



Benzobis(imidazolium) salts as templates for the self-assembly of starburst [2₄]pseudorotaxanes and their corresponding carbene-based classic [2₂]pseudorotaxanes

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Benzobis(imidazolium) salts as templates for the self-assembly of starburst [2₄]pseudorotaxanes and their corresponding carbene-based classic [2₂]pseudorotaxanes†

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Benzobis(imidazolium) salts ([BBI-H₂-R₄]²⁺, R = alkyl, aryl) interact with crown ethers through a combination of hydrogen bonds, ion-dipole, and π–π stacking interactions to form starburst [2₄]pseudorotaxanes. This new recognition motif allows the extension of four side-arms directly from the cavity of the crown ether, thus positioning the wheel component in a straddled orientation onto the axle, while their carbene-based derivatives show the classical shape of regular [2₂]pseudorotaxanes.

Since Pedersen published in 1967 his seminal paper on the cation complexation by a series of crown ethers,¹ these species and their derivatives have become key components in the chemistry of the mechanical bond.^{2–8} The threading of viologen species through the cavities of crown ethers such as bis(paraphenylene)-34-crown-10 (BPP34C10) and bis-1,5-(dinaphtho)-38-crown-10 (15DN38C10) to form [(viologen)⊂(crown ether)]²⁺ interlocked architectures lies at the foundation of a wide range of pseudorotaxane and rotaxane systems.^{9–18}

These species consist of one or more macrocycles threaded by one or more axles (linear, dumbbell shaped molecules). Fig. 1a pictures the simplest schematic representation of a [2₂]pseudorotaxane,‡ and originates from the fact that they are all templated by recognition sites incorporated into axles having only *two* side-arms protruding from the cavity of the wheel.

We wish to present here a new recognition motif for the template-directed formation of [2₄]pseudorotaxanes based on an axle that allows the extension of *four* side-arms directly from the cavity of the crown ether, and thus positioning the wheel component in a straddled orientation onto the axle (Fig. 1b).

In one of his seminal early papers,¹⁹ Stoddart noted that, in contrast to all viologens, the [BipyH₂]²⁺ dication (Scheme 1a) is

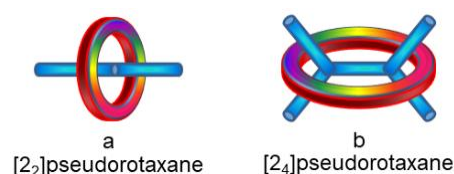
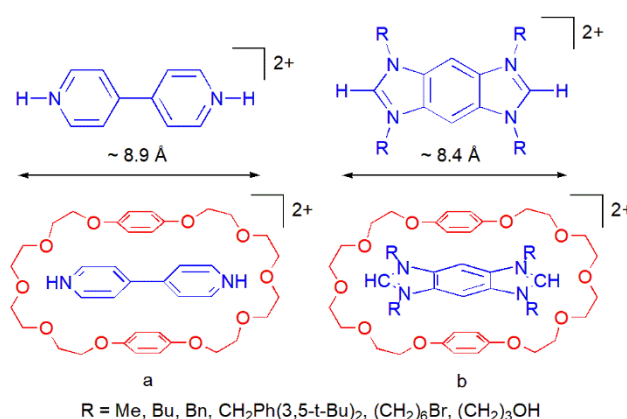


Fig. 1 Schematic representations of: a) regular [2₂]pseudorotaxanes; and b) starburst [2₄]pseudorotaxanes.



Scheme 1 Comparison between: a) [BipyH₂]²⁺ and b) [BBI-H₂-R₄]²⁺ dications and their interaction with BPP34C10.

completely encapsulated by BPP34C10, with the formation of two strong and nearly linear N⁺–H···O hydrogen bonds with the central oxygen atoms on the polyether linkage and of strong aromatic π–π stacking interactions between the bipyridine and phenylene moieties.

