Control of the hierarchical self-assembly of polyoxometalate-based metallomacrocycles by redox trigger and solvent composition

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Discrete metallomacrocycles are attractive scaffolds for the formation of complex supramolecular architectures with emergent properties. We herein describe the formation of hierarchical nanostructures using preformed metallo-macrocycles by coordination-driven self-assembly of a covalent organic-inorganic polyoxometalate (POM)-based hybrid. In this system, we take advantage of the presence of charged subunits (POM, metal linker, and counterions) within the metallo-macrocycles, which drive their aggregation through inter-molecular electrostatic interactions. We show that the solvent composition and the charge of the metal linker are key parameters that steer the supramolecular organization. Different types of hierarchical self-assemblies, zero-dimensional (0D) dense nanoparticles, and 1D worm-like nanoobjects, can be selectively formed owing to different aggregation modes of the metallo-macrocycles. Finally, we report that the worm-like structures drastically enhance the solubility in water of a pyrene derivative and can act as molecular carriers.

Significance

Hierarchical self-assembly is a powerful route allowing the elaboration of complex supramolecular architectures with emergent structuration or properties. Starting from well-defined molecular building units, this synthetic strategy relies on the construction of a preassembled structural motif that can further self-assemble through additional noncovalent interactions. In this context, we developed a system based on a covalent organic-inorganic polyoxometalate hybrid building block combining metal-driven self-assembly and electrostatic interactions. We herein show that in this system, the supramolecular organization can be controlled by a redox stimulus and/or the solvent composition giving rise to various types of nanoarchitectures from discrete metallo-macrocycles to 1D worm-like nanoobjects.

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POM-based metallomacrocycles through the increase of the cation linker charge. We also show that these worm-like nanostructures also form in DMSO/water mixtures. We thus report that using a single molecular building block different supramolecular organizations can be obtained according to the redox state of the metal linker (+2 and +3) and the solvent composition (DMSO, DMSO/MeCN, DMSO/H₂O). Finally, we show that these nanoaggregates drastically enhance the solubility in water of a pyrene derivative and can thus act as molecular carriers.

