrease in intensity during data collection. The data set was reduced, an analytical absorption correction applied, and Lorentz and polarization effects were accounted for. Crystallographic data (excluding structure factors) for the structure reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-100424. Copies of the data can be obtained free of charge on application to The Director, CCDC, 12 Union Road, Cambridge CB21EZ, UK (Fax: Int. code +(1223)336-033; e-mail: deposit@chemcrys.cam.ac.uk).

Structure solution and refinement: The structure was solved by direct methods[27] and expanded by Fourier techniques.[28] A diffuse area of electron density within the lattice was assumed to arise from disordered water molecules of solvation, and has been modelled by adding isotropic oxygen atoms, with occupancies set at appropriate values, at local maximum points. All other non-hydrogen atoms were refined anisotropically. Hydrogen atoms for the cation were included at calculated positions but were not refined. The final cycle of full-matrix least-squares refinement was based on 4513 observed reflections $\{I > 3.00\sigma(I)\}$ and 398 variable parameters and converged (largest parameter shift was 0.05 × its esd) with unweighted and weighted agreement factors of $R = \sum||F_o| - |F_c||/\sum|F_o| = 0.036$ and $R_w = [(\sum w(|F_o| - |F_c|)^2/\sum wF_o)^2]^{0.5} = 0.032$. The standard deviation of an observation of unit weight was 2.34. The weighting scheme was based on counting statistics and included a factor ($p = 0.005$) to downweight the intense reflections. Plots of $(\sum w(|F_o| - |F_c|)^2$ versus $|F_o|$, reflection order in data collection, $\sin\theta/\lambda$ and various classes of indices showed no unusual trends. The maximum and minimum peaks on the final difference Fourier map corresponded to 0.50 and −0.36 e^- Å^{-3}, respectively. Neutral atom scattering factors were taken from Cromer and Waber.[29] Anomalous dispersion effects were included in F_c;[30] the values for $\Delta f'$ and $\Delta f''$ were those of Creagh and McAuley.[31] The values of mass attenuation coefficients are those of Creagh and Hubbel.[32] All calculations were performed using the teXsan[33] crystallographic software package from Molecular Structure Corporation.

Fluorescence spectroscopy: Fluorescence and excitation spectra were recorded on aqueous solutions of the relevant cage complexes using a MFP4 Perkin Elmer spectrofluorimeter. Samples of the anthracene and phenanthrene ketone cage Co^{III} complexes were dissolved in water; the spectra were recorded initially and then after treatment with zinc dust for one hour to produce the Co^{II} aryl ketone cage complexes. The experiment was repeated with KBH_4 to reduce the metal ion to Co^{II} and the ketone groups to alcohols. Finally the solutions were acidified and purged with oxygen and the fluorescence spectra recorded again.

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