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Azolium-Linked Cyclophanes: A Comprehensive Examination of Conformations by ^{1}H NMR Spectroscopy and Structural Studies†

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The synthesis and characterization of a series of azolium-linked cyclophanes are reported. The cyclophanes consist of two azolium groups (17 examples) or three imidazolium groups (1 example) linked to two benzenoid units (benzene, naphthalene, *p*-xylene, mesitylene, 1,2,3,4- and 1,2,4,5-tetramethylbenzene, 2,6-pyridine, and *p*-*tert*-butylphenol) via methylene groups. Cyclophanes containing *ortho*-, *meta*-, and *para*-substitution patterns in the benzenoid units were examined. The conformations of the cyclophanes were examined in solution by variable-temperature NMR studies and in the solid state by crystallographic studies. The *p*-cyclophanes and mesitylene-based *m*- and *o*/*m*-cyclophanes are rigid on the NMR time scale, as indicated by sharp ^{1}H NMR spectra at all accessible temperatures. The non-mesitylene-based *m*-cyclophanes and the *o*-cyclophanes are fluxional on the NMR time scale at high temperatures, but in most cases, specific conformations can be "frozen out" at low temperatures. Many structures deduced from solution studies were consistent with those in the solid state.

Introduction

Cyclophanes have been of interest for many years.[1−3] The literature includes an eclectic array of cyclophanes, with examples containing various aromatic groups (e.g., benzene, pyridine, naphthalene, thiophene, pyrrole, imidazole, and so forth) linked by a variety of structural elements (e.g., aliphatic chains, chains containing heteroatoms, and aromatic and heteroaromatic groups). In this paper, we confine ourselves to the class of azolium-linked cyclophanes, structures in which two aromatic units (benzene-, pyridine-, and naphthalene-based units in our study) are linked by two or more azolium units (Figure 1). In recent years, much interest has focused on cationic azolium-linked cyclophane systems.[4−21] This class includes cyclophanes with two[5,12] or three linking units:[4,22] cyclophanes where the linking units are placed *ortho*, *meta*, or *para* on the aromatic units;[4,5,17] imidazolium, benzimidazolium, and benzotriazolium linking units;[12,18,19]

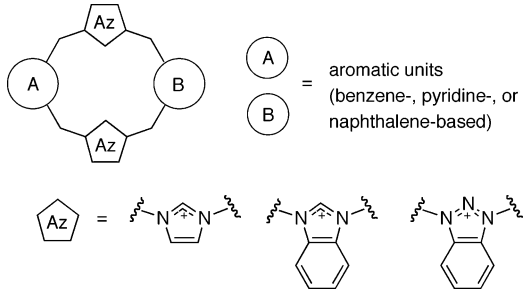

FIGURE 1. Azolium-linked cyclophanes.

† From the Ph.D. thesis of C. C. Williams.

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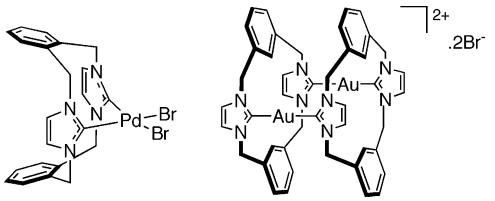
and aromatic units based on benzene, pyridine, and naphthalene (Figure 1).[5,9,12,16,19] A number of different aspects of these azolium-linked cyclophanes have been studied, including synthesis,[4,12,17−20] conformational behavior,[12,14] anion binding properties,[11,16] and mass spectral properties.[13] Imidazolium and benzimidazolium units of the cyclophanes are precursors to (benz)imidazolylidenes (*N*-heterocyclic carbenes), which are of much current interest in metal coordination chemistry (e.g., **1** and **2**).[5−7,9,15,23]



1 **2**

Many of the previous studies of azolium-linked cyclophanes have focused on synthesis or specific properties of a small number of cyclophanes. An exception is the recent work of Bitter et al., which included the synthesis of a broad selection of azolium-linked cyclophanes and the use of NMR spectroscopy, X-ray crystallography, and computational methods for the analysis of conformations.[12] Our interests in azolium-linked cyclophanes are also multidimensional. In this paper, we report a broad examination of a well-defined series of azolium-linked cyclophanes. Our study includes a 1,3,5-cyclophane and *ortho*-, *meta*-, *para*-, and mixed *ortho*/*meta*-substituted azolium-linked cyclophanes containing a variety of azolium units and aromatic units (Figure 2). We have used X-ray techniques and NMR methods, especially variable-temperature NMR, to gain insights into the conformational behavior of the cyclophanes in the solid state and in solution.

