Dalton Transactions

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Journal:	*Dalton Transactions*
Manuscript ID	DT-COM-03-2025-000623
Article Type:	Communication
Date Submitted by the Author:	15-Mar-2025
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Selective Synthesis of a Heterotetranuclear Complex from a Macrocyclic Ligand with Multiple Identical Chelating Units

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Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

Selective complexation of specific units in homooligomers is usually challenging due to their similar reactivity. We now report a heteronuclear complex using a macrocyclic ligand with four identical *ONO* chelating units, which was synthesized by selective coordination to molybdenum at two diagonal units, followed by palladium at the remaining units.

Multinuclear complexes composed of multidentate Schiff-base ligands have been widely studied due to their high application potentials, including catalytic properties[1–3], molecular recognition abilities[4–7], and optical properties[8–11]. The physical and chemical properties of these multinuclear complexes are determined by the element, valence state, and spatial arrangement of the metal centres. Rigid ligands with multiple chelating units are particularly well-suited for the precise arrangement of metals.[12–16] Developing a method for the selective coordination of multiple different metals with such ligands would allow for finer control over the properties of the metal complexes[17–20] and expand the range of applicable fields. However, achieving selective complexation to obtain a single product remains a significant challenge. This is especially true when oligomeric ligands contain multiple identical coordination units making it difficult to control the number of coordinated metal centres (Fig. 1a).[20] If such a selective coordination can be realized, it would provide a novel strategy for synthesizing heteromultinuclear complexes with various metals.[21] To date, heterodinuclear complexes made from cyclic ligands with two identical coordination units have been reported, which were obtained by stepwise complexation (Fig. 1b),[22] conversion from homodinuclear complexes,[23] or simultaneous complexation under thermodynamic control.[24] Despite these several examples of dinuclear complexes, the controlled synthesis of heteronuclear complexes with three or more metal centres arranged at defined distances remains considerably more challenging.

As part of our research on the precise synthesis of functional macrocyclic molecules[25–28], we have focused on macrocyclic oligomers of tridentate chelating units.[4,6] In this study, we synthesized $(CF_3)_2$C-tetrasap H_8**1**, a cyclic tetramer of the *ONO*-type tridentate sap (salicylidene-aminophenol)[29–31] unit. H_8**1** was obtained in high yield (94%) via 2+2 condensation reaction of bissalicylaldehyde and bisaminophenol. The resulting cyclic framework features four identical sap coordination units. By using this ligand, a dinuclear complex was successfully synthesized, in which two diagonally positioned sap units selectively coordinated to Mo, thus enabling its subsequent complexation with Pd to form a heterotetranuclear Mo_2Pd_2 complex (Fig. 1c).

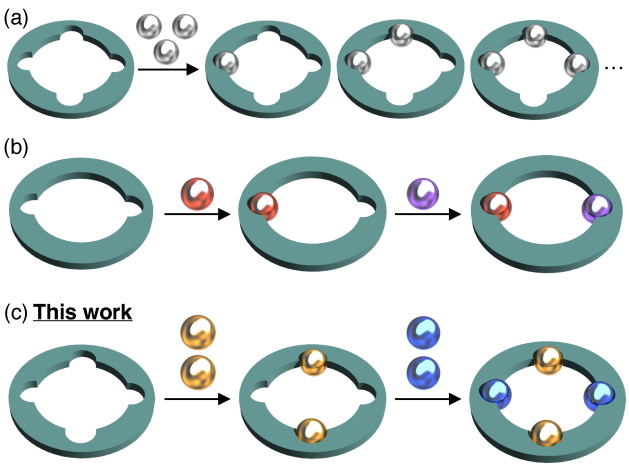

Fig. 1. (a) Difficulty in controlling the number of coordinating metal ions. (b) Stepwise formation of a heterodinuclear complex. (c) Selective coordination achieved in this study. First coordination at two diagonal units out of four identical chelates, and second coordination at the remaining units to form a heterotetranuclear complex.