Results and Discussion

Complexation of the POM-Based Building Block to [Co(H₂O)₆](NO₃)₂. The starting POM-based building block (TBA)₆[P₆₋₆W₁₋₆O₃₁{(OSi₆R₆H₁₈N₆)₂}] denoted I contains two terpyridine (tpy) units connected to the lacuna of the Dawson-type POM α₆[P₆₋₆W₁₋₆O₃₁] through a Si-O-Si anchorage (Fig. 1). Organosilanyl derivatives of monovacant lacunary POMs, either in the Keggin (i.e., [PW₁₀O₃₆(O(SiR)₆)]⁻) or Dawson (i.e., [P₆₋₆W₁₋₆O₃₁(O(SiR)₆)]⁰) series display very similar structures with orthogonal organic arms (25–27). Density functional theory calculations of I converged to an energy-minimized structure in which the angle between the arms was slightly higher (~97°) (21). In our previous study (21), the metal-directed self-assembly of this hybrid was performed using Fe(II) salts since the Fe(II) bis(terpyridine) complexes are diamagnetic (which facilitates NMR characterization) and display high stability. Upon the addition of one equiv of [Fe(H₂O)₆]ClO₄ onto I in DMSO-d₆, a single set of rather broad signals was observed in ¹H NMR spectroscopy, suggesting the formation of a unique cyclic oligomeric species (21). We assumed the formation of a molecular triangle by analogy to the reaction of the closely related bis(pyridine)-terminated Dawson-based system with trans-[PdCl₂(CH₃CN)₂] (22). The oxidation of Fe(II) bis(terpyridine) occurs at high potential (28) owing to the high stability of the low-spin t₂g⁰ electron configuration of Fe(II). On the counterpart, Co(II) bis(terpyridine) complexes can be much more easily oxidized (28, 29) since the resulting Co(III) bis(terpyridine) complexes display the stable low-spin t₂g⁰ electron configuration. This drove us to study the coordination-driven self-assembly of I with Co(II) salts with the aim of triggering the supramolecular organization by the redox state of the linking metal. The incremental addition of [Co(H₂O)₆](NO₃)₂ to a solution of I (1 mM in DMSO-d₆) up to ~0.5 equiv. mostly leads to the appearance of a single set of signals in the ¹H low-field region (above 10 ppm) attributed to coordinated terpyridine units (Fig. 2). In the following we define the composition by the parameter p = c₀/C·POM. For 0.5 < p < 1, this set of signals splits into two sets. When p = 1, the signals of the starting parent hybrid have disappeared, suggesting that the formed species display a POM:Co(II) 1:1 stoichiometry. The monitoring of the addition of [Co(H₂O)₆](NO₃)₂ to I by ³¹P NMR also indicates the initial formation of a single set of signals (~12.7 and ~9.7 ppm), for 0 < p < 0.5, close to those of the initial hybrid and attributed to the distal and proximal phosphorus atoms (with respect to the lacuna of the parent POM), respectively (SI Appendix; Fig. S1). When p ≈ 1 the resulting species displays a broad peak at ~12.6 ppm and two peaks, ~9.55 and ~9.6 ppm. Note that for 0.5 < p < 1, all ³¹P NMR signals are observed, indicating the presence of all species at this stage of the complexation. A variable temperature ¹H NMR study of a solution of I (1 mM in DMSO-d₆) with p = 1 in the 300–350-K range reveals that the ratio in peak intensity between the two sets of signals is significantly affected by the temperature (Fig. 3 and SI Appendix, Fig. S2). The minor set of signals at room temperature (represented in blue in Fig. 3) further decreases in intensity upon warming to 350 K. Note that, at each temperature, a long time is necessary (a few hours for temperature just above 300 K) so that the equilibrium is reached. Similarly, when decreasing the temperature from 350 to 300 K, it takes 1 d so that the relative intensity between the two sets of signals becomes similar to that of the spectrum before heating. All these findings indicate sluggish kinetics processes. To complete the characterization of the discrete supramolecular assemblies, we performed small-angle X-ray scattering (SAXS) experiments on solutions of I in DMSO-d₆ before and after the addition of 1 equiv of [Co(H₂O)₆](NO₃)₂ (SI Appendix, Fig. S4). SAXS is a very powerful technique that we and others have successfully used to characterize nanosized metal-oxo clusters (23, 30, 31). The SAXS patterns of a solution of the molecular building-block I (1 mM in DMSO-d₆) with p = 1 are very similar to those, previously reported, for the coordination-driven self-assembly of I with [Fe(H₂O)₆]ClO₄ (21). These SAXS signals display similar oscillations located at q > 0.1 Å⁻¹ (corresponding to POM-to-POM distances within the discrete supramolecular species) and same increase in intensity (neglecting the decrease in intensity when q → 0 caused by the electrostatic interactions) compared with that of the molecular building-block I in the low-q region. This indicates that similar discrete supramolecular species are formed in DMSO-d₆ either with [Co(H₂O)₆](NO₃)₂ or [Fe(H₂O)₆]ClO₄. The formation of a unique set of ¹H NMR signals at intermediate concentration of metal linker (i.e., for 0.5 < p < 1) that splits into two sets of signals upon the addition of 1 equiv of Co(II) per POM is similar to the behavior of a bis(pyridine)-terminated Keggin-based hybrid analog in the

Fig. 1. Schematic molecular representations of the hybrid 1 (derived from an energy-minimized structure) from two different viewpoints. Color code: WO₆ octahedra, blue; PO₄ tetrahedra, green.

