Reactions inside a porous nanocapsule/artificial cell: encapsulates' structuring directed by internal surface deprotonations†‡

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In the cavities of unprecedentedly functionalised, spherical, porous capsules of the type $\{Pentagon\}_{12}\{Linker\}_{30} \equiv [\{(Mo)Mo_5O_{21}(H_2O)_6\}_{12}\{Mo_2O_4(ligand)\}_{30}]^{n-}$ reactions with the ligands – *i.e.* at the internal shell surfaces – can be performed, in the present case deliberate aquation/hydration and deprotonation reactions at the linker fragments $\{(Mo_2O_4)C_2O_4H\}^+$ similar to that reported in the literature for $[(NH_3)_5CoC_2O_4H]^{2+}$ in solution.

Generally speaking, what is it like for molecules to be 'housed' inside a nanosized molecular capsule, *i.e.* under confined conditions, with respect to interactions between themselves? Can these interactions take place (nearly) independently from the cavity-interior shell-functionalities – as in a test-tube – or is there the option to influence deliberately the interactions of uptaken molecules by tuning appropriately the internal capsule functionalities? These questions can be addressed now as it is possible to fine-tune the functionalities – from rather inert to strongly directing – of the interior surface of soluble, spherical, porous capsules of the type $\{Pentagon\}_{12}\{Linker\}_{30} \equiv [\{(Mo)Mo_5O_{21}(H_2O)_6\}_{12}\{Mo_2O_4(ligand)\}_{30}]^{n-}$ (for ligand = acetate with $n = 42$ this corresponds to the educt **1a**).[1–5] Modifications of the cluster interiors can be carried out by exchanging the ligands coordinated to the 30 $\{Mo_2\}$ linkers, in the present case by substituting 30 acetate ligands existing in the easily obtained compound **1**,[4] by 30 monoprotonated oxalate ligands. In the resulting compound **2** internal surface reactions, *i.e.* aquations (oxalate–water exchange) and deprotonations were performed. This leads to **3**, demonstrating that the deprotonations direct the structuring of the encapsulated H_2O/NH_4^+ assemblies.

$(NH_4)_{42}[\{(Mo^{VI})Mo^{VI}{}_5O_{21}(H_2O)_6\}_{12}\{Mo^{V}{}_2O_4(OOCCH_3)\}_{30}]\cdot ca.\{300H_2O + 10CH_3COONH_4\} \equiv (NH_4)_{42}\cdot\mathbf{1a}\cdot$lattice ingredients $\equiv$ **1**.

$(NH_4)_{42}[\{(Mo^{VI})Mo^{VI}{}_5O_{21}(H_2O)_6\}_{12}\{Mo^{V}{}_2O_4(OOCCOOH)\}_{30}]\cdot ca.\{300H_2O + 2C_2H_2O_4\} \equiv (NH_4)_{42}\cdot\mathbf{2a}\cdot$lattice ingredients $\equiv$ **2**.

$(NH_4)_{38}[\{(H_2O)_x + (NH_4)_{14}\}\subset\{(Mo^{VI})Mo^{VI}{}_5O_{21}(H_2O)_6\}_{12}\{Mo^{V}{}_2O_4(OOCCOOH)\}_8\{Mo^{V}{}_2O_4(OOCCOO)\}_{16}\{Mo^{V}{}_2O_4(H_2O)_2\}_6]\cdot ca.(300 - x)H_2O \equiv (NH_4)_{36}\cdot\mathbf{3a}\cdot ca.(300 - x)H_2O \equiv \mathbf{3}$.

By reaction of an aqueous solution of **1** with oxalic acid§ compound **2** was obtained. Afterwards, **2** was dissolved in water to initiate ligand based reactions, *i.e.* aquations/hydrations and deprotonations, which led to compound **3** containing structured encapsulates not present in **2**.¶ Compounds **2** and **3** were characterised by elemental analysis, thermogravimetry (to determine the number of crystal water molecules), redox titration (to determine the number of Mo^V centres), bond valence sum (BVS) calculations,[6a] spectroscopically (NMR, IR, Raman), and by single crystal X-ray structure analysis.‖