The macrocyclic ligand H_8**1** was synthesized by heating diformylbiphenol **2**[32] and 2,2′-bis(aminophenol)-hexafluoropropane **3**[33] in THF/hexane = 1/4.5 for 40 h (Scheme S1). The resulting precipitate was filtered and dried to obtain H_8**1** in 94% yield (Fig. 2). H_8**1** was characterized by ^{1}H, ^{13}C, ^{19}F NMR, HRMS(ESI), and elemental analysis (Fig. S1–S4 in ESI†). In

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† Electronic supplementary information (ESI) available. CCDC 2424093-2424096. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/x0xx00000x

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the ^{1}H NMR spectrum, the number of observed signals corresponded to that of a single sap repeating unit, indicating that all four sap units in H_8**1** were equivalent on the NMR time scale (Fig. 4b). Meanwhile, an energy-minimized structure obtained by DFT calculations using a preliminary XRD data as the initial coordinates suggested that H_8**1** has two types of sap units (Fig. 2). For two diagonal sap units, both hydroxy groups face inward, adopting a conformation similar to that observed when coordinating to a metal in a tridentate *ONO* chelating mode. In contrast, the remaining two sap units adopt a different conformation, in which the hydroxy group of the salicylaldimine moiety faces inward, while that of the aminophenol moiety is oriented outward.

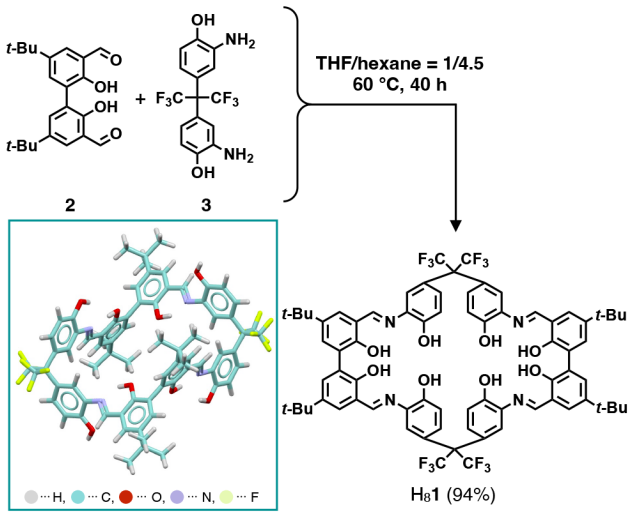

Fig. 2. Synthesis of $(CF_3)_2$C-tetrasap H_8**1**. (Inset) Structure of H_8**1** obtained by DFT calculations (B3LYP/6-31G*).

Monomeric sap molybdenum (VI) complexes [Mo(sap)O_2L] (L: solvent) with an octahedral geometry are known to be synthesized by heating sap and $MoO_2(acac)_2$, and are used as catalysts for epoxidation reactions.[31] Based on this, the tetranuclear Mo complex [**1**$Mo_4O_8(H_2O)_4$] was synthesized in 90% yield by heating 6 equiv. of $MoO_2(acac)_2$ and $(CF_3)_2$C-tetrasap H_8**1** in acetonitrile at 70 °C for 3 h, followed by reprecipitation with water (Fig. 3a) (Scheme S2 and Fig. S5–S12 in ESI†). The XRD result of the crystal obtained from a CH_3CN solution showed the complex moiety [**1**$Mo_4O_8(CH_3CN)_3$], in which each sap unit bound to Mo through a tridentate chelation (Fig. 3b,c). Unlike the metal-free H_8**1** (Fig. 2), all four sap units adopt nearly identical conformations, and the overall cyclic framework exhibits a twisted pseudo-D_2-symmetric structure with sap-Mo moieties alternating in an up-down-up-down manner. Three of the Mo centres are coordinated by acetonitrile, while the remaining one forms an intermolecular Mo=O ··· Mo bond. A ^{1}H NMR spectrum of [**1**$Mo_4O_8L_4$] in $CDCl_3/CD_3CN$ = 10/1 showed the number of signals corresponding to one monomeric unit (Fig. 4c), suggesting that the four sap units are equivalent in a time-averaged structure and that there are no intermolecular coordination bonds in solution.