Fig. 2. Evolution of the ¹H NMR (DMSO-d₆, 400 MHz) spectrum of a solution 1 (1 mM) upon the progressive addition of [Co(H₂O)₆](NO₃)₂. Note that for sake of clarity the intensity of paramagnetic region (12–90 ppm) was expanded.
presence of \(\text{trans}\{\text{PdCl}_2(\text{CH}_3\text{CN})_2\}\) (20). In this last system we observed the prior formation of a molecular dimer at intermediate concentration of metal linker, which evolves into molecular triangle and square in the presence of 1 equiv of metal linker. We concluded that the formation of the cyclic assembly in such system is a noncooperative process probably owing to a high entropic cost due to the global gathering of the associated counterions (20). In the present case, the presence of two sets of \(^1\text{H}\) and \(^{31}\text{P}\) signals for POM:Co(II) 1:1 stoichiometry can be attributed either to the presence of different isomers (displaying different orientations of the POM units with respect to the plane defined by the Co(II) centers) or to the formation of different cyclic oligomers (i.e., a triangle and a square). The fact that the ratio between the two sets of signals is noticeably affected by the temperature rules out the first hypothesis and can only be explained by the presence of metallomacrocycles of different nuclearities. Since the formation of a cyclic tetramer vs. a trimer is entropically unfavorable we assign the minor \(^1\text{H}\) NMR signals to the molecular square (Fig. 3). As in the bis(pyridine)-terminated Keggin-based system, the observation of a single set of signals at intermediate Co(II) concentration indicates that a molecular dimer with a POM:Co(II) 2:1 stoichiometry forms prior the discrete metallomacrocycles (Fig. 4). As previously mentioned, we observed a single set of signals when 1 equiv of \([\text{Fe(H}_2\text{O}_6]\)(\text{ClO}_4)\_2\) was added to 1 (21). Considering that Fe(II) and Co(II) bis(pyridine) complexes display same structure and charge it is very likely that coordination-driven self-assembly of 1 with Fe(II) and Co(II) would lead to similar supramolecular species. Note that in the previously reported 1.Fe\(^{\text{II}}\) system (in the following, 1.M\(^n\) stands for the supramolecular species displaying a 1:1 stoichiometry between the POM and the metal linker) we observed that the perchlorate ions are not associated with the metallomacrocyle (21), which is further confirmed by SAXS. While we initially proposed that in the 1.Fe\(^{\text{II}}\) system only triangles metallomacrocycles are formed, the current study suggests that molecular squares are also present, albeit in smaller quantity (Fig. 4). Note that because of the paramagnetism of Co(II) ions, we were not able to calculate the diffusion coefficient of the different Co(II)-containing species. However, we succeeded in evaluating the \(T_2\) relaxation time of selected signals of both species (SI Appendix, Fig. S3). We observed that the signals of the molecular square have a shorter \(T_2\) than those of the triangle as expected for bigger species (transverse relaxation is known to be faster for large molecules for which Brownian motions are slower).

Oxidation of the Co(II) Centers with Tribromide. The addition of tetrabutyl ammonium tribromide (1 equiv, 20 mM in DMSO-\(d_6\)) to a DMSO-\(d_6\) solution containing 1.Co\(^{\text{II}}\) leads to a rapid fading of the solution color from bright orange to the characteristic yellow color of the low-spin Co(III) bis(pyridine) complex, the process being complete in a few minutes. The \(^1\text{H}\) NMR spectrum of the resulting species displays ill-defined signals in the aromatic region, while no signal are observed above 10 ppm, indicating the absence of paramagnetic species (SI Appendix, Fig. S5). Similarly, the \(^{31}\text{P}\) NMR spectrum of the solution displays a set of very broad signals at \(-9.7\) and \(-12.8\) ppm (SI Appendix, Fig. S1). Finally, SAXS intensity in the low-q region of the solution after oxidation of the Co(II) centers is enhanced by a factor of \(~4.5\) (SI Appendix, Fig. S4). From the Guinier regime of SAXS curve (32), we can extract a radius of gyration \(r_g = 2.8\) nm for the
assemblies of \( \text{Co}^{\text{II}} \) in DMSO-\( \text{d}_6 \). These features indicate the formation of aggregated species. In the \( \text{Fe}^{\text{II}} \) system, the aggregation of the discrete metallomacrocyle was achieved through the change of the composition of the solvent (21). Upon the dilution of the preformed metallomacrocycles with acetonitrile (i.e., a less-dissociating solvent than DMSO), the solvation energy of the metallomacrocycles becomes weaker than the electrostatic interactions, which forces their aggregation into dense nanoobjects. In the present case, aggregation is induced by an increase in the electrostatic interactions through the modification of the charge of the metal linker. The solvent composition and the redox state of the metal linker are thus two control levers of the formation of the hierarchical supramolecular assemblies based on the POM-based building unit \( \text{I} \).