The capsules **2a** and **3a** exhibit the above mentioned "classical" spherical polyoxomolybdate skeleton found in **1** and in several other related compounds (Fig. 1).[1–5] Whereas **2a** shows at the 30 equivalent linker positions 30 identical monoprotonated oxalate ligands, **3a** shows unprecedented internal structural features¶ as a result of reactions at the internal cavity surface. The detailed interpretation of the single crystal X-ray structure and the elemental analysis of **3**‖ proves the presence of (i) 24 partially deprotonated ligands distributed statistically over the related 30 positions, *i.e.* coordinated to the $\{Mo_2\}$ type linkers, and (ii) six binuclear linkers $\{Mo_2\}$ carrying two water molecules as ligands (see formula). Hence, six monoprotonated oxalate ligands are replaced due to aquation/hydration reactions (Fig. 2). This ligand exchange $\{(Mo_2O_4)C_2O_4H\}^+ \rightarrow \{(Mo_2O_4)(H_2O)_2\}^{2+}$ favours deprotonation§ due to the corresponding decrease of the overall negative cluster charge. In **2a** the ligands are not deprotonated, as **2** is formed in the presence of an excess of oxalic acid.§ But the deprotonation of **2a** – resulting in the

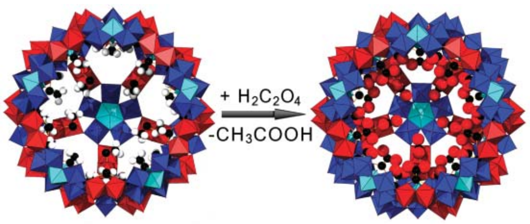

Fig. 1 Schematic demonstration of how the inner surface of the porous spherical nanocapsule **1a** changes on replacing acetate (left) by oxalate ligands (right). For clarity, one pentagonal unit and five linkers are omitted ($\{(Mo)Mo_5\}$ units (blue/cyan), $\{Mo^V{}_2\}$ type linkers (red) in polyhedral representation, C black, H white). Right: corresponding hydrophilic inner capsule surface in **2a** without H atoms.

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† Dedicated to Professor F. A. Cotton on the occasion of his 75th birthday.

‡ Electronic supplementary information (ESI) available: NMR, IR and Raman spectroscopy; further crystallographic, model calculations and analytical results; Hofmeister series. See DOI: 10.1039/b604557j

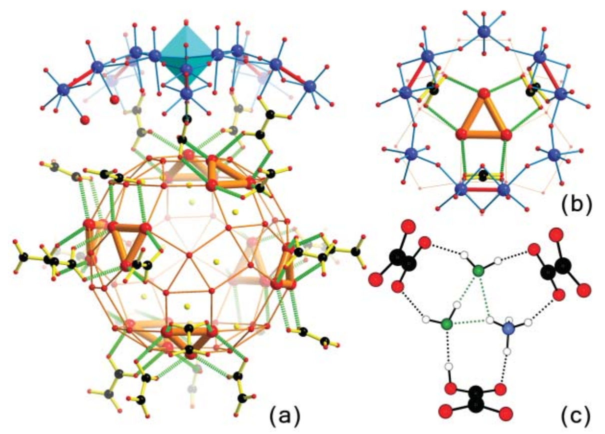

Fig. 2 (a) The interior of the capsule **3a** showing its connection to a segment of the spherical polyoxomolybdate skeleton with one of the six {Mo_2} linkers carrying H_2O molecules (enlarged red spheres; see formula **3a**) instead of an oxalate ligands. The basic part is, geometrically speaking, the (distorted) X_{60} type Archimedean solid (brown), the corners of which are formed by H_2O and NH_4^+ on the related partially occupied 60 positions; only eight of the 20 triangles corresponding to the eight present $(H_2O)_2NH_4^+$ units lying below the pores at the C_3 axes are highlighted (in brown, bold). The hydrogen bonds between the oxalate ligand O atoms (C black, O red) and atoms of the triangles are emphasised (green lines). Additionally shown is the other type of encapsulated NH_4^+ ions (yellow spheres); (b) view of one pore situation with one $(H_2O)_2NH_4^+$ unit interacting with three "oxalates" (colours as in (a)); (c) computed H-bond pattern obtained by minimising the internal energy for the triangular unit $(H_2O)_2NH_4^+$ of **3a** in a system of three (only one protonated) oxalate groups, which leads to a minimisation of charge differences (oxalate O red, water O green, C black, N blue, H white). The optimal hydrogen bond situation has been calculated employing the PACHA formalism.[6b]‡ A comparison with cyclic $\{H_2O\}_3$ trimers would be especially interesting.[6c]

formation of **3a** – can also be proven simply by ^1H NMR: solutions of **2** and **3** of equal concentrations in DMF-d_7 were measured under the same conditions at 223 K. Compared to **2a**, the signal intensity of the oxalate proton of **3** at 13.12 ppm is significantly decreased. In the present context a study of Andrade and Taube[6d] should be referred to: the authors investigated the acid and the aquation equilibrium of $[(NH_3)_5Co^{III}C_2O_4H]^{2+}$ in aqueous medium and discussed the influence of the charge on the metal centre. The comparison shows that the monoprotonated oxalate ligand of **2a** under confined conditions is rather acidic. (Note: water molecules and small cations can pass through the capsule pores.[6e])

