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Hydrogen bonded driven anion binding by dicationic [1$_4$]imidazoliophanes

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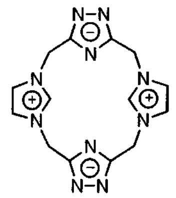
Imidazolium units represent the main structural motifs for the formation of unconventional C–H···Cl^- hydrogen bonds which become the noncovalent forces driving the anion interactions exibited by dicationic [1$_4$]imidazoliophanes in the solid state, while C–H···O hydrogen bonds with water play a crucial role in governing the conformation of the solid–state aggregates, as well as in solution, wherein NMR studies also reveal the importance of hydrogen bonds in controlling the tendency to anion binding.

The molecular diversity within molecular *hosts* permits the design of new architectures with capacity for specific biological or physical properties.[1] The increasing interest in anion recognition phenomena is mainly directed towards synthetic receptors based on positively charged moieties.[2] Consequently, the primary noncovalent driving forces are controlled by electrostatic interactions,[2] whereas hydrogen bonding forces[3] are known to play a significant role in a few host systems.[4] Developing the chemistry of heterocyclic betaines, we have reported the first examples of quadrupolar architectures within [1$_4$]heterophanes built up from imidazolium methylene triazolate subunits, *e.g.* the bis-betaine **1**, as well as its precursors the dicationic macrocycle **2** and betaine **3**.[5] We now report the synthesis and structural properties of simple dicationic [1$_4$]heterophanes **4·2X** containing two imidazolium nuclei in a 1,3-alternating manner as models for anion recognition.



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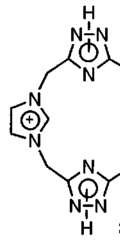
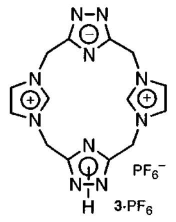
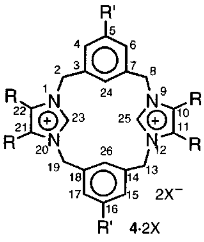


2·2X



3·PF$_6$

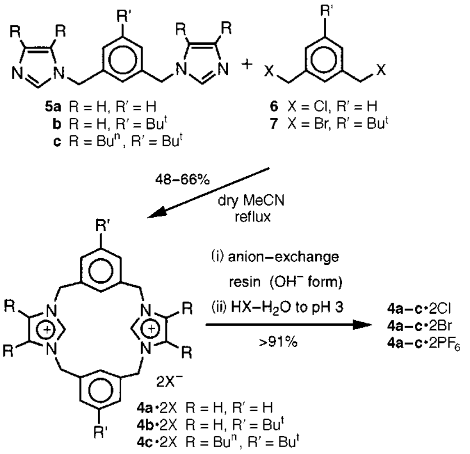


4·2X

The dicationic phanes **4·2X** were prepared following a '3+1' convergent approach (Scheme 1), efficiently applied for synthesizing the dicationic azolophane **2**. Thus, macrocyclization of the trinuclear compounds **5a–c**† with 1,3-bis(halomethyl)benzenes **6** or **7** produced the title phanes **4a–c·2X**.‡

The targeted macrocycles were characterized on the basis of their spectroscopic data.§ Furthermore, the structure of macrocycles **4a·2Cl·2H$_2$O** and **4b·2Cl·3.5H$_2$O** were confirmed by X-ray crystallography.¶||

Concerning **4a·2Cl·2H$_2$O**, the dication **4a** adopts a chair-like conformation (Fig.1 and 2). Regarding hydrogen bonds,** in the highly directional C–H···Cl^- interactions (θ *ca.* 160°), each chlorine counterion is three-centered between a *m*-xylyl hydrogen atom, *e.g.* H6, and the acidic hydrogen atom on the imidazolium ring, *e.g.* H10, the latter being the shortest hydrogen bond interaction (2.54 Å, θ = 157°).†† Moreover, there are *weak* interactions with water.**



Scheme 1 '3+1' Convergent synthesis of dicationic imidazoliophanes **4·2X**.