Benzobis(imidazolium) salts ([BBI-H₂-R₄]²⁺, R = alkyl, aryl, Scheme 1b) are shorter than BipyH₂²⁺ and have two positive charges localized on the N-CH-N regions, thus making the C2 hydrogen atoms highly acidic. We reasoned that, in

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resemblance with the BipyH₂²⁺ dication, these H atoms could be involved in H-bonding with the O atoms within the ethylene glycol chains of the crown ethers. [N-CH-N]⁺ ... O ion-dipole interactions between the positively charged atoms of the BBI²⁺ component and the Lewis basic atoms of the crown ether could also make a significant contribution to the binding.²⁰ Further, the BBI²⁺ dication consists of an electron deficient rigid framework with a π -conjugated linker between the two imidazolium moieties and could interact through π - π stacking interactions with the electron rich aromatic rings of the hosts. These characteristics make the BBI²⁺ salts excellent candidates for the template-directed formation of interlocked molecules in conjunction with BPP34C10 and 15DN38C10 wheels.

More importantly, in contrast to the 4,4'-bipyridine based (pseudo)rotaxanes or benzimidazolium-based examples,^{21,22} this recognition motif is easily functionalized with four side-arms through the N-atoms of the BBI²⁺ core, thus allowing the formation of starburst [2₄]pseudorotaxane architectures.

The BBI²⁺ salts depicted in Scheme 1 were prepared using a modified reported synthetic procedure,²³ by the reaction of benzobis(imidazole) with four equivalents of the corresponding halo-derivatives. In the case of {BBI-H₂-[(CH₂)₆Br]₄}(PF₆)₂, a tenfold excess of 1,6-dibromohexane was employed, to minimize the formation of polymeric species. The resulting [BBI-H₂-R₄]X₂ halides (X = Br, I) were subjected to X⁻/PF₆⁻ anion exchange, affording the desired axles as white powders.

The first evidence for pseudorotaxane formation from BBI²⁺ axles and BPP34C10 and 15DN38C10 crown ethers was obtained by ¹H-NMR spectroscopy. Upon mixing equimolar solutions of [BBI-H₂-R₄](PF₆)₂ and 15DN38C10 or BPP34C10 in acetone-d₆, a situation of rapid exchange between the complexed and uncomplexed species was observed on the ¹H-NMR timescale: the signals for both host and guest appear either as sharp or broad resonances, and all signals, particularly those of the protons of the BBI²⁺ cation, are significantly displaced from their original chemical shifts in the absence of the complementary molecule, suggesting a strong interaction between the two components in solution. Fig. 2 shows the NMR spectrum of the Me derivative with 15DN38C10; all other compounds have similar ¹H-NMR spectra (see Figs. S1-S10, ESI[†]), except for the axles with R = Bn and CH₂Ph(3,5-*t*-Bu)₂ as side-arms, where little or no interaction was observed, due to steric hindrances. As such, these two axles were excluded from subsequent investigations.

Further characterization of these interlocked species was obtained from ESI[†]/MS investigations of a 1 : 1 mixture of the components. In all cases, signals corresponding to either {[Axle]Crown}²⁺ or {[Axle]Crown}(PF₆)⁺ species were observed. For example, in the case of the [BBI-H₂-Me₄](PF₆)₂ - 15DN38C10 pair (Fig. S11, ESI[†]), the base peak at *m/z* 426 corresponds to the 1 : 1 {[BBI-H₂-Me₄]C15DN38C10}²⁺ complex, while the peak at *m/z* 997 was assigned to the {[BBI-H₂-Me₄]C15DN38C10}(PF₆)⁺ cation. Interestingly, the second peak in intensity (*m/z* 851, ca. 25% of that of the base peak) corresponds to the half-imidazolium - half-free carbene inclusion complex with one crown ether molecule, {[BBI-H-Me₄]C15DN38C10}⁺. The peaks at *m/z* 654, 659, and 675,