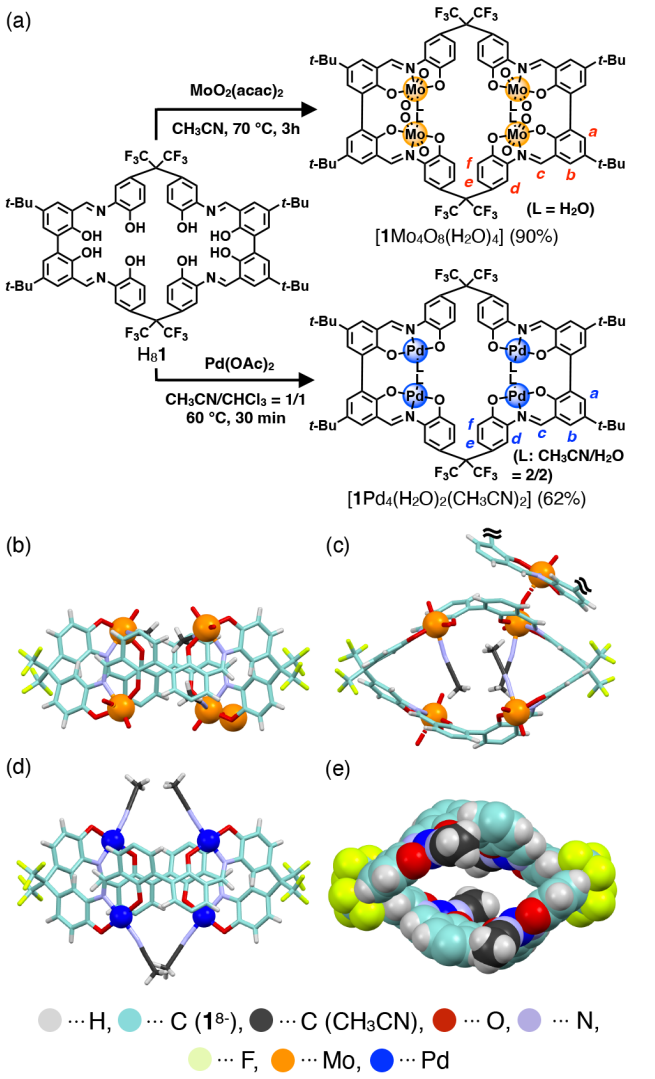

Fig. 3. (a) Synthesis of homotetranuclear complexes. The labels (*a*–*f*) on the complexes correspond to the assignment of ^{1}H NMR signals in Fig. 4c,d. (b–e) Structures of [**1**$Mo_4O_8(CH_3CN)_3$] (b,c) and [**1**$Pd_4(CH_3CN)_4$] (d,e) determined by single-crystal X-ray diffraction analysis. Solvents and *tert*-butyl groups have been omitted for clarity. In (c), an adjacent Mo(sap) unit that forms an intermolecular Mo=O ··· M coordination bond is shown. (b–d) Ball-and-stick models. (e) Space-fill model.

As an example of complexes with other elements, we also synthesized a tetranuclear Pd complex by reacting 6 equiv. of $Pd(OAc)_2$ with H_8**1** (Fig. 3a) (Scheme S3 and Fig. S13–S21 in ESI†). The XRD analysis of [**1**$Pd_4(CH_3CN)_4$] showed that Pd was also bound in a tridentate manner by the four sap units, with acetonitrile coordinating to all the Pd centres. The macrocyclic framework was similar to that of the Mo complex (Fig. 3d). The internal space of the macrocyclic framework was sufficient for potential future applications such as molecular encapsulation (Fig. 3e).

