Narcissistic self-sorting vs. statistic ligand shuffling within a series of phenothiazine-based coordination cages†

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Previously, we introduced a series of anion-binding interpenetrated double-cages based on phenothiazine and its mono- and di-S-oxygenated derivatives. Here, we complete the structural comparison of the three related assemblies by an X-ray single crystal analysis of the sulfone derivative. We further show that the three palladium cages coexist in solution upon post-assembly mixing due to the very slow ligand exchange whereas treatment of binary mixtures of the corresponding ligands with Pd(II) leads to the formation of mixed cages comprising a statistical ligand distribution. In contrast, mixtures of one of these ligands with a shorter ligand derivative lead to narcissistic self-assembly into a double-cage and a coexisting small monomeric cage, regardless of the order of mixing and Pd(II) addition.

Introduction

Self-assembled coordination cages¹ have found application in various areas such as selective guest binding,² stabilisation of reactive compounds,³ catalysis,⁴ redoxactive⁵ and light switchable materials.⁶ We have recently reported on a number of interpenetrated double-cages [Pd₄Lₘ] containing concave bis-monodentate pyridyl ligands L showing an allosteric anion binding behaviour.⁷ We further showed that small structural changes modulate the binding affinity of these cages for different halide anions⁸ whereas more extensive structural changes lead to a selectivity switch towards larger oxoanions such as perrenenate.⁹

Among the reported structures, three closely related double-cage species based on the heterocycle phenothiazine and its mono- and di-oxygenated derivatives were shown to have a redox chemistry that makes them promising candidates for application in molecular electronics and organic photovoltaics. The molecular structures of the first two cages were reported by us before.¹⁰

Here, we deliver the single-crystal structure of the di-S-oxygenated double-cage, thus allowing for a comprehensive comparison of the structure–function relationships of the three cage derivatives. Furthermore, we extended our examination of the cage assembly process to mixtures of phenothiazine-based ligands and their corresponding cages in order to study the role of kinetic effects¹¹ on the double-cage assembly. In addition, we show a phenomenon of narcissistic self-sorting¹² when a shorter ligand derivative, not capable of forming a double-cage, is brought into the system.

Results and discussion

The chemical structures of the long ligands L¹⁻³ and the shorter derivative L⁴ are depicted in Fig. 1a. All three long ligands were previously shown to quantitatively yield interpenetrated double-cages [Pd₄L¹⁻³] upon treatment with the metal source [Pd-(CH₃CN)₄](BF₄)₂ in acetonitrile solution.¹⁰ The structures were found to contain BF₄⁻ counter anions encapsulated in their two outer pockets and one inside their central cavity. We further showed that the two outer anions could be replaced by tightly binding halides in an allosteric fashion.⁵ In contrast, the shorter ligand L⁴ was shown to assemble into a monomeric cage [Pd₄L⁴] that cannot undergo dimerization for steric reasons.¹⁰

The X-ray structural data for coordination cages [Pd₄L₁₈] and [Pd₄L³₈] showed that both are interpenetrated dimers sharing a common topology but differing in their shape with regard to the Pd–Pd distances, ligand bending and pocket sizes.¹⁰ Here, we report on the single crystal X-ray structure of the third member of the three related cages, [Pd₄L¹₈], thus filling a gap in the systematic structural comparison. Table 1 lists the crystallographic parameters for the [Pd₄L³₈] double
cage. After refinement of the cage scaffold, all necessary BF$_4^-$ and Cl$^-$ anions could be found in the Fourier difference map. The BF$_4^-$ anions are located on special positions. All but one are exhibiting disorder and are not obeying the crystallographic symmetry. They were modeled using distance restraints with lowered standard deviations. Diffuse residual electron density was observed in the crystal voids. Heavily disordered lattice solvent (ethanol) could be modeled into these voids but a 'squeezed' model was superior. (see the ESI†).

Fig. 2a and b show the double cage structure from two different perspectives. The topology of this cage assembly is in
agreement with the structures reported for [Pd₄L₁₆] and [Pd₄L₂₆]. It is interesting to note that the examined crystals of [Pd₄L₁₆] were found to contain one equivalent of chloride counter anions per double-cage, positioned on the Pd₄-axis between the double-cages, which was not observed in the previously reported solid states structures of [Pd₄L₃₆] and [Pd₄L₅₆]. Particularly surprising is the observation that the chloride anions (most probably being the result of a contamination) were not found in the outer two pockets of the double-cage structure but in the space outside the linearly aligned cages, which is in clear contrast to the solution behaviour. A plausible explanation is given as follows: in solution, the chloride anions are tightly bound outside the outer two pockets by electrostatic interactions from both Pd(pyridine)₄ planes lining the cavities. As we have demonstrated previously, chloride binding is accompanied by a compression of the double cage structure along the Pd₄-axis thus bringing the Pd centres of the double-cage closer together. This allosteric e ect helps to accommodate the chloride anions in the outer pockets because they are smaller than the tetrafluoroborate counter anions. As a consequence of this structural change, however, an energetic penalty has to be paid due to the enlargement of the central portion because here the cationic metal centres are moved away from the contained tetrafluoroborate anion. Still, the incorporation of the chloride inside the outer pockets is the favoured process in solution, whereas chloride binding to the outer faces of the double cage is occurring with much lower affinity. The situation seems to change in the solid state structure due to the linear alignment of the double cages. Here, the cages can adopt an optimal spacing for the tight binding of a chloride anion between them (6.54 Å). Most importantly, binding of the chloride anion between the cages does not come with the mentioned energetic drawback of having to enlarge the cage’s central cavity. For a graphical comparison of the solid state packings of the three cage derivatives see the ESL.

