A metal complex that imitates a micelle†‡

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A metal complex with a micelle-like, core–shell structure adopts higher nuclearity in water than in organic solvents, thereby imitating also the growth of a micelle, but through covalent rather than non-covalent aggregation.

The concept of 'metal-complex-as-amphiphile', in which metal complexes act as components of metallo-micelles, is well established.[1,2] However, an alternative concept, that of 'metal-complex-as-micelle', in which a single metal complex imitates the structure and behaviour of a complete micelle, has not yet been described. Here we report an example of such a metal complex. The structure is shown generically in Fig. 1a, and can be seen as a hybrid of a metal complex and a micelle, since it is based on amphiphilic ligands which form a hydrophobic interior surrounded by hydrophilic head groups. Importantly, the stability of this type of complex in water is therefore not only due to metal coordination but also hydrophobic interactions. For the complex reported here, we show that the structure it adopts is indeed directed by hydrophobic interactions. In particular, in pure water the complex is dinuclear with bridging ligands. However, if the hydrophobic interactions are negated or overcome by lowering the solvent polarity or pH, the complex switches to a mononuclear state, with its ligands changing from bridging to chelating. In this way the complex therefore imitates a true micelle by growing or shrinking in response to its medium, but by a non-micelle-like mechanism which requires breaking and remaking of coordination bonds.

The system described here is based around types of silver complex formed by bidentate phosphines such as dppe, bis(diphenylphosphino)ethane. The complex $[Ag(dppe)_2]^+$ is normally mononuclear (*i.e.* both ligands chelating) but can become dinuclear for certain ligand variants or upon crystallisation (Fig. 1b).[3] Therefore the monomer–dimer equilibrium appears to be finely balanced for this type of complex. In the present work, the complex was given a pseudo-micellar structure by using an amphiphilic variant of dppe. Specifically, hydrophilic piperazine groups were added to the *para* positions of the diphosphine's hydrophobic aryl groups. The amphiphilic ligand (**L1**, Fig. 1c) can therefore generate complexes with hydrophobic cores surrounded by hydrophilic head groups.

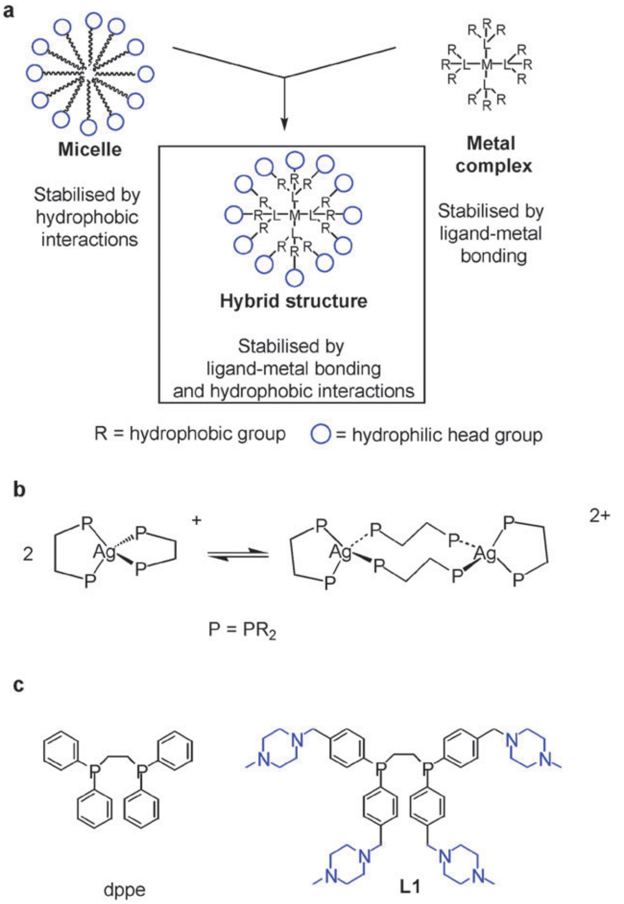

Fig. 1 (a) Schematic of micelles, metal complexes and hybrid structures, (b) equilibrium between mono-silver and di-silver complexes of diphosphines and (c) structures of dppe and **L1**.

The behaviours of free, uncoordinated **L1** and its silver(I) complex are summarised in Fig. 2. Free **L1** forms micelles in water, behaving as a non-ionic surfactant,[3] as revealed by the following observations: (i) a critical micelle concentration (CMC) of 5 mM was determined using the dye inclusion technique,[5] corroborated by DLS (dynamic light scattering), (ii) DLS shows particles of hydrodynamic diameter 5.0 nm in D_2O (20 mM, pH 9.0, Fig. 3b) with low polydispersity whereas chloroform solutions showed no aggregation, (iii) the size of the micelles in water was not influenced by ionic strength since 10 mM NaCl solutions gave identical results to those in deionized water, (iv) concentration-dependent line broadening is seen in ^1H and ^{31}P-NMR spectra in D_2O with upfield ^{31}P shifts relative to those in $CDCl_3$ (Fig. 3a), and (v) a cloud point (33 °C) was observed in water which is a phenomenon well known for related non-ionic surfactants.[6]