Remarkably, **3a** shows in its cavity, according to the present X-ray crystallography study, 60 (underoccupied) positions (Fig. 2a) which build up a distorted Archimedean solid, *i.e.* the rhombicosidodecahedron. This is formed by the encapsulated H_2O/NH_4^+ guests, comprising the characteristic faces, *i.e.* besides the 20 chemically relevant triangles (with corresponding short edges), 12 pentagons and 30 rectangles. The underoccupation is due to the fact that only eight trimers, $(H_2O)_2/(NH_4^+)$, can be present because of geometrical restrictions (see ref. 6*f*). Furthermore, in **3a** there is one set of 12 positions located below the rectangles of the mentioned distorted Archimedean solid having an occupation factor of 0.5. This type of position should be assigned to NH_4^+ ions (there might be a small contribution of H_2O molecules in agreement with the comparably large thermal ellipsoids) because (i) it has the same short distance of *ca.* 2.9 Å to the two different O atoms of the same "free" carboxylate group, which corresponds to the situation in many oxalato complexes,[7a] and (ii) it corresponds exactly to the capsule type position at which in many cases metal cations could be identified by X-ray crystallography.[1–5]

Further information on the encapsulates is derived from NMR investigations and model calculations (Fig. 2). The ^{15}N-HSQC-NMR spectrum of a solution of **3** in DMSO to which $(^{15}NH_4)Br$ was added proves the unequivocal presence of (at least) two kinds of encapsulated NH_4^+ ions in agreement with the results of our single crystal X-ray study (Fig. 3). The spectrum shows cross peaks due to the entrance of $^{15}NH_4^+$ into the capsule, *i.e.* due to an exchange with the $^{14}NH_4^+$ present in the capsule **3a** (for this type of cation transport flexibility of the sulfate ligands is necessary, which was first considered in ref. 7*b*).

The deprotonated carboxylate groups in **3a** are attractors/receptors for cations, and interact strongly *via* H-bonding with the encapsulated water molecules and especially with the ammonium ions. This leads to the presence of just eight $(H_2O)_2NH_4^+$ trinuclear units "linked" to eight oxalate ligand groups each containing three oxalates with one being protonated (Fig. 2). The addition of more than one ammonium ion per triangle is not favourable due to a $NH_4^+\cdots NH_4^+$ repulsion.

The results of the present study dealing with the electrolyte influence, *i.e.* in the form of oxalates and NH_4^+ ions on "water structures" under confined conditions might be correlated to some aspects of the Hofmeister series for anions and cations that reflect their different ordering power on the surrounding water medium.[5a]‡ The ionic sequence of the series spreads from stabilising "cosmotropes" to disrupting "chaotropes" (for related information including general problems of water structures, see ref. 8). Small and highly charged ions (cosmotropes) cause well defined structuring, *i.e.* symmetrical oriented water molecules in their neighbourhood (therefore the name!).‡ In the present situation, we have the interesting case of a cationic (NH_4^+) and clear anionic function (deprotonated oxalic acid), which hinders the formation

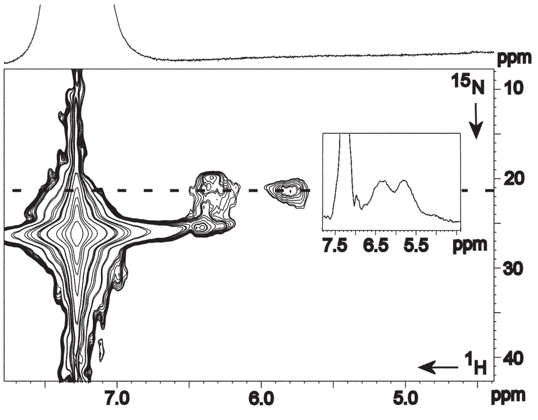

Fig. 3 ^{15}N-HSQC spectrum (^{15}N-decoupled) of **3** in DMSO. The spectrum exhibits additional peaks besides the correlation signal for the free ammonium ions (7.3/26 ppm) with exclusively upfield ^1H (6.3 and 5.8 ppm) and ^{15}N chemical shifts (21.5 ppm). The insert is the 1D spectrum of the trace at ~21.5 ppm (dotted line) to demonstrate that there is a minimum between the two additional signals.

of well defined large pure water structures/shells like in $\{H_2O\}_{100}$ and $\{H_2O\}_{80}$ found in the case where sulfate ligands (coordinated in a bidentate fashion to the $\{Mo_2\}^{2+}$ linkers) have no anionic function as they have two terminal doubly bonded O atoms with low(!) electron density and therefore negligible directing power.[5b,c]