Results and Discussion

Synthesis and General Properties. The azolium-linked cyclophanes (Figure 2), as bromide salts, were easily synthesized by the reaction of a poly(azol-1-ylmethyl)arene and an appropriate poly(bromomethyl)-arene in a suitable solvent (usually acetone) at reflux or at room temperature (Scheme 1). The cyclophanes either precipitated from the reaction solution or were readily recovered by the removal of solvent. This method produced the azolium-linked cyclophanes in good to high yields (60−90%) and is similar to methods reported recently for various cyclophanes, including some listed in Figure 2.[4−6,9−12,14,15,17−19,21] *p*-Cyclophane **5**·2Br is produced as a mixture of two isomers, pseudo-*geminal*-**5a** and pseudo-*ortho*-**5b**, and from this mixture, pseudo-*geminal* isomer **5a** can be selectively crystallized.[4] Interestingly, *m*-cyclophane **10**·2Br, which incorporates both pyridine and mesitylene units, could only be prepared if the precursors were 2,6-bis(bromomethyl)pyridine and 2,4-bis(imidazol-1-ylmethyl)mesitylene. However, *o*/*m*-cyclophane **18**·2Br was easily prepared via both possible pathways, for example, from 1,2-bis(bromo-

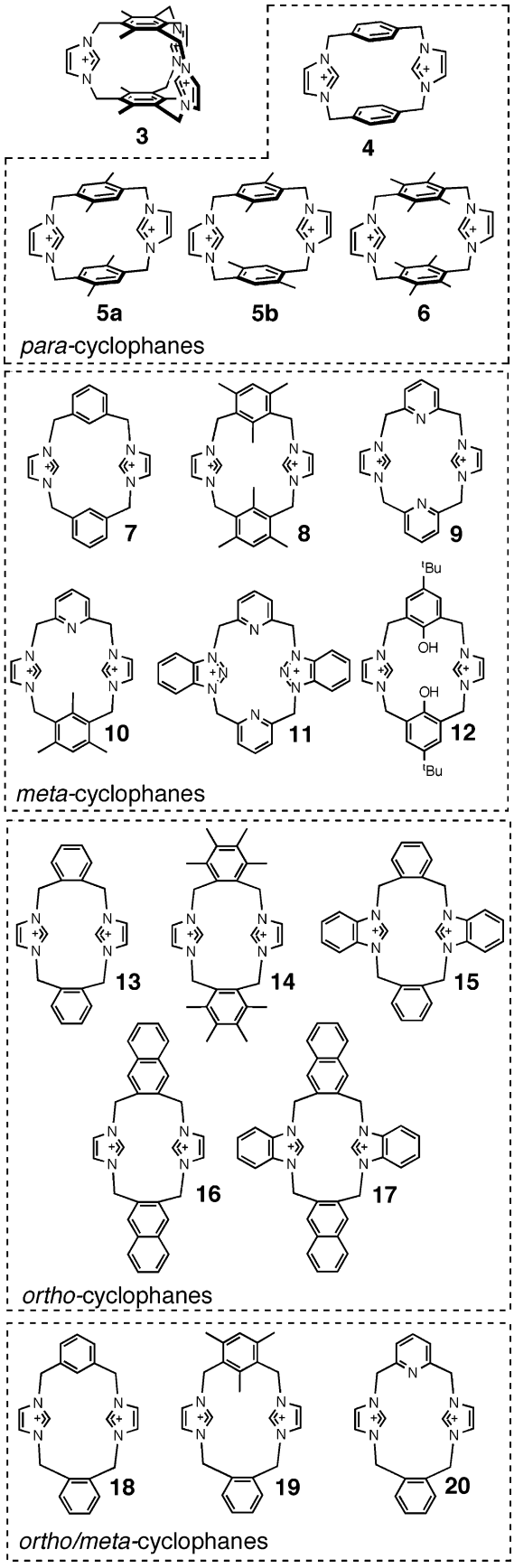


FIGURE 2. Azolium-linked cyclophanes in this study, grouped according to substitution pattern.