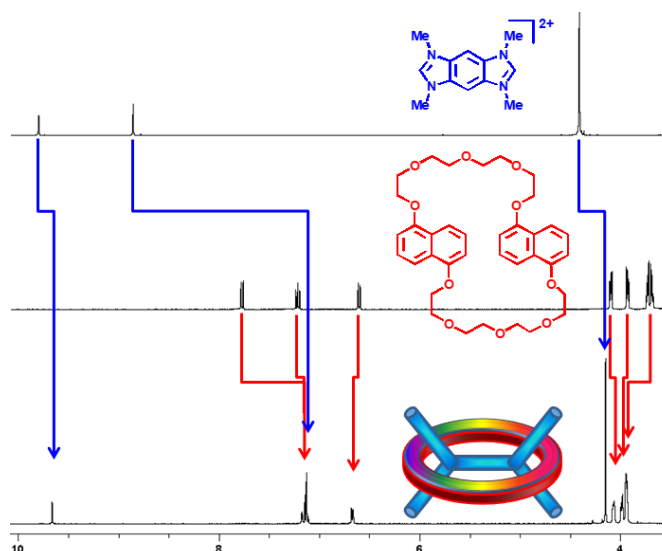


Fig. 2 ¹H-NMR spectra (acetone-d₆) of: [BBI-H₂-Me₄]²⁺ (top); 15DN38C10 (middle); and an equimolar mixture of the two components (bottom).

associated with the 15DN38C10 macrocycle accommodating various cations present in the system (NH₄⁺, Na⁺ and K⁺, respectively), have less than 10% of the base peak's height. Similar behavior was observed for all other mixtures; the results of these experiments are collected in Table S1, ESI[†].

To further probe the solution structure of these species, we performed a NOESY experiment on the [BBI-H₂-Me₄](PF₆)₂ - 15DN38C10 pair (Fig. S12, ESI[†]). The results of the experiment clearly suggest a straddled orientation of the crown relative to the axle, as the protons from the ethylene glycol chains are spatially close to the C2-H protons positioned on the BBI²⁺ axles. This orientation also explains the relatively small shift of these protons observed in the regular ¹H-NMR spectra of the [2₄]pseudorotaxanes. On one hand, they are involved in C-H...O hydrogen bonds, which would have as a consequence a downfield shift, and on another, they experience a shielding effect of the crown ether, thus being pushed upfield. The combination of these opposite effects leads to the observed overall small shift of these protons from their original position.

Pseudorotaxane assembly association constants (*K*_a) and the free energies of complexation (ΔG^0) are listed in Table 1 and were determined from ¹H-NMR titration experiments for the [BBI-H₂-Me₄]²⁺ and [BBI-H₂-Bu₄]²⁺ axles (Fig. S13 ESI[†]). The shift of the C2-H and N-bonded C-H proton resonances was monitored upon addition of increasing amounts of crown ethers to the solutions of the BBI²⁺ axles. Job plot analyses derived from these experiments confirmed the exclusive formation of species with 1 : 1 axle : crown stoichiometries (Fig. S14 ESI[†]).^{24,25}

Vapor diffusion of diethyl ether into an acetone solution of the components yielded single crystals which were subjected to X-ray diffraction studies. The structures of these species consist of [BBI-H₂-R₄]²⁺ cations surrounded by the crown ethers, and all have bond lengths and angles typical for this type of compounds. As inferred from the NOESY experiments, the acidic protons situated on the C2 atoms of the BBI²⁺ moieties are indeed involved in H-bonds with the oxygen atoms within the crown ether; the complexes are also supported by π - π

stacking interactions between the central arene ring of the BBI²⁺ dication and the aromatic groups of the crown ethers. In addition, several [N-CH-N]⁺ ... O ion-dipole interactions stabilize the assembly.

Table 1 Association constants (K_a) and free energies of complexation (ΔG^0)^a for the {[BBI-H₂-R₄]c15DN38C10}²⁺ pseudorotaxanes (R = Me, Bu).