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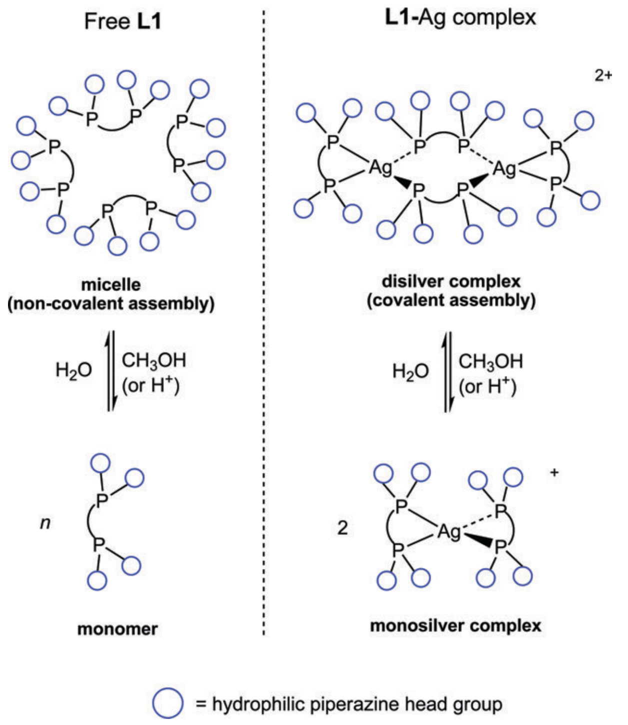

Fig. 2 Schematic diagram to show the structures adopted by the free ligand and its silver complex change in response to the medium.

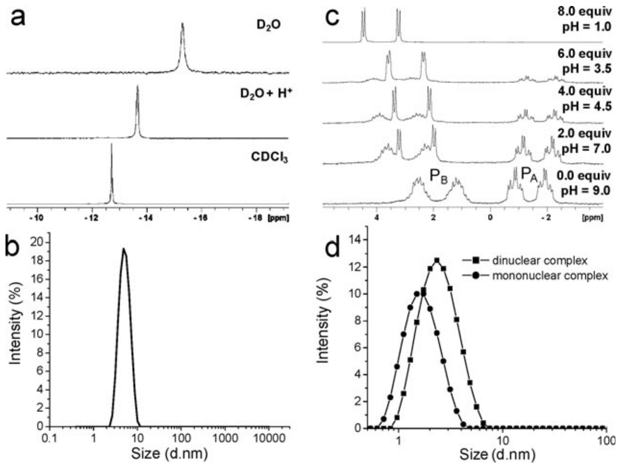

Fig. 3 (a) ^{31}P NMR spectra for **L1**, (b) dynamic light scattering of **L1** micelles in water, (c) ^{31}P NMR spectra showing interconversion between mono- and di-nuclear silver complexes with addition of HOTf, and (d) dynamic light scattering for the mono- and di-nuclear complexes.

Addition of methanol (to 30% v/v) or acid (HO_3SCF_3) to aqueous **L1** disrupted the micelles as shown by DLS and sharpening of NMR signals. Micelle disruption by methanol is expected because it lowers the hydrophobicity of the medium. Micelle disruption by acid is also expected since protonation generates positive charges on the piperazine groups, increasing the water-solubility of **L1** as well as electrostatic repulsion between the piperazine head groups in the micelles.[4] The free ligand therefore serves to illustrate typical micellar behaviour.

For the metal complex, in pure D_2O a 2 : 1 mixture of **L1** and AgOTf was found to adopt the dinuclear structure $[Ag_2(\mathbf{L1})_4]^{2+}$ as revealed by ^{31}P-NMR spectroscopy. The spectrum consists of two pairs of multiplets at $\delta = -1.5$ (P_A) and 1.9 (P_B) which can be assigned to the chelating and bridging ligands respectively (Fig. 3c). P_A consists of a pair of triplets of doublets from which both P–Ag and P_A–P_B coupling constants could be extracted ($^1J(^{109}Ag–^{31}P_A) = 225$ Hz and $^2J(P_A–P_B) = 42$ Hz). The P_B signal is complicated by coupling to both Ag centres and the pattern was not readily analysable. However, based on the separation between the two symmetrical halves of the multiplet, $^1J(^{109}Ag–^{31}P_B)$ was estimated to be 290 Hz. The magnitudes of the silver–phosphorus couplings are diagnostic of AgP_4 coordination centres.[7] The assignments were consistent with a ^{31}P COSY NMR spectrum which showed P_A and P_B to be mutually coupled. Further substantiation came from literature values for the analogous disilver complex formed by 1,2-bis(di-4-pyridylphosphino)-ethane.[3c] The ^{1}H-NMR spectrum also showed the expected two ligand environments.