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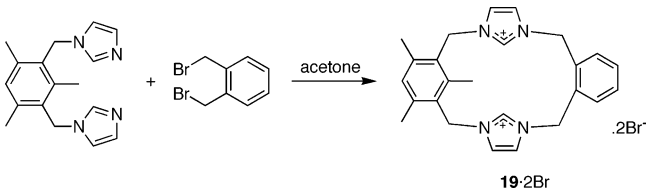
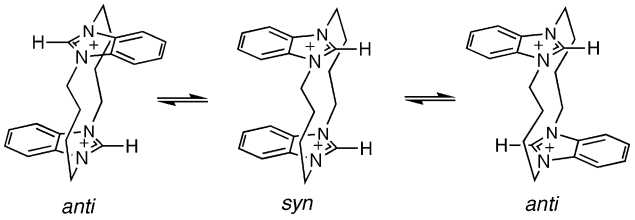
SCHEME 1



19·2Br

SCHEME 2



methyl)benzene and 1,3-bis(imidazol-1-ylmethyl)benzene or from 1,2-bis(imidazol-1-ylmethyl)benzene and 1,3-bis-(bromomethyl)benzene.

In general, the cationic cyclophanes, as their bromide salts, were insoluble in acetone, sparingly soluble in DMSO and methanol, and freely soluble in water. Most of the cyclophanes were purified by recrystallization from methanol that had not been rigorously dried and were crystallized with occluded water, which was evident from the microanalytical data and ^{1}H NMR spectra. Crystals grown more slowly, for single-crystal X-ray studies, often contained methanol or water molecules in the crystal lattice (see Structural Studies). Benzotriazolium/pyridine *m*-cyclophane **11**·2Br and octamethyl *o*-cyclophane **14**·2Br proved to be quite soluble and were readily recrystallized from acetone, dichloromethane, or methanol.

^{1}H NMR Studies: Conformations of Cyclophanes in Solution. Various azolium-linked cyclophanes and related bridged azolium species in solution have been observed previously to exhibit interesting dynamic behavior.[12,14,16,21] Such behavior has been interpreted in terms of interconversion between *syn* and *anti* conformations (Scheme 2, showing the *syn* and *anti* conformations of a bridged azolium species reported by Shi and Thummel).[21]

For the azolium-linked cyclophanes studied in this work, the number and multiplicity of signals in the ^{1}H NMR spectra showed that these structures can also exist in a variety of conformations. Some cyclophanes consisted of a single conformation that was rigid on the NMR time scale; others consisted of at least two distinct conformations interconverting rapidly on the NMR time scale, and some showed conformational lability on a time scale that was amenable to variable-temperature NMR studies. The ^{1}H NMR data for the cyclophanes are summarized in Tables 1 and 2, with Table 1 containing data for the rigid cyclophanes and for the nonrigid cyclophanes at the "slow-exchange" limit and Table 2 containing data for the nonrigid cyclophanes at the "fast-exchange" limit. In the NMR studies discussed below, the cyclophanes were characterized as their bromide salts. In all of the identified conformations of the cyclophanes, the azolium units were mutually *syn*. This assignment is based on the symmetry of the ^{1}H NMR signals due to the protons of the arene groups (e.g., AA′XX′ rather than ABCD patterns for the *o*-C_6H_4 units in the case of **13**, Figure 3). The benzenoid moieties in each conformation were either mutually *syn* or *anti*, and the basis for the assignment in each case is discussed in detail below.

1,3,5-Cyclophane and the *p*-Cyclophanes. 1,3,5-Cyclophane (**3**) and *p*-cyclophanes **4**−**6** showed beautifully simple NMR spectra (Table 1) containing only sharp lines, with no evidence of any significant conformational exchange process.[4] The NMR spectra for **3**−**6** do not change significantly with temperature. In each case, the signal due to the imidazolium H2 protons is considerably upfield compared to the H2 signals for acyclic imidazolium salts (**3**, δ 5.79; **4**, δ 7.93; **5**, δ 6.32; and **6**, δ 5.86; cf. 1,3-dibenzylimidazolium chloride,[24] δ 10.04, d_6-DMSO; δ 9.49, D_2O). This result is consistent with the H2 protons in the cyclophanes being magnetically shielded by the benzene rings.[4] For the series of *p*-cyclophanes **4**−**6**, as the number of methyl groups on the cyclophane increases, the signal due to the azolium H2 protons shifts upfield, possibly reflecting slight changes in the orientation of the imidazolium rings. As the number of methyl groups on the aromatic core increases, pivoting of the imidazolium rings about their N−N axes should be restricted by steric interactions with the methyl groups, in turn, forcing the imidazolium groups to orient such that their H2 protons would be directed more toward the center of the region of magnetic shielding from the benzene rings. Alternatively, it may be that increased electron density in the benzene rings due to the electron donating effect of the additional methyl groups may increase the shielding effects.