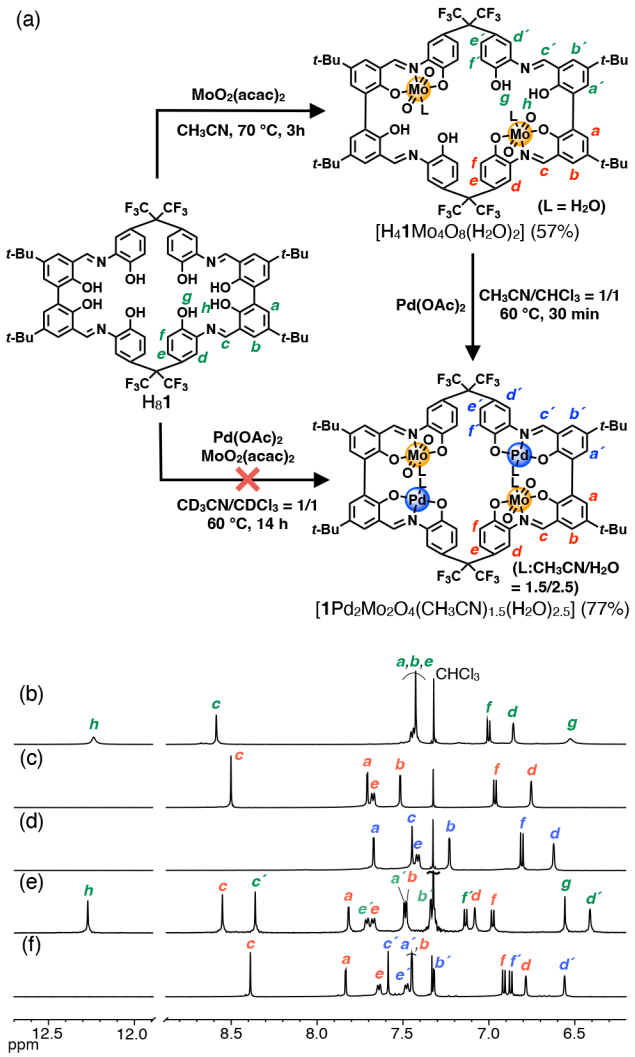

Fig. 4. (a) Synthesis of dinuclear Mo and heterotetranuclear Mo-Pd complexes. (b–f) ^{1}H NMR spectra of ligand and complexes (600 MHz, $CDCl_3/CD_3CN$ = 10/1). (b) H_8**1**. (c) [**1**$Mo_4O_8L_4$]. (d) [**1**Pd_4L_4]. (e) [H_4**1**$Mo_2O_4L_2$]. (f) [**1**$Pd_2Mo_2O_4L_4$].

Since the macrocyclic ligand H_8**1** has four chemically-equivalent sap units but two out of the four are suggested to take different arrangements of the hydroxy groups as described above, we postulated that it would be possible to control the number of coordinating metals by utilizing this structural heterogeneity. Heating 2 equiv. of $MoO_2(acac)_2$ and ligand H_8**1** in acetonitrile at 70 °C for 3 h resulted in the formation of a precipitate, which was collected by filtration to afford the dinuclear Mo complex in 57% yield (Fig. 4a) (Scheme S4 and Fig. S22–S31 in ESI†). The ^{1}H NMR spectrum of [H_4**1**$Mo_2O_4L_2$] exhibited signals of phenolic protons (*g* and *h*) of the metal-free sap units, and two sets of signals for *tert*-Bu and aromatic protons were observed, corresponding to Mo-bound and metal-free units (Fig. 4e). A single-crystal XRD analysis revealed that Mo is coordinated to the two diagonal sap units (Fig. 5a, b). The hydroxyl groups of the remaining metal-free sap units both faced inward, and the overall framework of the macrocyclic was like that of the tetranuclear Mo or tetranuclear Pd complexes described above. Compared to the structure of the metal-free H_8**1** (Fig. 2), it was indicated that the coordination of the two Mo centres caused the structural changes in the macrocyclic framework and sap chelating units.

