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Bridged Dihydroxypyridine Ligands for the Synthesis of Expanded Helicates

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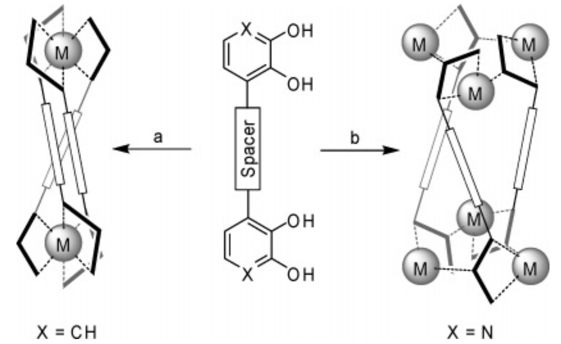
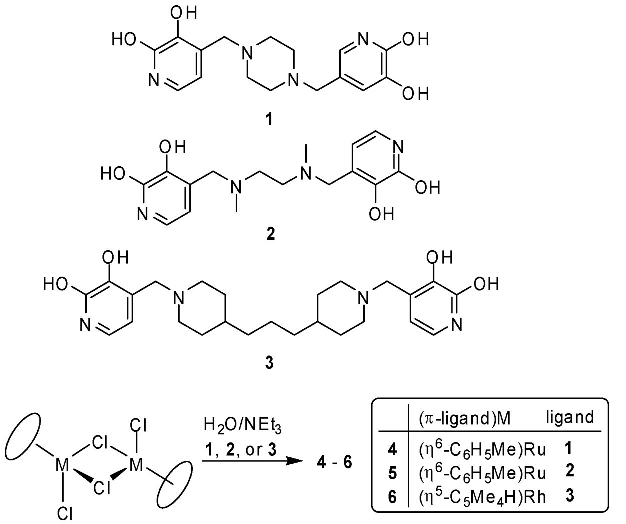
Ligands, in which two catechol groups are connected by a spacer, have been used extensively as building blocks in supramolecular chemistry. Various architectures have been realized, including metallamacrocycles,[1] heterometallic clusters,[2] tetrahedral coordination cages,[3] and most notably triple-stranded helicates.[3c,4] In the following, we demonstrate that the exchange of the catechol group with a dihydroxypyridine group allows access to a new structural motif, which can be described as an expanded triple-stranded helicate. In these complexes, the two chiral ML_3 units are replaced by likewise chiral M_3L_3 units (Scheme 1). Structural evidence is presented that expanded helicates with a length of 2.8 nm can be obtained.

Scheme 1. Metal-Based Self-Assembly of Bridged Catechol or Dihydroxypyridine Ligands Can Lead to the Formation of Helicates (a) or Expanded Helicates (b)



Scheme 2. Synthesis of the Expanded Helicates **4**−**6** by Reaction of the Multifunctional Ligands **1**−**3** with $[(\eta^6\text{-}C_6H_5Me)RuCl_2]_2$ or $[(\eta^5\text{-}C_5Me_4H)RhCl_2]_2$, Respectively



	(π-ligand)M	ligand
4	$(\eta^6\text{-}C_6H_5Me)Ru$	1
5	$(\eta^6\text{-}C_6H_5Me)Ru$	2
6	$(\eta^5\text{-}C_5Me_4H)Rh$	3

The Mannich reaction of 2,3-dihydroxypyridine with formaldehyde and secondary amines is known to give 4-aminomethyl-substituted products.[5] In a similar fashion, we prepared the multifunctional ligands **1**−**3** (Scheme 2) using the commercially available diamines piperazine, *N,N′*-dimethylethylenediamine, or 1,3-di(4-piperidyl)propane (see Supporting Information). Subsequently, we examined the reaction with the ruthenium complex $[(\eta^6\text{-}C_6H_5Me)RuCl_2]_2$. This organometallic half-sandwich complex was chosen because we had previously observed that $[(arene)RuCl_2]_2$ complexes react with 2,3-dihydroxypyridine ligands in the presence of base to give trinuclear metallamacrocycles.[6] These trimers are compatible with aqueous solvents,[7] which was of importance because the polar ligands **1**−**3** display a very limited solubility in organic solvents.

When an aqueous solution of complex $[(\eta^6\text{-}C_6H_5Me)RuCl_2]_2$ and equivalent amounts of ligand **1** or **2** was carefully layered with NEt_3, the complexes **4** and **5** were obtained in the form of orange crystals in 60% (**4**) or 41% (**5**) yield, respectively (Scheme 2). A similar reaction with ligand **3** did not provide a crystalline material.[8] Using the structurally related dimer $[(\eta^5\text{-}C_5Me_4H)RhCl_2]_2$, however, we were able to isolate crystals of the corresponding complex **6** in 37% yield.

The complexes **4**−**6** were characterized by NMR spectroscopy and single-crystal X-ray analysis. The ^1H NMR spectra of the Ru complexes **4** and **5** in $CDCl_3$ showed a single set of signals for the toluene and the hydroxypyridine ligand, which was indicative of a highly symmetrical structure. Five distinct signals were observed for the aromatic protons of the π-ligand, and two doublets were found for the methylene protons adjacent to the pyridine ring. This was a clear sign for the presence of stereogenic centers. The ^1H NMR spectrum of the rhodium complex **6** showed likewise a single set of signals for the ligands. Four singlets were observed for the CH_3 groups of the tetramethylcyclopentadienyl ligand, and well resolved diastereotopic methylene protons were found for the NCH_2 group next to the heterocycle.