**Modification of the Solvent Composition: DMSO-MeCN Mixture.** The effect of the addition of CD3CN to DMSO-\( \text{d}_6 \) solutions of \( \text{Co}^{\text{II}} \) and \( \text{Co}^{\text{III}} \) was investigated by SAXS. For these experiments concentrated solutions of \( \text{Co}^{\text{II}} \) and \( \text{Co}^{\text{III}} \) (pPOM = 5 mM) in DMSO-\( \text{d}_6 \) were prepared before their dilution with CD3CN or DMSO-\( \text{d}_6 \). The signal intensity in the low-q region of a solution of \( \text{Co}^{\text{II}} \) (pPOM = 1 mM) in a DMSO-\( \text{d}_6 / \text{CD}_3 \text{CN} \) (1:4, vol/vol) mixture is significantly higher (by a factor of 12.3) than that of \( \text{Co}^{\text{II}} \) in DMSO-\( \text{d}_6 \) for the same concentration, which suggests the presence of nanoaggregates similar to those described with the \( \text{Fe}^{\text{II}} \) system (SI Appendix, Fig. S4). From the Guinier regime of SAXS curve, we can extract a radius of gyration of 3.7 nm for the aggregates of \( \text{Co}^{\text{II}} \) in the DMSO-\( \text{d}_6 / \text{CD}_3 \text{CN} \) (1:4, vol/vol) mixture, which is similar to the value found for \( \text{Fe}^{\text{II}} \). As regards the \( \text{Co}^{\text{II}} \) system, SAXS patterns of a DMSO-\( \text{d}_6 / \text{CD}_3 \text{CN} \) (1:4, vol/vol) mixture of the species (pPOM = 1 mM) display unusual features. While the signals of the aggregated species of \( \text{Co}^{\text{II}} \) in DMSO-\( \text{d}_6 / \text{CD}_3 \text{CN} \) (1:4, vol/vol) and \( \text{Co}^{\text{II}} \) in DMSO-\( \text{d}_6 \) reach a plateau in the low-q region, indicative of zero-dimensional nanoobjects, the SAXS intensity of \( \text{Co}^{\text{II}} \) in DMSO-\( \text{d}_6 / \text{CD}_3 \text{CN} \) (1:4, vol/vol) keeps increasing for q → 0 with a slope of -q\(^{-1}\). This suggests that the aggregated species are rod-shaped. In the low-q region, these SAXS patterns can be very well reproduced by a model of flexible cylinders measuring 94 nm in length and 3.4 nm in radius (35% polydispersity) and a Kuhn length (i.e., average segment length of the flexible polymer) of 51 nm (Fig. 5). Note that the exact evaluation of the length of the cylinder (above tens of nanometers) is not possible with q > 5 \cdot 10^{-3} \text{ Å}^{-1}. Furthermore, for q > 0.1 \text{ Å}^{-1}, similar oscillations to those observed with the discrete \( \text{Co}^{\text{II}} \) and aggregated \( \text{Co}^{\text{III}} \) species in DMSO-\( \text{d}_6 \) solutions are present and indicate that all these aggregated species are composed of the metallomacrocycles, acting as secondary building units. The fact that in DMSO-\( \text{d}_6 / \text{CD}_3 \text{CN} \) (1:4, vol/vol) mixtures \( \text{Co}^{\text{II}} \) and \( \text{Co}^{\text{III}} \) display different SAXS patterns indicate that the metallomacrocycles are differently organized in their aggregated forms. Transmission electron microscopy (TEM) of the supramolecular organization was performed after the deposition of a few drops of a solution of \( \text{Co}^{\text{III}} \) in a DMSO-\( \text{d}_6 / \text{MeCN} \) (1:4 vol/vol) mixture on a Cu grid covered with an amorphous carbon film. Electron micrographs at high magnification show worm-like structures with variable lengths (up to 60 nm) and rather homogeneous width (5–7 nm) in agreement with SAXS (Fig. 6).

Some apparently multibranched nanoobjects are observed and possibly result from further aggregation of different nanostructures during deposition. Note that few ellipsoidal objects with length inferior to 10 nm are also present and may correspond to the small aggregates of \( \text{Co}^{\text{III}} \) in pure DMSO-\( \text{d}_6 \).