Axle / Crown	K_a ($\times 10^3$) (M ⁻¹)	$-\Delta G^0$ (kcal · mol ⁻¹)	K_a ($\times 10^3$) (M ⁻¹)	$-\Delta G^0$ (kcal · mol ⁻¹)
	15DN38C10		BPP34C10	
[BBI-H ₂ -Me ₄]	9.26±0.24	5.35±0.14	8.92±0.18	5.33±0.11
[BBI-H ₂ -Bu ₄]	8.36±0.31	5.29±0.19	7.88±0.27	5.26±0.18

a) The free energies of complexation (ΔG^0) were calculated from the K_a values, using the equation $\Delta G^0 = -RT \ln K_a$.

Fig. 3 shows the structures of the {[BBI-H₂-Me₄]c15DN38C10}²⁺ and {[BBI-H₂-((CH₂)₆Br)₄]c15DN38C10}²⁺ derivatives; the other species are presented as ESI⁺ (see Fig. S15, Table S2, and Table S3). While the Me derivatives are best described as inclusion compounds (the Me groups are not large enough to extend away from the cavity of the crown ethers), all other derivatives have the shape of “starburst” [2₄]pseudorotaxanes, with all four side-arms of the BBI²⁺ moiety oriented away from the crown ethers.

The bromo [2₄] derivative was used to probe the synthesis of more complex species. After a Br/N₃ exchange, followed by a CuAAC “click” reaction, a phenyl-triazole functionalized axle was prepared ([BBI-H₂-PhTz₄](PF₆)₂, see ESI⁺ for details) and tested in combination with both crown ethers. The ¹H-NMR spectrum of a 1 : 1 mixture of these components in acetone-d₆ shows signals associated with the free host and guest, as well as those attributable to the 1 : 1 complexes (see Fig. 4 and Fig. S16 ESI⁺), because of their slow rate of association and dissociation on the NMR timescale. The pseudorotaxane formation is indicated by the upfield shift of the BBI²⁺ and crown aromatic peaks, due to aromatic shielding effects resulting from the BBI²⁺ – crown interaction. For example, in the case of {[BBI-H₂-PhTz₄]c15DN38C10}²⁺, the peaks found at 10.02, and 9.03 ppm for the free [BBI-H₂-PhTz₄]²⁺ axle could also be identified in the spectrum of the mixture, along with a new set of peaks at 9.59 and 8.44 ppm, corresponding to the same protons situated on the interlocked species. Using the convenient single-point method,²⁶ the K_a and ΔG^0 parameters were found to be $2.78 \cdot 10^3$ M⁻¹ and - 4.70 kcal · mol⁻¹, respectively.

Since BBI²⁺ axles are good carbene precursors,²³ we have also explored the possibility to prepare interlocked compounds using metal-carbene complexes as axles. To date, we have investigated the interaction between the digold carbene complexes [BBI-R₄-(AuPPh₃)₂](PF₆)₂ (R = Me, Bu) and the 15DN38C10 and BPP34C10 wheels. The axles were easily prepared from the [BBI-H₂-R₄](PF₆)₂ salts and two equivalents of Ph₃PAu(acac) (see ESI⁺). Since the C2-H atoms were replaced by the AuPPh₃ moieties, a straddled orientation of the crowns around the axles is now precluded, leaving as the only possible structural feature for these compounds the “classic” [2₂]pseudorotaxane orientation.