A comparison of all three X-ray structures reveals how the sulfur atoms (and the attached oxygen atoms) of the interpenetrating ligands of one cage subunit are positioned relative to the inner Pd(pyridine)₄-plane of the other cage subunit (Fig. 2c). Compared to the situation observed for [Pd₄L₁₆] (left) and [Pd₄L₃₆] (middle), the extra oxygen of [Pd₄L₅₆] (right) has to squeeze between the sulfur atom and the gap between two neighbouring pyridine rings, which moves the sulfur atom further away from the palladium centre. A further structural feature, which is interesting to compare between the three cage derivatives, is the ligand bending (as defined by the angle between both of the phenothiazines’ benzene rings). Fig. 2d shows that the attachment of one oxygen substituent to the sulfur decreases the bending angle from 155° (in [Pd₄L₁₆]) to 150° (in [Pd₄L₃₆]) and back to 152° (in [Pd₄L₅₆]) which can be explained by the steric demands of the lone pairs and oxygen substituents, respectively.

Since no single crystals suitable for X-ray crystallography were obtained for the monomeric cage [Pd₂L₄], its structure was calculated by an unconstrained geometry optimization on the PM6 semiempirical level of theory (charge: +4; spin-

Fig. 3 (a) Side view and (b) view along the Pd₂-axis of a PM6 model of the monomeric cage [Pd₂L₄] (alkyl chains have been truncated and anions omitted).

Fig. 4 Comparison of ¹H NMR spectra (300 MHz, 298 K, CD₃CN) of the experiments described in Fig. 1 with a combination of (a) ligands L¹ + L³ and (b) ligands L² + L⁴.
(and corresponding double cages) are clearly distinguishable. The spectrum obtained after Pd(II) treatment of the ligand mixture unambiguously shows the pattern expected for an interpenetrated double-cage; it is however broadened as compared to the spectrum obtained for the mixture of the preformed cages.

The latter spectrum does not undergo substantial changes upon prolonged heating of the sample. The ESI mass spectrometric analysis of both mixtures nicely reveals that Pd(II) addition after ligand mixing indeed leads to a binomial distribution (Fig. 5a) whereas mixing of the preformed double-cages does not (Fig. 5b). Apart from some peaks resulting from contaminating counter anions, the observed peak pattern of this sample is in very good agreement with the simulated pattern for a 1 : 1 mixture of [Pd₄L₁₈] + [Pd₄L₃₈].

Heating the double-cage mixture at 70 °C overnight did not result in significant formation of mixed-ligand cages. Prolonged heating, however, led to the slow occurrence of new peaks with low intensity in the ESI mass spectra showing the formation of the one-ligand-exchanged species [Pd₄L₁₈] and [Pd₄L₃₈] after 279 hours (Fig. 6). Even further heating for up to 26 days led to the rise of the species where more than one ligand is exchanged, thus indicating a very slow ligand exchange. In addition the intensity of the signals for the homogeneous double cages [Pd₄L₁₈] and [Pd₄L₃₈] were found to decrease after this time. Since the same procedure conducted with the mixed-ligand double-cage samples did not result in any significant deviation from the statistical distribution, we conclude that the latter state is the global thermodynamic minimum of the system.

Similar results were obtained for mixtures containing L¹ + L² and L² + L³, although the NMR spectroscopic analyses involving ligand L² were somewhat hampered by the previously reported signal broadening in the spectra of [Pd₄L²₈] (see the ESI). The picture changes when the short ligand L⁴ is brought into the system. Experiments involving one of the long ligands...
L⁻³ plus L⁴ were found to always result in a mixture of the homogeneous double-cage [Pd₄L⁻³₈] and the small, monomeric cage [Pd₄L₈], regardless of the order of component addition (premixing of the ligands followed by Pd(u) vs. mixing of preassembled cages). This narcissistic self-sorting behaviour can be both seen in the ¹H NMR spectroscopic examinations (Fig. 4b) and the ESI mass spectrometric analyses (Fig. 5c and d) for the combination L¹ + L⁴ (for results of the other ligand combinations see the ESI†).