Addition of methanol or acid to the disilver complex converted it to the mononuclear bis-chelate $[Ag(\mathbf{L1})_2]^+$ (Fig. 2, right) as indicated by simpler NMR spectra and DLS (Fig. 3c, d). At pH 1.0 with four equivalents of HO_3SCF_3 per **L1** (one for each piperazine group) a single ^{31}P environment coupled to ^{107}Ag and ^{109}Ag was seen (δP = 3.8 ppm, $^1J_{^{109}Ag-^{31}P}$ = 263 Hz). The data are similar to those for the analogous dppe complex $[Ag(dppe)_2]^+$ (4.4 ppm, 266 Hz[3a]).

Molecular models of the mono- and di-silver complexes are shown in Fig. 4. They exhibit micelle-like core–shell structures, each complex having a hydrophobic interior surrounded by hydrophilic head groups. Importantly, the models also show that some of the hydrophobic interior of the monosilver complex remains exposed to the solvent and that in the disilver complex more of this hydrophobic surface is shielded from the solvent. This helps to understand adoption of the dinuclear structure in pure water as being driven by hydrophobic interactions.

Overall, as shown in Fig. 2, there are similarities between the behaviour of the free ligand and its Ag complex. In pure water, where hydrophobic interactions are present, free **L1** forms micelles and its silver complex is large (dinuclear). When hydrophobic interactions are absent (in organic solvents or low pH) free **L1** is monomeric and its silver complex is correspondingly small (mononuclear). The driving forces for the changes in structure are the same for the free ligand and metal complex. For both species methanol decreases the hydrophobic interactions. Similarly, protonation destabilises both the micelle and the disilver complex by causing head group–head group repulsions between the piperazine groups. However, an important difference is that whereas the micelle is a non-covalent assembly of individual molecules, the disilver complex is a single, covalently bonded molecule. Changing between mono- and di-nuclear complexes requires breaking and then remaking of coordination bonds. Therefore, the silver complex can be seen to *imitate* the growth of a true micelle but through covalent rather than non-covalent aggregation.

In summary, we report that hydrophobic interactions can be important in directing the structures adopted by metal

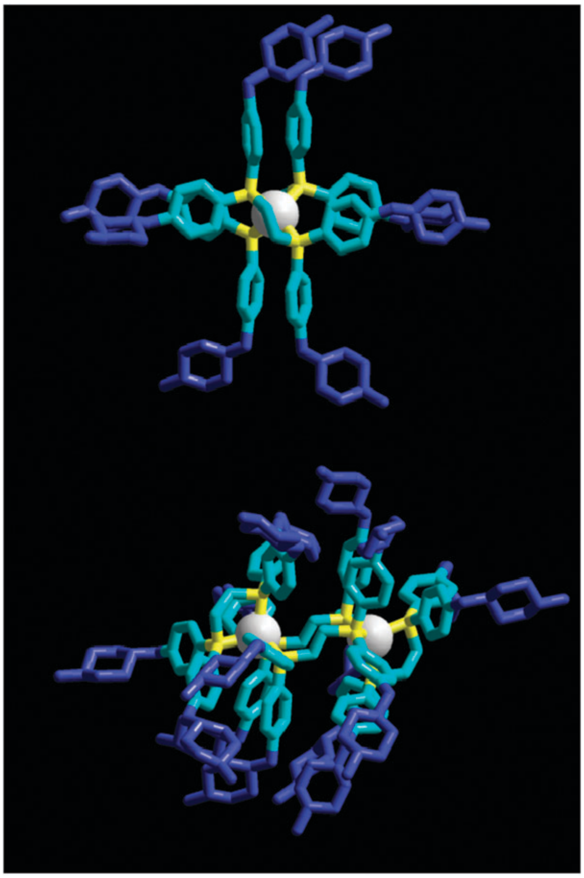

Fig. 4 Modelled structures of $[Ag(\mathbf{L1})_2]^+$ (above) and $[Ag_2(\mathbf{L1})_4]^{2+}$ (below) showing their *pseudo*-micellar structures. Piperazine substituents = blue, Ag = white, and P = yellow. For clarity H-atoms are not shown.

complexes which have micelle-like core–shell configurations. Previous work on the aggregation of metal complexes by hydrophobic interactions can be described as 'metal-complex-as-amphiphile', because of the head-group-and-tail structure of the complexes and the fact that non-covalent aggregation preserves the original molecular species. However, the situation here is better described as 'metal-complex-as-micelle'.[8] This description relates to the structural similarity of the complexes to micelles (core–shell) as well as the fact that the larger species stabilised by hydrophobic interactions is a single metal complex and not a non-covalent aggregate.

The concept may also be relevant to other metal complexes based on hydrophobic ligands to which hydrophilic substituents have been added (to render them water soluble). Examples of such complexes can be found in homogeneous catalysis[9] and medicinal chemistry.[3c,10] It also points to a general way of making coordination systems which respond to their medium in ways typically associated with micelles. Work is currently underway with further discrete and polymeric systems.

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