Host–Guest Systems

An Aromatic Anion Receptor: Anion–π Interactions do Exist**

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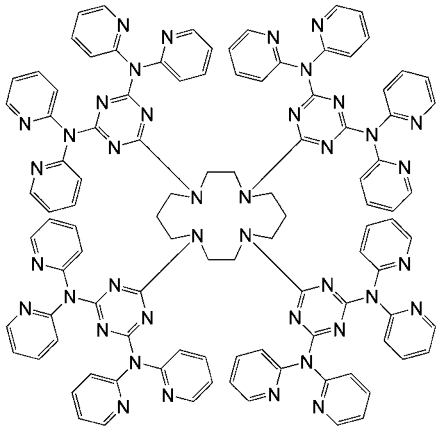
Noncovalent supramolecular interactions involving aromatic rings play a significant role in both chemical and biological recognition.[1] For example, π-stacking interactions between the aryl rings of nucleobase pairs help to stabilize the DNA double helix.[2,3] It is well known that cation–π interactions are of great importance for many biological systems.[4,5] Thus, the binding of the agonist acetylcholine to its receptor is very selective and involves cation–π interactions between a quaternary ammonium group and a tryptophan amino acid residue.[6] Design and preparation of supramolecular host–guest compounds involving neutral or cationic entities have therefore received much attention during the last two decades.[7] In contrast, the chemistry of noncovalent anion–π interactions is much less developed.[8,9] This is most likely due to the electron-donating character of anions, which is expected to lead to repulsive interactions with aromatic π clouds. However, in the last few years, an increasing number of aryl hosts for anionic guests have been studied, probably because of their potential medicinal and biological applications.[8] Indeed, more than 70% of enzyme substrates and cofactors are anions.[10]

Interactions between π-electron-poor aromatic moieties and anions were first demonstrated by NMR studies.[11–13] Several recent articles have reported theoretical investigations on the binding of halides with electron-deficient π systems such as fluorobenzene derivatives,[14–16] fluoro-*s*-triazine[17] and *s*-tetrazine derivatives,[18] and tetrafluoroethene.[19] All calculations clearly indicated an energetically favorable noncovalent interaction between halide and π system.[20] Lately, the first crystallographic evidence was reported for such interactions, between the 1,3,5-triazine group of the ligand 2,4,6-tris(di-2-pyridylamino)-1,3,5-triazine[21,22] and chloride and tetrachlorocuprate[23] anions.

In the course of research on the preparation of triazine-based coordination polymers[24,25] and their physical and catalytic properties,[26,27] the dendritic octadentate ligand *N,N′,N″,N‴*-tetrakis{2,4-bis(di-2-pyridylamino)-1,3,5-triazinyl}-1,4,8,11-tetraazacyclotetradecane (azadendtriz) was synthesized.[27]



Layering an aqueous solution of CuCl$_2$ (2 mL, 32 mM) with a solution of azadendtriz in dichloromethane (2 mL, 3.6 mM) gave blue prismatic crystals of [Cu$_4$(azadendtriz)Cl$_4$](Cl)$_4$(H$_2$O)$_{13}$ (**1**) in 54% yield by slow diffusion of the ligand into the aqueous phase, which gradually turned from colorless to dark blue (see Supporting Information).

The structure of **1** (Figure 1) shows a cationic tetranuclear copper moiety formed by one dendritic ligand, where the four *s*-triazinyl groups stack two by two in a parallel fashion. Consequently, the copper ions are coordinated by two 2,2′-dipyridylamino units belonging to two different *s*-triazine rings. The coordination spheres of the square-pyramidal ($\tau =$ 0.11, 0.13, 0.11, and 0.13 for Cu1, Cu2, Cu3, and Cu4, respectively)[28] metal centers are completed by a chloride anion at the apical position at a distance varying from 2.406(6) to 2.431(5) Å. The Cu–N distances of 1.991(9)–2.056(12) Å can be considered normal for square-pyramidal Cu^{II} ions. In

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[**] Financial support from COST Action D21/003/2001 and the Dutch National Research School Combination Catalysis (HRSMC and NIOK) are thankfully acknowledged.

Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.

DOI: 10.1002/ange.200460486

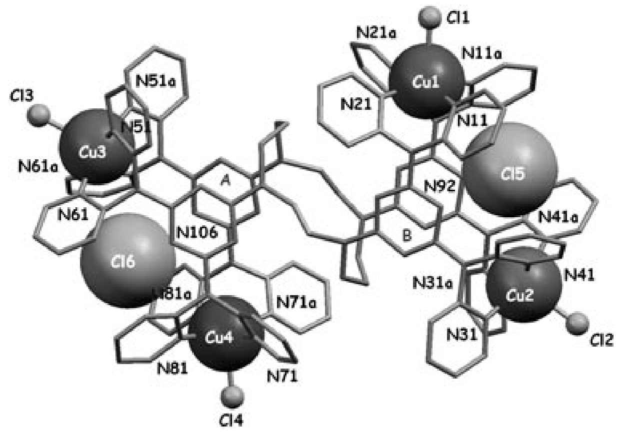

Figure 1. Representation of **1**, showing the four pentacoordinate Cu^{II} ions and the two encapsulated chloride anions Cl5 and Cl6.

addition, four chloride anions and thirteen water molecules are located in the crystal lattice. Some of these noncoordinated entities are disordered, for example, two carbon atoms of the azacrown group. The triazine rings are π–π stacked in pairs with nearly perfect face-to-face alignment (Figure 1), which is quite a rare phenomenon.[23,29] The distances between the triazine centroids of 3.65 (rings A) and 3.60 Å (rings B) are slightly longer than the usual values for π–π interactions (ca. 3.5 Å). However, such elongation is commonly observed with N-heteroaromatic ligands, especially when the nitrogen atoms of one ring face the nitrogen atoms of the other, which leads to unfavorable electrostatic interactions.[3] A shorter distance has been observed with a less repulsive N/C face-to-face alignment between two *s*-triazine rings.[30]

The most fascinating feature of this supramolecular species is its ability to encapsulate two chloride anions. Indeed, Cl5 and Cl6 are the guests of two host cavities formed by four pyridine rings of the ligand (Figure 1). The centroid···Cl$^-$ distances vary from 3.521(6) to 3.559(5) Å for Cl5, and from 3.466(5) to 3.697(5) Å for Cl6. These distances are longer than the values calculated for the model *s*-triazine anion.[17,19] Unfortunately, no theoretical investigations are yet available for the pyridine ring, which is a much less electron deficient aromatic ring, but one would reasonably expect longer ring–anion bonds. The anion–π interactions observed here are favored by the fact that the pyridine rings involved are coordinated to copper ions, which enhances their electron-poor character. In addition to the π interaction, the chloride ions are close to the neighboring triazine rings. Indeed, the Cl5···N92 and Cl6···N106 distances of 3.013(12) and 3.119(13) Å, respectively, suggest some electrostatic interactions between the guest anions and the electron-deficient triazine rings. The combination of both electronic effects confers electrophilic character on the host cavity. The angles of the Cl$^-$···centroid axis to the plane of the different pyridine rings are 78 and 80° for Cl5, and 74 and 82° for Cl6. The ideal anion–aromatic plane angle of the extensively studied *s*-triazine moiety is 90°. However, again, no theoretical calculations have been performed on the pyridine ring, and thus the optimal angle has not yet been determined.

In summary, the first coordination compound of the ligand azadendtriz is reported. The supramolecular copper complex **1** shows unusual intramolecular π–π interactions between 1,3,5-triazine rings. Furthermore, this tetranuclear complex exhibits host–guest properties, and the first encapsulation of a chloride anion by four pyridine rings is described, which demonstrates the possible existence of anion–π interactions. The encapsulation of the bromide anion is currently being investigated. A theoretical approach to study this non-hydrogen bonding artificial anionic receptor is also proposed. Understanding how nature can selectively bind, functionalize, and transport anionic species in biological systems would undoubtedly be of great importance for the design of new drugs.

Received: April 28, 2004
Revised: June 30, 2004

Keywords: copper · host–guest systems · N ligands · Pi interactions · supramolecular chemistry

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