Conclusions

In summary, the successful X-ray structure determination of [Pd₄L₈] allows now for a systematic comparison between all three members of the family of interpenetrated cages based on phenothiazine. The effect of the extra oxygen substituent attached to each of the eight sulfur atoms in [Pd₄L₈] has essentially two structural implications: first, it leads to a displacement of the sulfur atoms of the interpenetrating ligands away from the inner Pd atom of the other cage substructure, and second, it influences the bending angle of the ligands with respect to the non-flat phenothiazine component. Both factors also have implications on the pocket sizes (Pd–Pd distances) and overall double-cage shapes.

We further showed that binary mixtures of the long ligands L¹⁻³ give a statistical distribution of mixed-ligand cages upon treatment with Pd(u). This is remarkable given the fact that all three ligands differ in their lengths, bending angle and steric situation around the sulfur atoms. Apparently, these discrepancies between the ligands are tolerated in the mixed cages, showing again the versatility of the [Pd₄L₈] structural motif. Heating a mixture of preassembled double-cages, however, only resulted in extremely slow ligand shuffling, thus indicating a strong kinetic barrier of ligand exchange once the completely assembled double-cages have been obtained. The substantial structural differences between the long ligands L¹⁻³ and the much shorter derivative L⁴, however, led to a narcissistic self-sorting behaviour in binary mixtures giving the corresponding double-cage [Pd₄L¹⁻³₈] and the monomeric cage [Pd₄L₄].

Together, these results strengthen the knowledge about the structural features that govern the formation of self-assembled coordination cages from concave bispyridyl ligands. Furthermore, the observed signs of a strong kinetic influence on the double-cage assembly mechanism allow us to study self-assembled host–guest systems away from thermodynamic equilibrium in our following investigations.

Experimental

¹H NMR spectra were recorded on a Bruker Avance-300 spectrometer (300 MHz) in CD₃CN. ESI mass spectra were obtained using a Bruker micrOTOF mass spectrometer in positive mode. Samples were injected as acetoniitrile solutions. All observed isotope patterns were in good agreement with the calculated ones.

Synthesis of the cages¹⁰ and preparation of the solutions for the mixing experiments: cage compounds [Pd₄L¹⁻³₈] and [Pd₄L₄] were synthesized in quantitative yield by heating a mixture of the ligand L¹⁻³ (2.8 μmol) in 930 μL CD₃CN and a solution of [Pd(CH₃CN)₄][BF₄]₂ (1.4 μmol, 93 μL of a 15 mM solution in CD₃CN) at 70 °C for 6 h to give a 0.35 mM solution of [Pd₄L¹⁻³₈] or a 0.7 mM solution of [Pd₄L₄], respectively. Mixing experiments (Fig. 1b, left side): A binary solution of two ligands was prepared by mixing the solution of ligand L₄ (250 μL, 2.8 mM) and L⁴ (250 μL, 2.8 mM) in CD₃CN. To this solution, [Pd(CH₃CN)₄][BF₄]₂ (0.75 μmol, 50 μL of a 15 mM solution in CD₃CN) was added and the mixture was heated at 70 °C to give [Pd₄L₄₃L₈] with L₄L₄ = L¹⁻³₈; L₄L₄ ≠ L¹; and m = 1–8.

Mixing experiment (Fig. 1b, right side): A binary solution of preassembled double cages was prepared in CD₃CN by mixing 250 μL of each cage solution and heated at 70 °C.

X-ray crystallography: Yellow block shaped crystals of [Pd₄L₈] were grown from the solution of the acetonitrile by diffusion of ethanol. A suitable crystal of size 0.09 × 0.08 × 0.06 mm³ was selected from a batch of crystals using the X-TEMP 2 device.¹⁴ The crystal was mounted on top of glass fiber using inert perfluorinated polyether oil and placed in the cold gas stream of a Bruker Kryoflex 2 low-temperature device with a cold stream at 100(2) K on a Bruker D8 three circle diffractometer. The diffractometer was equipped with a SMART APEX II CCD detector and a rotating anode source (Mo-Kα; λ = 0.71073 Å). Data were collected in omega-scan mode at different detector 20° angles ranging between 0° and 90°. The scan width was set to 0.5°.

Data integration was done with SAINT 8.30C.¹⁵ Each run with constant 2θ and φ settings was integrated using a separate orientation matrix. Data scaling and absorption correction were done with SADABS 2012/1.¹⁶ The space group was determined using XPREP.¹⁷ The structure was solved by direct methods using SHELXS-97.¹⁸ Refinement by full-matrix least-squares procedures was done with SHELXL-2013¹⁹ within the SHELXLle-GUI.²⁰ The hydrogen atoms were refined isotropically at calculated positions using a riding model with their Uiso values constrained to 1.5Ueq of their pivot atoms for terminal sp³ carbon atoms and 1.2 times for all other carbon atoms. All non-hydrogen atoms were refined with anisotropic displacement parameters. For the severely disordered solvent region the SQUEEZE routine of the PLATON program package was utilized (see ESI†).

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References