***o*-Cyclophanes.** At room temperature, the ^{1}H NMR spectra of *o*-cyclophanes **13**−**17** were very broad and proved difficult to interpret. At higher temperatures, the spectra sharpened and each system showed a single signal for the benzylic protons. These results suggest that the *o*-cyclophanes exist in various conformations that interconvert on the NMR time scale at elevated temperatures. The benzylic signals still remained somewhat broad, however, even at 66 °C, suggesting that the interconversion of the different conformations was slow on the NMR time scale. Low-temperature ^{1}H NMR studies were undertaken for three imidazolium-linked *o*-cyclophanes (**13**, **14**, and **16**). These studies showed two conformations of the cyclophanes (*syn* and *anti*) to be "frozen out" at −73 °C.

Low-Temperature ^{1}H NMR Studies of *o*-Cyclophane 13. At −73 °C, ^{1}H NMR signals due to distinct *syn* and *anti* conformations are present, with the *anti* conformations being dominant (*anti*:*syn* 3.5:1, Figure 3a; the *anti* conformation is also found in the solid state; see Structural Studies and Figure 7a). Two benzylic signals (δ 5.30, 6.33), one imidazolium H4/H5 signal (δ 6.93), and an imidazolium H2 signal (δ 9.67) were assigned to a *syn* conformation. Four benzylic signals (δ 5.20, 5.43, 5.90, 5.93), two imidazolium H4/H5 signals (δ 6.98, 7.64), and an imidazolium H2 signal (δ 8.63) were assigned to an *anti* conformation. The signals due to the arene protons of both conformations overlapped in the region δ 7.7−7.9. For the *syn* conformation, the downfield position of the imidazolium H2 signal and the upfield position of the

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TABLE 1. ^{1}H NMR Data for Rigid Cyclophane Bromide Salts and for Fluxional Cyclophane Dibromide Salts at the "Slow-Exchange" Limit