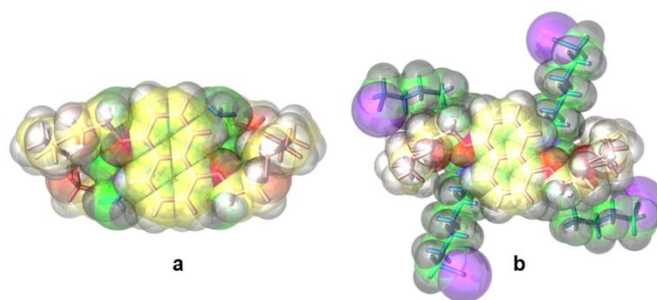


Fig. 3 Space filling representation of: a) {[BBI-H₂-Me₄]c15DN38C10}²⁺, and b) {[BBI-H₂-((CH₂)₆Br)₄]c15DN38C10}²⁺ dications; color code: axle – carbon = green, hydrogen = black; wheel – carbon = yellow, hydrogen = white.

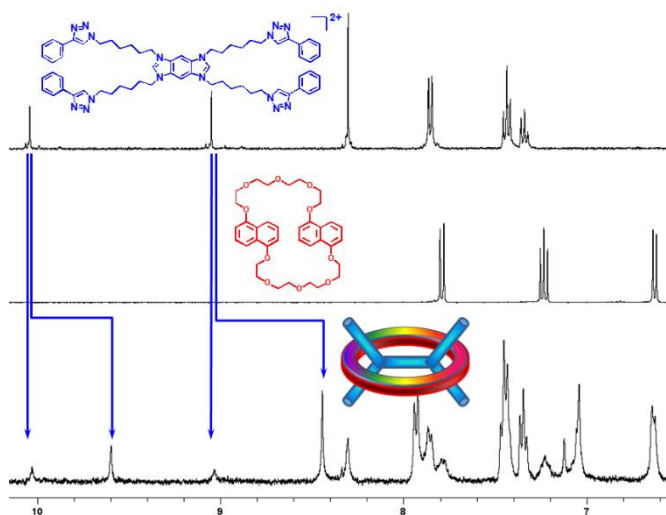


Fig. 4 ¹H-NMR spectra (aromatic region, acetone-d₆) of: [BBI-H₂-PhTz₄]²⁺ (top); 15DN38C10 (middle); and an equimolar mixture of the two components (bottom).

The ¹H-NMR spectrum of a 1 : 1 mixture of [BBI-Me₄-(AuPPh₃)₂](PF₆)₂ and 15DN38C10 in acetone-d₆ shows again signals associated with the free host and guest, as well as those corresponding to the 1 : 1 complex (see Fig. S17 ESI⁺). As with {[BBI-H₂-PhTz₄]c15DN38C10}²⁺, pseudorotaxane formation is indicated by the upfield shift of the BBI²⁺ and crown peaks. The signal at about 7.8 ppm is composed of a multiplet originating from the -PPh₃ protons overlapped with the singlet corresponding to the free central aromatic ring of the Au-carbene body, and the doublet of the unthreaded crown ether. However, the singlet and doublet peaks corresponding to the same protons situated on the {[BBI-Me₄-(AuPPh₃)₂]c15DN38C10}²⁺ [2₂]pseudorotaxane are clearly visible at 7.14 ppm and 7.31 ppm, respectively. Using the same single-point method, the K_a and ΔG^0 parameters were found to be $3.61 \cdot 10^3$ M⁻¹ and - 4.85 kcal · mol⁻¹, respectively.

Definite proof of the structure of this complex was obtained from X-ray diffraction experiments (see Tables S2 and S3 ESI⁺). Crystals of this complex were grown using the same vapor diffusion method and subjected to structural analysis. The complex (Fig. 5a) shows the geometry of a “classic” [2₂]pseudorotaxane. The central arene ring of the [BBI-Me₄-(AuPPh₃)₂]²⁺ cation is positioned at the center of the crown’s cavity, with the Au-PPh₃ groups oriented away from the crown ether. Each naphthalene moiety is positioned over a different

[N-CH-N]⁺ region, suggesting the presence of strong interactions between the carbene N-C-N skeleton and the electron rich naphthalene moieties. This architecture is also held together by π – stacking interactions between the electron rich naphthalene moieties and electron deficient BBI²⁺ group, with several C-C and C-N distances in the 3.4–3.6 Å range. Further stabilization of this pseudorotaxane comes from C-H...O bonds between the oxygen atoms of the crown and the protons of two of the Me groups situated *trans* with respect to the Au-C-C-Au axis.