**Modification of the Solvent Composition: DMSO–H₂O Mixtures.** We previously observed that the addition of water to a diluted solution of \( \text{Fe}^{\text{II}} \) in DMSO-\( \text{d}_6 \) system did not lead to precipitation while the starting hybrid \( \text{I} \) is fully insoluble in water (as almost all POM-based hybrids is tetraethyl ammonium salt). The intriguing and unexpected aqueous solubility of these systems led us to investigate the structural organization of both \( \text{Co}^{\text{II}} \) and \( \text{Co}^{\text{III}} \) in DMSO/water mixtures by SAXS and TEM. The SAXS patterns of \( \text{Co}^{\text{III}} \) (pPOM = 1 mM) in DMSO-\( \text{d}_6 / \text{H}_2\text{O} \) (1:1, vol/vol) is very similar to that of \( \text{Co}^{\text{II}} \) in DMSO-\( \text{d}_6 / \text{CD}_3\text{CN} \) (1:4 vol/vol) mixture (SI Appendix, Fig. S6). The SAXS signal can be nicely fitted in the low-q region by a theoretical SAXS of flexible cylinder of similar dimensions (i.e., 3–3.6 nm in radius). Similarly, the SAXS curve of \( \text{Co}^{\text{II}} \) in DMSO-\( \text{d}_6 / \text{H}_2\text{O} \) (1:1, vol/vol) is similar to that of \( \text{Co}^{\text{III}} \) in DMSO-\( \text{d}_6 / \text{CD}_3\text{CN} \) or DMSO-\( \text{d}_6 / \text{H}_2\text{O} \) mixtures (SI Appendix, Fig. S7). This indicates that in the presence of an excess of water only the worm-like nanostructures are stabilized regardless of the charge of the metal linker. However, in a DMSO-\( \text{d}_6 / \text{H}_2\text{O} \) (1:1, vol/vol) mixture, the SAXS curve of \( \text{Co}^{\text{III}} \) (pPOM = 1 mM) displays a different growth in the low-q region (SI Appendix, Fig. S7), suggesting the presence of smaller aggregates in such mixture. TEM micrographs of the nanoaggregate of \( \text{Co}^{\text{II}} \) and \( \text{Co}^{\text{III}} \) from DMSO-\( \text{d}_6 / \text{H}_2\text{O} \) (1:1, vol/vol) mixtures confirmed the formation of the worm-like nanostructures (SI Appendix, Fig. S8).

The nanoobjects formed with the \( \text{Fe}^{\text{II}} \) system in DMSO-\( \text{d}_6 / \text{CD}_3\text{CN} \) mixtures were described as monodisperse nanoparticles (21). These nanoobjects result from the aggregation of the preformed metallomacrocycles through electrostatic interactions owing to the presence of the anionic (POMs) and cationic (metal linker and TBA) moieties within their structure. We noticed that these types of supramolecular architectures have a maximum compactness probability at the expense of electrostatic interactions (21). In the

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**Fig. 5.** Comparison of the experimental SAXS pattern of \( \text{Co}^{\text{II}} \) (red) in DMSO-\( \text{d}_6 / \text{CD}_3\text{CN} \) (1:4, vol/vol) to the theoretical SAXS intensity (computed using SasView) (36) of a flexible cylinder of 94 nm in length, 3.4 nm in radius (polydispersity 35%) and a Kuhn length of 51 nm (black).