The NMR data for the complexes **4**−**6** in solution were in agreement with the structures observed in the solid state (Figure 1). The complexes are comprised of six (π-ligand)M fragments, which are connected by three deprotonated ligands. Two pairs of 12-membered metallamacrocycles are observed for each complex, with the metals coordinated to the two O atoms and the N atom of the dihydroxypyridine group. The diamine linker connects the two macrocycles to form a cylindrical structure. The lengths of these cylinders (maximum H-to-H distance) is 2.1 nm (**4**), 1.9 nm (**5**), and 2.8 nm (**6**). All three complexes co-crystallize with significant amounts of water molecules, several of which are hydrogen bonded to the O and N atoms of the complexes.

Complex **6** is remarkable because of its length of nearly 3 nm. The macrocycles formed between two opposite metals have a ring size of 44 atoms containing a total of 18 CH_2 groups, only 8 of which are part of semirigid piperidine units. Complex **6** is therefore a rare example of a discrete, multinuclear complex, which was obtained by metal-based self-assembly with a highly flexible ligand.[9]

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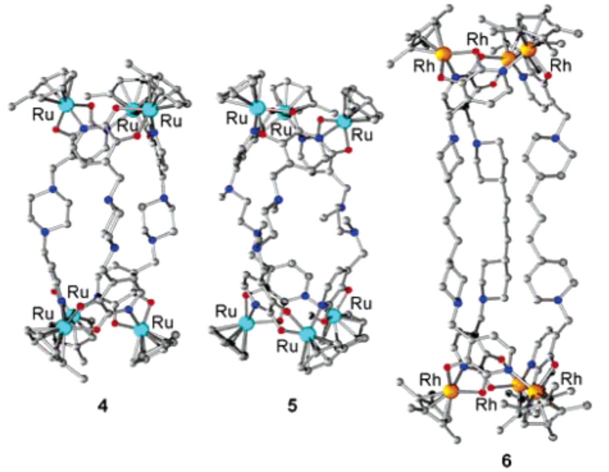

Figure 1. Graphic representation of the molecular structures of the complexes **4**−**6** in the crystal (C = gray, N = blue, O = red). The hydrogen atoms and the co-crystallized solvent molecules are not shown for clarity.

The Ru complexes **4** and **5** display pseudo D_3 symmetry, with all six metal centers having the same configuration. The Rh complex **6**, on the other hand, has a crystallographic C_3 axis and an idealized overall C_{3h} symmetry. The metal centers at one end of the molecule have thus the opposite configuration to the metal centers at the other end. Interestingly, this parallels what has been observed for catecholate-based triple-stranded helicates: ligands with an even number of methylene groups in the spacer were found to form chiral helicates, whereas ligands with an odd number of methylene groups in the spacer gave rise to achiral *meso*-helicates, in which the metal centers have the opposite configuration.[4,10]

Epimerization processes at the metal centers were expected to be slow.[11] The NMR data of the complexes **4**−**6** therefore suggested that the structures observed in the solid state were maintained in solution.[12] This led to the conclusion that only one diastereoisomer had crystallized from the aqueous solution and that the ligands—despite their flexibility—are able to control the stereochemistry of all six metal centers. Attempts to investigate the self-assembly process of **4**−**6** in situ by ^{1}H NMR in D_2O were hampered by the low solubility of the fully deprotonated products. Preliminary NMR studies of the reaction of $[(C_5Me_4H)RhCl_2]_2$ with ligand **3** with variable amounts of CsOH in D_2O suggest that **6** is formed in over 90% yield with excellent diastereoselectivity (see Supporting Information). Presently, it is not clear whether the complexes are formed under thermodynamic or kinetic control. Prolonged heating of chloroform solutions of **4**−**6** led unfortunately to a partial decomposition.

In summary, we have described the syntheses and the structures of three hexanuclear complexes, which were obtained by base-induced assembly of organometallic half-sandwich complexes with bis(dihydroxypyridine) ligands. The complexes display a unique structural motif: two chiral $[(\pi\text{-ligand})M]_3L_3$ fragments are connected by three flexible linkers. They can thus be described as expanded triple-stranded helicates.[13] The synthetic concept appears to be quite flexible because the bridging ligand as well as the metal fragment can be varied. Complexes of this kind are expected to display an interesting host−guest chemistry because they contain 12-metallacrown-3 sites, which should be suited for the complexation of small metal ions,[6,7] as well as a flexible cavity decorated by amine groups. Investigations in this direction are currently being pursued in our laboratory.

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Supporting Information Available: Experimental procedures and spectroscopic properties for the ligands **1**−**3** and the metal complexes **4**−**6** and crystallographic data in CIF format (**4**−**6**). This material is available free of charge via the Internet at http://pubs.acs.org.

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(11) Trinuclear organometallic macrocycles based on dihydroxypyridine ligands are known to be configurationally stable on the NMR time scale, even in polar solvents such as water (see ref 7a).

(12) For a complex with a structure such as **6**, the *meso* and the chiral form can in principle be distinguished by ^{1}H NMR spectroscopy because the multiplicity of the central CH_2 group of the linker is different. In the case of **6**, however, these signals were not resolved.

(13) For multimetallic helicates, in which the metal centers are disposed in a polyhedral mode, see: Bermejo, M. R.; González-Noya, A. M.; Pedrino, R. M.; Romero, M. J.; Vázquez, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 4182−4187.

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