cyclophane	H2	H4/H5	benzylic CH_2	arene	other
3[a]	5.79 (br t, 1.8 Hz)	7.97 (d, 1.8 Hz)	5.61 (s)		2.21 (6 × CH_3)
4[b]	7.93 (s)	7.96 (s)	5.32 (s)	7.35 (s)	
5a[a]	6.32 (br t, 1.7 Hz)	7.62 (d, 1.7 Hz)	4.95 (d, 14.1 Hz), 5.32 (d, 14.1 Hz)	7.12 (s)	1.90 (4 × CH_3)
6[c]	5.86 (s)	8.04 (s)	5.47 (s)		2.01 (8 × CH_3)
8[c]	7.23 (s)	8.02 (s)	5.31 (d, 15.3 Hz), 5.49 (d, 15.3 Hz)	7.10 (s)	1.53 (2 × CH_3), 2.35 (4 × CH_3)
10[a]	8.14 (br s, $W_{h/2}$ 4 Hz)	7.46 (d, 2.1 Hz), 7.47 (d, 2.1 Hz)	5.14 (d, 14.7 Hz), 5.29 (d, 14.7 Hz), 5.31 (d, 15.1 Hz), 5.42 (d, 15.1 Hz)	7.19 (s), 7.49 (d, 7.8 Hz), 7.80 (t, 7.8 Hz)	1.49 (1 × CH_3), 2.36 (2 × CH_3)
12[d]	*syn* A 9.19 (s);[e] *syn* B 8.20 (s)[e]	*syn* A 7.73 (s); *syn* B 7.85 (s)	*syn* A 5.13 (d, 14 Hz), 5.75 (d, 14 Hz); *syn* B 5.19 (d, 14 Hz), 5.53 (d, 14 Hz)	*syn* A 7.66 (s); *syn* B 7.73 (s)	*syn* A 1.28 (s, ^{t}Bu), 9.9 (OH);[e] *syn* B 1.36 (s, ^{t}Bu), 9.6 (OH)[e]
13[d]	*anti* 8.63 (br s, $W_{h/2}$ 18 Hz); *syn* 9.67 (br s, $W_{h/2}$ 17 Hz)	*anti* 6.98, 7.64 (2 × s); *syn* 6.93 (s)	*anti* 5.20, 5.43, 5.90, 5.93 (4 × d, 14.4 Hz); *syn* 5.30, 6.33 (2 × d, 14.4 Hz)	7.68−7.90 (m)	
14[d]	8.48 (br s, $W_{h/2}$ 7 Hz)	6.84, 7.54	5.45−5.80[f] (several d)		2.37 (2 × CH_3), 2.41 (2 × CH_3), 2.43 (4 × CH_3)
16[d]	*anti* 8.97 (br s, $W_{h/2}$ 30 Hz); *syn* 9.65 (br s, $W_{h/2}$ 23 Hz)	*anti* 7.04, 7.64 (2 × s); *syn* 6.91 (s)	*anti* 5.30, 5.61, 5.76, 6.00 (4 × d, 14.8 Hz); *syn* 5.47, 6.42 (2 × d, 14.8 Hz)	7.70−7.79, 8.05−8.13, 8.18−8.24 (3 × m); 8.34, 8.44 (2 × s)	
18[d]	9.11 (s)	7.61, 8.00 (2 × br m)	5.41−5.57 (3 × d), 6.25 (d, 14.2 Hz)	4.51 (s), 7.33−7.38 (br d, ∼7 Hz), 7.39−7.45 (br t, ∼7 Hz), 7.73−7.79 (m), 7.90−7.96 (m)	
19[c]	8.50 (br s, $W_{h/2}$ 8 Hz)	7.75, 7.93 (2 × s)	5.20 (d, 14.5 Hz), 5.41 (d, 15.4 Hz), 5.49 (d, 15.4 Hz), 5.67 (d, 14.5 Hz)	7.27 (s), 7.57−7.63, 7.94−8.00 (2 × m)	1.14 (1 × CH_3), 2.49 (2 × CH_3)

[a] Solution in D_2O recorded at 500 MHz at ambient temperature. [b] Solutions in d_6-DMSO recorded at 300 MHz at ambient temperature. [c] Solution in d_6-DMSO recorded at 500 MHz at ambient temperature. [d] Solutions in CD_3OD at −70 ± 3 °C at 500 MHz. [e] H/D exchanges occur rapidly in CD_3OD; data obtained using solutions in CH_3OH at −70 ± 3 °C at 500 MHz. [f] Peaks obscured by the large solvent (OH) signal.

imidazolium H4/H5 signal indicate that the conformation is one in which the imidazolium H2 protons are directed away from the *o*-xylyl units (i.e., the H2 protons do not point into the cavity formed by the magnetically anisotropic benzene rings and, therefore, are not shielded by them). As the temperature is increased to −53 °C (Figure 3b), signals due to the *anti* conformation begin to broaden and have almost merged into the spectrum baseline at −33 °C (Figure 3c). The fact that the signals due to the *anti* conformation begin to broaden, while the signals due to the *syn* conformation remain sharp, can be explained in terms of an interconversion of two equivalent *anti* conformations by rotation of the imidazolium units about their N−N axes (Scheme 3). This process would exchange the imidazolium H4 and H5 environments and exchange the environments of the two types of *exo*-benzylic protons and the two types of *endo*-benzylic protons. At temperatures above −33 °C, the signals due to the *syn* conformation also begin to broaden, and as the temperature is increased further, they appear to coalesce with signals from the *anti* conformation (Figure 3, parts d−f). These changes can be interpreted in terms of the flipping of the *o*-xylyl units, which would interconvert *syn* and *anti* conformations. At 57 °C (Figure 3g), rapid exchange between the *syn* and *anti* conformations causes all of the benzylic protons to become equivalent and all the imidazolium H4/H5 protons to also become equivalent.