The molecular shape of dication **4b** assumes a cone-like conformation in contrast with the partial cone-like arrangement observed for **4a**. However, both dications **4a** and **4b** have similar molecular cavity dimensions: a square of 5 Å side.[5] The assemblages depicted in Fig. 3 show that the asymmetric unit of **4b·2Cl·3.5H$_2$O** contains two different dication—**A** and **B**. Dication **A** has the propensity to form hydrogen bonds with one of the chlorine counterions (Cl2), meanwhile dication **B** interacts with one water molecule (O7).||**

For the title dications **4a–c·2X** (X = Cl^-, Br^-, PF_6^-) reported, the ^{1}H NMR spectra showed a sharp singlet for the methylene

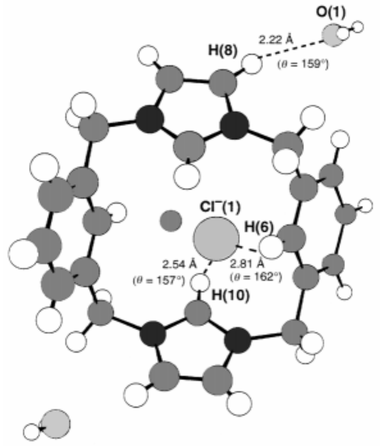


Fig. 1 Molecular structure of **4a·2Cl·2H$_2$O**, showing the non-covalent interactions.

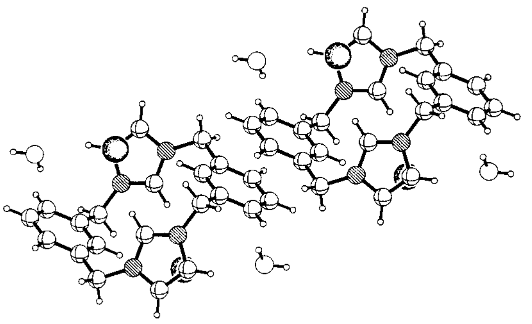


Fig. 2 Unit cell diagram for **4a·2Cl·2H$_2$O**.

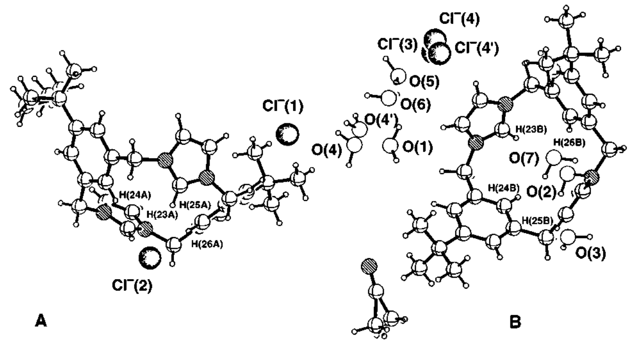


Fig. 3 Unit cell diagram for **4b·2Cl·3.5H$_2$O·0.5CH$_3$N**.

proton atoms, indicating the rapid interconversion of the different possible conformations, comparable to those of [1$_4$]azolophane **2·2X**.[5]‡‡ Moreover, the δ_H values of H-23 and H-25 (Im$^+$) together with H-24 and H-26 (aromatic fragments) are sensitive to the nature of the anion and to the solvent polarity, moving to lower fields.

As a consequence of the hydrogen bonding with the counteranion present in the macrocycle, the acidic H-23 and H-25 hydrogen atoms are shifted downfield in comparison with standard values for these protons within azolophanes (*e.g.* **2·2X**) and a variety of *N*-azolylimidazolium salts with different spacers.[5,8] Furthermore, significant changes in δ_H were induced by addition of various tetrabutylammonium salts [*ca.* 6 mM] to a DMSO-d_6 solution of the model dication **4c·2PF$_6$** [*ca.* 3 mM]. The major deshielding effect observed was up to 302 Hz for the imidazolium ring protons H-23 and H-25, and followed the order $H_2PO_4^- > F^- > CH_3CO_2^- > CN^- > Cl^-$.

In summary, a convergent '3 + 1' synthesis led to model dicationic heterophanes based on imidazolium units as molecular recognition motifs for anions. Structural studies both in solution and in the solid-state reveal that dications **4·2X** are unusual hydrogen bond donor-rich organic macrocycles, and their anion interactions are controlled by hydrogen bonding networks. These simple dicationic systems may be exploited for template phenomena and transport processes.

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Notes and references

† Protophanes **5a–c** (ref. 6) were obtained by reaction of conveniently substituted imidazoles with a 1,3-bis(halomethyl)benzene **6** or **7** (ref. 7).

‡ Counterion exchange was performed by treatment of the [1$_4$]heterophanes **4a–c·2X** with a strongly basic anion exchange resin (ref. 8) followed by immediate collection of the eluates in acid solutions (either aq. HCl, aq. HBr or aq. HPF$_6$) to pH 3–4, following a standard protocol (ref. 5, 8).