The use of dicarboxylate ligands with "free" non-coordinating deprotonated acidic groups in our capsules opens perspectives for studying structuring processes in which encapsulated water/electrolyte hybrids are generated. The generation of the deprotonated forms is especially important because of their high directing power. Based on the present results, it becomes also feasible to study the selectivity of encapsulated ions for specific recognitions based on oxalates on a molecular scale, for instance with Ca^{2+} ions, where the interactions are known to be quite strong.[9]

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Notes and references

§ *Synthesis of* **2**: A solution of **1**[4] (2.0 g, 0.07 mmol) and $C_2H_2O_4 \cdot 2H_2O$ (1.0 g, 7.9 mmol) in 50 ml water is stirred for 2 hours (pH < 2). After addition of NH_4Cl (2.0 g, 37 mmol) and further stirring for 10 minutes the solution is filtered and kept in a 250 ml beaker under open conditions for crystallisation at room temperature. The brown rhombohedral crystals which precipitate after three days are filtered off through a glass frit (D2), washed with ice-cold ethanol and diethyl ether, and finally dried in air. Yield: 1.2 g (59% based on Mo). Note: the crystals used for the X-ray diffraction were not washed. Anal. calcd for **2** (%): C 2.74, H 3.04, N 2.10; found: C 2.8, H 2.8, N 2.4% (see ESI‡).

Synthesis of **3**: A solution of **2** (1.0 g, 0.035 mmol) and NH_4Cl (1.5 g, 28 mmol) in 50 ml water is stirred for 1 hour (pH ≈ 2) and is then kept in an open 250 ml beaker for crystallisation at room temperature. The brown rhombohedral crystals which precipitate after 3 days are filtered off through a glass frit (D2), washed with ice-cold ethanol and diethyl ether, and finally dried in air. Yield: 0.8 g (79% based on Mo). Note: the crystals used for the X-ray diffraction were not washed.

Because of the high solubility of **2** and **3** one gets the crystals only if a rather large amount of water has been evaporated. There is an error limit regarding the number of deprotonated/protonated oxalate ligands of **3**; the number given is calculated according to the nitrogen/(NH_4^+) value obtained from the elemental analysis while the total number of oxalates is obtained from X-ray crystallography and the C-value. Whereas in **3a** the total number of encapsulated NH_4^+ could be given (within a small error limit), this is not the case for the encapsulated H_2O molecules as some are found disordered in the central part of the cavity (*i.e.* below the mentioned shells).

Anal. calcd for **3** (%): C 2.08, H 3.22, N 2.63; found: C 2.1, H 2.9, N 2.5% (see ESI‡).

¶ Structurally well defined water/electrolyte structures as found in **3** are not present in **2** because of the non-symmetrical positions of the H atoms of the ligands as well as the (probable) presence of a very few oxalic acid molecules in its cavity (see formula; anionic forms should not occur in the negatively charged capsule). Important: there is indication for disordered molecules from the X-ray study. The partial deprotonation in **3** refers to the speciation for the equilibrium between the mono- and non-deprotonated form in water (equilibrium constant $K \approx 10^{-1}$: ref. 13). During the dissolution of **2** the oxalic acid molecules are, besides some of the "oxalate" ligands, released while the latter event opens the pores drastically.

‖ *Crystal data for* **2**: $C_{64}H_{946}Mo_{132}N_{42}O_{872}$, M = 28926.7 g mol^{-1}, rhombohedral, space group $R\bar{3}$, a = 32.6802 (8), c = 73.440 (2) Å, V = 67926 (3) Å^3. Z = 3, ρ = 2.121 g cm^{-3}, μ = 1.884 mm^{-1}, F(000) = 42432, crystal size = 0.20 × 0.20 × 0.12 mm, T = 188(2) K. Total reflections 136068 ($1.66 < \theta < 26.99°$), 32868 unique (R(int) = 0.0310). The structure was refined using SHELXL-97 to R = 0.0453 for 26266 reflections with $I > 2\,\sigma(I)$, R = 0.0614 for all reflections. CCDC 297963. *Crystal data for* **3**: $C_{48}H_{984}Mo_{132}N_{52}O_{852}$, M = 28592.9 g mol^{-1}, rhombohedral, space group $R\bar{3}$, a = 32.6616 (8), c = 73.307 (3) Å, V = 67725 (3) Å^3, Z = 3, ρ = 2.103 g cm^{-3}, μ = 1.886 mm^{-1}, F(000) = 41988, crystal size = 0.50 × 0.40 × 0.40 mm, T = 183(2) K. Total reflections 111107 ($1.47 < \theta < 27.00°$), 31558 unique (R(int) = 0.0354). The structure was refined using SHELXL-97 to R = 0.0475 for 25654 reflections with $I > 2\sigma(I)$, R = 0.0641 for all reflections. CCDC 277334. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b604557j

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