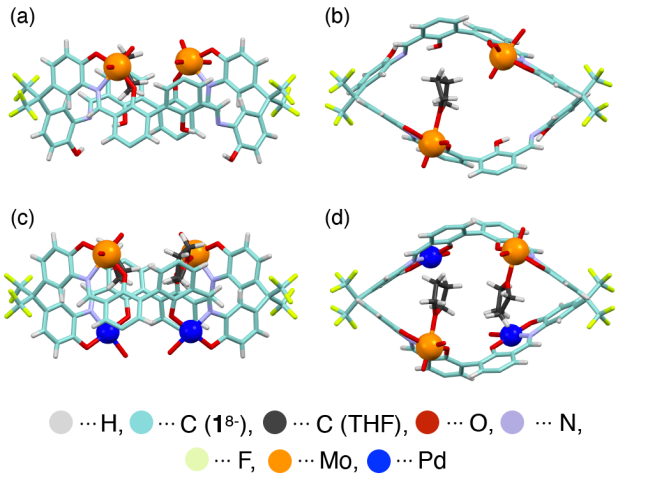

Fig. 5. (a–d) Structures of dinuclear Mo complex [H_4**1**$Mo_2O_4(H_2O)$(thf)] (a,b) and heterotetranuclear Mo-Pd complex [**1**$Pd_2Mo_2O_4(H_2O)_2$(thf)$_2$] (c,d) determined by single-crystal XRD analyses. Ball-and-stick models. Solvents and *tert*-butyl groups have been omitted for clarity.

Having succeeded in isolating dinuclear complexes, we next aimed at synthesizing heteronuclear complexes by coordinating metals other than Mo to the metal-free sap units. Indeed, the heterotetranuclear Mo-Pd complex [**1**$Pd_2Mo_2O_4L_4$] was successfully synthesized by reacting the dinuclear Mo complex [H_4**1**$Mo_2O_4L_2$] and $Pd(OAc)_2$ (Fig. 4a) (Scheme S5). [**1**$Pd_2Mo_2O_4L_4$] was unambiguously characterized by ^{1}H, ^{19}F, ^{13}C NMR, elemental analysis and XRD measurements (Fig. S32–S40 in ESI†). Its ^{1}H NMR spectrum showed the disappearance of signals of the phenolic protons and the presence of two sets of aromatic signals corresponding to the Mo-sap and Pd-sap units (Fig. 4f). An XRD analysis confirmed that Pd is bound to the two diagonal positions, consistent with the binding of Pd to the unit that was originally free in the dinuclear Mo complex (Fig. 5c,d).

As a control experiment, we attempted to synthesize the heterotetranuclear complex by simultaneously adding two metals (Mo and Pd) to the $(CF_3)_2$C-tetrasap ligand. H_8**1** was first dissolved in $CDCl_3/CD_3CN$ =1/1, followed by the addition of 2 equiv. each of $Pd(OAc)_2$. The mixture was then heated at 60 °C for 14 h (Scheme S6). The ^{1}H NMR spectrum of the reaction mixture displayed numerous signals, indicating the formation of multiple species in solution (Fig. S41 in ESI†). This result suggested that simultaneous metal addition does not lead to a selective complexation. In another experiment, pre-formed tetranuclear Mo complex [**1**$Mo_4O_8(H_2O)_4$] and tetranuclear Pd complex [**1**$Pd_4(CH_3CN)_2(H_2O)_2$] were mixed and heated at 60 °C, but no significant changes were observed in the ^{1}H NMR spectra of the solution (Fig. S42 in ESI†). This result suggests that [**1**$Pd_2Mo_2O_4L_4$] was not the thermodynamic product of reversible complexation reactions. Therefore, the key to the selective synthesis of the heterotetranuclear complex lies in the

stepwise approach via the dinuclear complexes, in other words, the successful isolation of [H_4**1**$Mo_2O_4L_2$].

In conclusion, we have synthesized the macrocyclic ligand H_8**1** with four sap units in high yield (94%) using diformylbiphenol **2** and $(CF_3)_2$C-bisaminophenol **3**. The tetranuclear complexes, [**1**$Mo_4O_8L_4$] and [**1**Pd_4L_4], exhibited intriguing cyclic structures, in which the chelating sap units were oriented alternately upward and downward utilizing the rotational flexibility of the biphenyl units. Furthermore, we successfully isolated a dinuclear Mo complex, and synthesized a heterotetranuclear complex by coordinating Pd to its metal-free sap units. Since sap complexes have been reported with various metals[29–31], it is reasonable to expect that this method can be easily extended to combinations of elements beyond Mo and Pd. In the future, we aim to explore the chemical properties and reactivity derived from the precise arrangement of heterometals.

This research was supported by JST PRESTO (Grant Number JPMJPR2475), the Asahi Glass Foundation, the Amano Institute of Technology, the Samco Foundation and the TRiSTAR program.

Data availability

The data supporting this article have been included as the ESI.†

Conflicts of interest

There are no conflicts to declare.

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The data supporting this article have been included as the ESI.