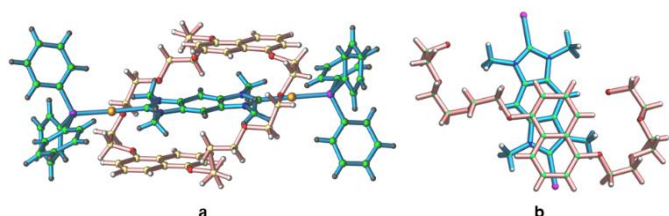


Fig. 5 The crystal structure of $\{[BBI-Me_4-(AuPPh_3)_2] \subset 15DN38C10\}^{2+}$, b) top view of the assembly, showing the orientation of the ethylene glycol chains around the Me groups.

Interestingly, no pseudorotaxane formation was observed with the rest of the components. An explanation for this fact could be found after a close inspection of the $\{[BBI-Me_4-(AuPPh_3)_2] \subset 15DN38C10\}(PF_6)_2$ structure. As it can be seen in Fig. 5b, due to the 1,5 connectivity of the naphthalene ring, one ethylene glycol arm of the crown ether passes over one methyl group, and the other is positioned in the proximity of the central arene ring, thus avoiding the second methyl moiety. The replacement of the methyl with the butyl group induces a steric hindrance that prevents the formation of the [2₂]pseudorotaxane from the $[BBI-Bu_4-(AuPPh_3)_2]^{2+}$ and 15DN38C10 components. In the case of the BPP34C10 wheel, this steric hindrance is even more pronounced, as this crown has only one central aromatic ring. Thus, even a small group such as the methyl moiety acts as a steric impediment for this smaller crown ether.

To conclude, we have presented here a new binding motif for the formation of pseudorotaxanes with a unique topology, which we call starburst [2₄]pseudorotaxanes. These species are readily formed from benzobis(imidazolium) salts and BPP34C10 and 15DN38C10 crown ethers and are held together by a combination of hydrogen bonds, ion-dipole, and π – π stacking interactions. Their structures show four side-arms protruding directly from the center of the macrocyclic component, thus positioning the wheel component in a straddled orientation onto the axle. The successful synthesis of the $[BBI-H_2-(CH_2)_3OH]_4^{2+}$ and $[BBI-H_2-(CH_2)_6Br]_4^{2+}$ axles opens the door for the incorporation of this motif into more intricate systems through simple chemical modifications of their side-arms, as demonstrated by the $\{[BBI-H_2-PhTz_4] \subset Crown\}(PF_6)_2$ assemblies. The $[BBI-H_2-R_4]^{2+}$ axles are easily transformed into their metal carbene counter-parts, producing classic [2₂]pseudorotaxane architectures in combination with the same crown ethers.

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Conflicts of interest

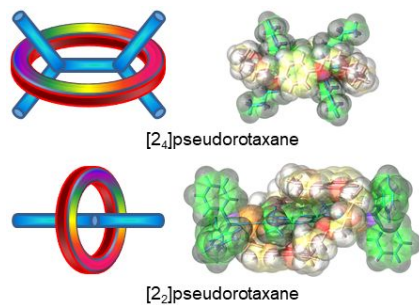
There are no conflicts to declare.

Notes and references

‡ To differentiate between the different topologies of the species described in this paper, we use here the following notation: [2₂] and [2₄]pseudorotaxanes; the first integer in square brackets designates the number of the components of the assembly and the second, placed as a subscript, indicates the number of side-arms protruding from the center of the macrocyclic component.

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Table of Contents entry:



Starburst [2₄]pseudorotaxanes and classic [2₂]pseudorotaxanes were prepared from benzobis(imidazolium) salts and their carbene derivatives, respectively.