**Fig. 6.** Representative TEM micrographs of worm-like \( \text{Co}^{\text{II}} \) supramolecular organizations from a DMSO-\( \text{d}_6 / \text{MeCN} \) solution.
Molecular Carrier Properties. The assemblies 1,Co\textsuperscript{II} and 1,Co\textsuperscript{III} are soluble upon dilution with water and both form similar worm-like structures. Owing to the emergent water solubility of these nanoaggregates we investigated, in a preliminary study, their ability to act as molecular carrier. Pyrene derivatives are well-known polyaromatic compounds that are almost insoluble in DMSO/H\textsubscript{2}O mixtures. When a DMSO-d\textsubscript{6} solution of the preformed 1,Co\textsuperscript{II} and 1,Co\textsuperscript{III} species (c\textsubscript{POM} = 0.5 mM) containing a very large excess of 1-bromopyrene is diluted with water, an instant precipitation of the 1-bromopyrene and the POM-based assemblies occurs, producing a colorless solution. However, for solutions containing 10 equiv (or less) of 1-bromopyrene per POM (c\textsubscript{POM} = 0.5 mM) in DMSO-d\textsubscript{6}, only a slight, almost colorless precipitate (corresponding to excess of 1-bromopyrene) forms upon dilution with water. UV-vis spectra of 1,Co\textsuperscript{II} and 1,Co\textsuperscript{III} in DMSO: H\textsubscript{2}O (2:98, vol/vol, c\textsubscript{POM} = 10 \mu M) mixtures were recorded after filtration of the solution through a polytetrafluoroethylene membrane (0.45 \mu m). Above 350 nm, the spectra are dominated by the cobalt bis(terpyridine) absorption since the POM only contributes to the intense absorption below 300 nm (SI Appendix, Fig. S9). When 1-bromopyrene (10 equiv per POM) was added to the POM-based assemblies in DMSO, the UV-vis spectra of the solution obtained after dilution with water (yielding DMSO:H\textsubscript{2}O (2:98, vol/vol) mixtures, c\textsubscript{POM} = 10 \mu M) and filtration on a PTFE membrane, clearly indicate the presence of 1-bromopyrene (with characteristic absorption features at 280 and 340 nm) with a slight decrease in the global absorption (compared with spectra of pure 1,Co\textsuperscript{II} and 1,Co\textsuperscript{III} in DMSO-d\textsubscript{6}:H\textsubscript{2}O mixtures with the same initial concentration of POMs), the absorption solution remaining then stable for few hours (Fig. 8). While the absorption decrease of the solution is almost null for 1,Co\textsuperscript{II} (3% signal loss at \(\lambda = 400\) nm), it is more pronounced for 1,Co\textsuperscript{III} (24% signal loss at \(\lambda = 400\) nm), suggesting that 1,Co\textsuperscript{III} is more prone to precipitation than 1,Co\textsuperscript{II} in the presence of hydrophobic species. After subtraction of the absorbance of the POM-based assemblies, the calculated absorbance at 337 nm (maximum absorption of the 1-bromopyrene) is \(\Delta A = 0.27\) and \(\Delta A = 0.48\) for solutions of 1,Co\textsuperscript{II} and 1,Co\textsuperscript{III}, respectively. In DMSO, 1-bromopyrene displays a maximum absorption at 332 nm with an extinction coefficient of \(e_{332} = 3.6 \times 10^4\) M\textsuperscript{-1} cm\textsuperscript{-1} (SI Appendix, Fig. S10). Considering that this \(\pi^*\) transition is only slightly affected by the solvent composition this would give a concentration present case the modification of the metal linker charge (or the addition of water) give rise to a type of supramolecular organization. Indeed, the increase of the metal linker charge strengthens the electrostatic interactions and thus initiates the aggregation even in DMSO-d\textsubscript{6}. In DMSO-d\textsubscript{6}:CD\textsubscript{3}CN mixtures, 1,Co\textsuperscript{III} display worm-like structures. From SAXS and TEM micrographs the width of these structures is estimated to range between 5 and 7 \textmu m. Interestingly, these values match the dimensions of energy-minimized structures of the molecular triangle and square (Fig. 7) (21). We propose that the 1,Co\textsuperscript{III} worm-like structures arise from a stacking of the macrocycles along a preferential direction. This aggregation mode would favor electrostatic interactions between the metal-lamacrocycles at the expense of a lower compacity compared with the previously reported nanoparticles of 1,Fe\textsuperscript{II}. Fits of the SAXS signals of 1,Co\textsuperscript{II} in DMSO-d\textsubscript{6}:CD\textsubscript{3}CN (1:4, vol/vol) using a core shell cylinder model were tried but the calculated SAXS patterns did not satisfactorily reproduce the experimental SAXS features in the intermediate (\(\sim 10^{-1}\) \AA\textsuperscript{-1}) region. Consequently, it is unlikely that in the aggregated species of 1,Co\textsuperscript{III} in DMSO-d\textsubscript{6}:CD\textsubscript{3}CN (1:4, vol/vol), the metalmacrocycles would stack in a columnar arrangement with the organic arms forming a hydrophobic channel. It is more likely that the metalmacrocycles would perform a tilted stacking such as exemplified in Fig. 7, forming thus an oblique cylinder. Molecular dynamics of the aggregation processes using simple point-charge models should be useful to investigate in more detail what are the most favorable aggregation modes. While the metalmacrocycles are mixtures of molecular triangles and squares, the mismatch between these two species would lead to defects in the stacking of the metalmacrocycles, generating the worm-like structures (Fig. 7). We can observe that the discrete metal-macrocycles display amphiphilic character owing to the presence of the hydrophilic POMs, hydrophobic organic moieties, and amphiphilic TBA cations. As the section of the worm-like assemblies (5–7-nm diameter) roughly corresponds to that of the discrete metalmacrocycles, it is likely that in this nanoorganization, POMs mostly point toward the solvent. In contrast, in the dense nanoaggregates a number of POMs are buried inside the aggregate, the diameter of the nanoparticles being bigger than the POM-to-POM distance within the macromacrocycle. The worm-like nanostructures would then preferentially form in the presence of water owing to improved interactions between the charged POMs and TBA with water.
of ∼7.5 and 13 μM of 1-bromopyrene for solutions containing 1. CoII and LCoII, respectively, i.e., similar concentrations to that of the POMs. As a non-negligible amount of LCoII is removed by filtration on the PTFE membrane in the presence of 1-bromopyrene, the lower incorporation of 1-bromopyrene with this system may only in part arise from the lower solubility of the resulting assembly. Finally, TEM micrographs of the nanoaggregates of LCoII and LCoIII containing 1-bromopyrene in DMSO-d6/H2O mixtures show the presence of the worm-like nanostructures (SI Appendix, Fig. S11) indicating that the presence of 1-bromopyrene in the nanoaggregates does not significantly modify the supramolecular architecture. However, it can be noted that for LCoII a significant number of smaller aggregates is observed. The formation of such smaller aggregates with LCoII in the presence of 1-bromopyrene may also accounts for the lower incorporation of the polyaromatic guest. Owing to the well-known bioactivity of POMs (33–35), these aqueous soluble nanoobjects further displaying molecular carrier properties (drug delivery) hold great promise for biological applications.