The ^{1}H NMR signals due to the imidazolium H4 and H5 protons of the *anti* conformation coalesce at −13 ± 5 °C. Assuming that the separation of the signals at this temperature in the absence of exchange is 334 Hz (the value seen at −73 °C), we estimate the rate constant for the *anti*/*anti* exchange process at −13 °C to be ∼740 s^{-1} and the free energy of activation for this process to be ∼49 kJ mol^{-1} (12 kcal mol^{-1}). Similarly, the signals due to the imidazolium H4/H5 protons of the *anti* and *syn* conformations coalesce at 27 ± 2 °C. Assuming the separation of these signals in the absence of exchange to be 200 Hz (the value estimated from spectrum recorded at −13 °C), we estimate the rate constant for the *anti* → *syn* conversion at 27 °C to be ∼120 s^{-1} and the free energy of activation for this process to be ∼61 kJ mol^{-1} (15 kcal mol^{-1}). (Full details of these calculations are provided in the Supporting Information.)

Low-Temperature ^{1}H NMR Studies of Octamethyl *o*-Cyclophane 14 and Naphthalene-Based *o*-Cyclophane 16. In solutions at −70 °C, **14** existed primarily in the *anti* conformation and was rigid on the NMR time scale. (The conformation identified in the solid state by X-ray studies was also *anti*; see Structural Studies.) Key features of the ^{1}H NMR spectrum (freshly prepared solution) that lead to this conclusion included sharp doublets at δ 6.84 and 7.54 ($^3J_{H,H}$ = 1.9 Hz), which are attributed to the imidazolium H4/H5 protons, and a

TABLE 2. ^{1}H NMR Data for Fluxional Cyclophane Dibromide Salts at the "Fast-Exchange" Limit[a]

cyclophane	H2	H4/H5	benzylic CH_2	arene	other
7	9.42 (s)	7.82 (s)	5.44 (s)	7.10 (s); 7.42−7.51, 7.57−7.63 (2 × m)	
9	9.20 (br m)	7.67 (br m)	5.62 (s)	7.59 (d, 7.7 Hz), 7.98 (t, 7.7 Hz)	
11[b]			6.32 (s)	7.60−7.89 (m), 7.77 (d, 7.8 Hz), 8.13 (t, 7.8 Hz)	
12[c]	8.65 (br s)	7.70 (d, 1.6 Hz)	5.43 (s)	7.61 (s)	1.28 (^{t}Bu), 9.56 (br s, OH)
13[d]	8.60 (br s, $W_{h/2}$ 90 Hz)	7.12 (br s, $W_{h/2}$ 20 Hz)	5.60 (br s, $W_{h/2}$ 40 Hz)	7.64−7.72, 7.80−7.88 (2 × m)	
14[d]	8.52 (br s, $W_{h/2}$ 10 Hz)	7.10 (br s, $W_{h/2}$ 6 Hz)	5.60 (br s, $W_{h/2}$ 5 Hz)		2.33, 2.37 (2 × s)
15[d]	8.76 (br s, $W_{h/2}$ 12 Hz)		5.77 (br s, $W_{h/2}$ 15 Hz)	7.12 (br s, $W_{h/2}$ 16 Hz), 7.34 (br s, $W_{h/2}$ 35 Hz); 7.74−7.82, 7.95−8.04 (2 × m)	
16[d]	8.83 (br s, $W_{h/2}$ 45 Hz)	7.24 (br s, $W_{h/2}$ 9 Hz)	5.78 (br s, $W_{h/2}$ 15 Hz)	7.69−7.77, 8.03−8.11 (2 × m); 8.42 (s)	
17[e]	9.04 (br s, $W_{h/2}$ 17 Hz)		5.97 (br s, $W_{h/2}$ 40 Hz)	7.11 (br s, $W_{h/2}$ 19 Hz), 7.18−7.71 (very br s); 7.73−7.82, 8.11−8.20 (2 × m); 8.59 (br s, $W_{h/2}$ 5 Hz)	
18	9.00 (s)	7.73 (d, 1.9 Hz), 7.93 (d, 1.9 Hz)	5.49, 5.77 (2 × s)	4.92 (s); 7.36−7.48, 7.66−7.69, 7.86−7.89 (3 × m)	
20	8.79 (s)	7.55, 7.80 (2 × br m)	5.60 (s), 5.82 (br s, $W_{h/2}$ 17 Hz)	7.44 (d, 7.7 Hz); 7.64−7.69, 7.85−7.89 (2 × m); 7.90 (t, 7.7 Hz)	