§ As for ES mass spectra, the heterophanes **4a·2X** revealed characteristic peaks for the successive loss one and two counterions.

¶ *Crystal data* for **4a·2Cl·2H$_2$O:** $C_{22}H_{26}Cl_2N_4O_2$, M = 449.37, colorless crystal, 0.53 × 0.53 × 0.43 mm^3 size, monoclinic, a = 8.627(2), b = 15.788(1), c = 8.735(2) Å, β = 113.38(1)°, V = 1092.0(3) Å^3, space group $P2_{1/c}$, Z = 2, ρ = 367 g cm^{-3}, Mo-Kα radiation (graphite crystal monochromator, λ = 0.71073 Å), μ = 0.324 mm^{-1}, T = 200(2) K. Of 2828 reflections measured, 1910 were unique with R_{int} = 0.019, of which only 1674 reflections were observed with $I > 2\sigma(I)$, final GoF = 1.076, refined to R_1 = 0.027, wR_2 = 0.067. For **4b·2Cl·3.5H$_2$O·0.5CH$_3$CN**: $(C_{30}H_{38}N_4Cl_2)\cdot 3.5H_2O\cdot 0.5CH_3CN$, M = 609.13, colorless crystal, 0.26 × 0.23 × 0.26 mm^3 size, triclinic, a = 12.240(4), b = 12.837(5), c = 21.579(8) Å, α = 90.50(3), β = 96.55(4), γ = 98.03(3), V = 3334(2) Å^3, space group $P\bar{1}$, Z = 4, ρ = 1.213 g cm^{-3}, Mo-Kα radiation (graphite crystal monochromator, λ = 0.71073 Å), μ = 0.233 mm^{-1}, T = 200(2) K. Of 12321 reflections measured, 11718 were unique with R_{int} = 0.0509 and 5375 observed with $I > 2\sigma(I)$, final GoF = 1.029, refined to R_1 = 0.1032, wR_2 = 0.2512. Data collected on a Nonius CAD-4 single-crystal diffractometer, ω–2Θ scans. Lorent and polarization corrections were applied and the data were reduced to F_o^2 values. The structures were solved by direct methods using the program SHELXS (ref. 9), were further refined using SHELXL (ref. 10), and the major occupancy non-hydrogen atoms refined anisotropically. The hydrogen atoms, located by Fourier difference synthesis, were isotropically refined with a common thermal parameter. Crystals of compound **4b·2Cl** were very unstable, and were mounted on a X-TEMP2 device (ref. 11). CCDC 182/1132.

‖ The atom numbering system is not the same as that obtained from the X-ray analysis.

** For **4a·2Cl**, the most relevant geometrical data for hydrogen bonds, distances (Å) and angles (°) (with esds) are: C(10)–H(10), 0.976 (19), C(10)···Cl⁻(1), 3.456 (2), H(10)···Cl⁻(1), 2.538 (19), C(10)–H(10)···Cl⁻(1),156.7 (1.5); C(6)–H(6), 1.005 (18), C(6)···Cl⁻(1), 3.781 (2), H(6)···Cl⁻(1), 2.811 (19), C(6)–H(6)···Cl⁻(1), 162.3 (1.3). Concerning interactions with water, the C–H···O hydrogen bond connects the trifurcated acceptor (O1) with the cationic ring, *e.g.* H8, the *m*-xylene ring, *e.g.* H2, and the spacer, *e.g.* H27.

†† Steiner (ref. 12) pointed out that hydrogen bonds from C–H groups to halide ions are only rarely discussed in the literature, even though stronger C–H donors exhibit CH···Hal⁻ distributions of similar shape as for O/N–H donors and can be analyzed in the same way. As for the (NN)C(sp^2)–H fragment, the mean C–H···Cl⁻ distance of 2.54 Å was found (ref. 12). Within NH···Hal⁻ bonds, we should mention the calix[4]pyrroles described by Sessler (ref. 13) as anion binding agents in CH_2Cl_2 solution and in the solid state. Both in the chloride and fluoride complexes, the anions occupy a perching position above the main plain of the nitrogen atoms.

‡‡ ^{1}H NMR spectra were recorded at room temperature (22 °C) on a Varian Gemini 300 spectrometer operating at 300 MHz, in polar aprotic solvents (DMSO-d_6, CD_3CN).

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