Conclusion

We showed that the POM-based building unit I can give access to multiscale nanoarchitectures through metal-driven self-assembly processes. Different nanoorganizations can be selectively formed according to the solvent composition and the charge of the metal linker. These two parameters modulate the electrostatic interactions between the metallomacrocycles, acting as secondary building units, and constitute control levers of the formation of the hierarchical supramolecular architectures. In pure DMSO-d6, we observed the minor presence of molecular squares, which could not be identified in a previous study (21). In DMSO-d6/C2D2CN mixtures, when the metallomacrocyle is connected by a divalent transition metal (FeII or CoII) the nanoaggregates display nanoparticle-like structures. In these highly compact nanoassemblies the metallomacrocycles building units have probably no specific orientation. By contrast with a trivalent metal linker (CoIII) the aggregation of the metallomacrocyle occurs along a preferential orientation owing to increased electrostatic interactions yielding the worm-like assemblies. These nanostructures were also obtained in DMSO-d6/H2O mixtures whether with divalent or trivalent metal linker probably since they optimize the interactions of the POMs (and TBA cations) with water. The emergent aqueous soluble of the nanoaggregates drove us to explore the ability of these systems to act as molecular carriers. We observed that in both cases the supramolecular assemblies allow dissolving polyaromatic guests at concentrations similar to those of the starting POM-based building blocks. This opens the way to potential applications of these nanoobjects for chemical biology.

Materials

Compound 1 was prepared according to a published procedures (22). All other reagents were used as supplied. The preparation of the supramolecular species 1-CoII always relies on the prior formation of 1-CoII in DMSO-d6 followed by its oxidation through the addition of 1 equiv TBA2P2.

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