[a] Solutions in d_6-DMSO at 500 MHz at ambient temperature, unless otherwise indicated. [b] Solution in CD_3OD at 500 MHz at ambient temperature. [c] Solution in d_6-DMSO at 500 MHz at 50 °C. [d] Solutions in d_6-DMSO at 300 MHz at 66 °C. [e] Solutions in d_6-DMSO at 300 MHz at 77 °C.

singlet at δ 8.48, which is attributed to the imidazolium H2 protons. The fact that the imidazolium H4/H5 protons had different chemical shifts, combined with the H2 protons having a chemical shift indicative of shielding by one aromatic ring (cf. δ 8.63 for the H2 protons in *anti*-**13**), points to an *anti* conformation. The various methyl groups appeared in the region δ 2.37−2.43, but unfortunately, the expected set of four doublets for the benzylic protons was obscured by the large methanol/water (OH) signal. In spectra of solutions containing **14** recorded at −73 °C, a small signal at δ 9.61 was tentatively assigned to the imidazolium H2 protons of *syn*-**14**. The signal was small, however, corresponding to only about 3% of the total amount of cyclophane present, and other signals due to this conformation (if present) were obscured by signals due to the *anti* conformation and the solvent. The small proportion of the *syn* conformation in this sample may be a consequence of the added bulk of the tetramethyl functionalized aromatic rings and consequent steric interactions between these rings and the imidazolium units that disfavor the *syn* conformation in this system.

Naphthalene-based *o*-cyclophane **16** was shown by ^{1}H NMR spectroscopy to exist as a mixture of frozen out *syn* and *anti* conformations in a CD_3OD solution at −73 °C (see also Figure S1 in the Supporting Information). For *o*-cyclophanes **13**, **16**, and **14**, the *anti*:*syn* ratios at −73 °C were 3.5:1, 4.3:1, and >30:1, respectively. In this series, the *anti*:*syn* ratio increases with the steric bulk of the aromatic group (benzene vs naphthalene vs tetramethylbenzene).

***m*-Cyclophanes and *o*/*m*-Cyclophanes.** The *m*- and *o*/*m*-cyclophanes studied can be broadly categorized into two groups: those that contain a mesitylene unit (**8**, **10**, and **19**) and those that do not (**7**, **9**, **11**, **12**, **18**, and **20**). Cyclophanes incorporating a mesitylene unit are rigid on the NMR time scale at all accessible temperatures, as indicated by sharp ^{1}H NMR spectra in which the signals for the benzylic protons appear as characteristic sharp doublets; an analogous result was recently reported for **21**·2PF_6.[16] In the ^{1}H NMR spectrum of a solution of **8** (see Figure S2 in the Supporting Information), there are only two doublets for the benzylic protons, which suggests that the cyclophane is locked in a *syn* conformation (Figure 4). The H2 signal for **8** (δ 7.23, d_6-DMSO) is upfield relative to those of simple imidazolium ions. This upfield chemical shift is consistent with **8** being in a conformation where the H2 protons are shielded by the magnetically anisotropic mesitylene rings (Figure 4). For **10** (see Figure S3 in the Supporting Information), there are four doublets for the benzylic protons, two for the benzylic protons adjacent to the pyridine group, and two for the benzylic protons adjacent to the mesitylene group (assignments confirmed by ^{1}H−^{13}C HSQC and ^{1}H−^{13}C HMBC 2D NMR experiments). The similarities of the chemical shifts for the mesitylene/benzylic protons in **8** and **10** suggest that the conformation of the mesitylene unit with respect to the imidazolium units in **10** is the same as that in **8**. Furthermore, the chemical shift of the imidazolium H2 protons for **10** (δ 8.14, D_2O) is significantly more downfield than that for **8** (δ 7.23, d_6-DMSO), which suggests that in **10** these protons are subjected to shielding by only one aromatic ring. These observations suggest that, in solution, cyclophane **10** is in the *anti* conformation (Figure 4). We note, however, that in the ^{1}H NMR spectrum of **10**, H4 and H5 have very similar chemical shifts. This result at first seems counter to the

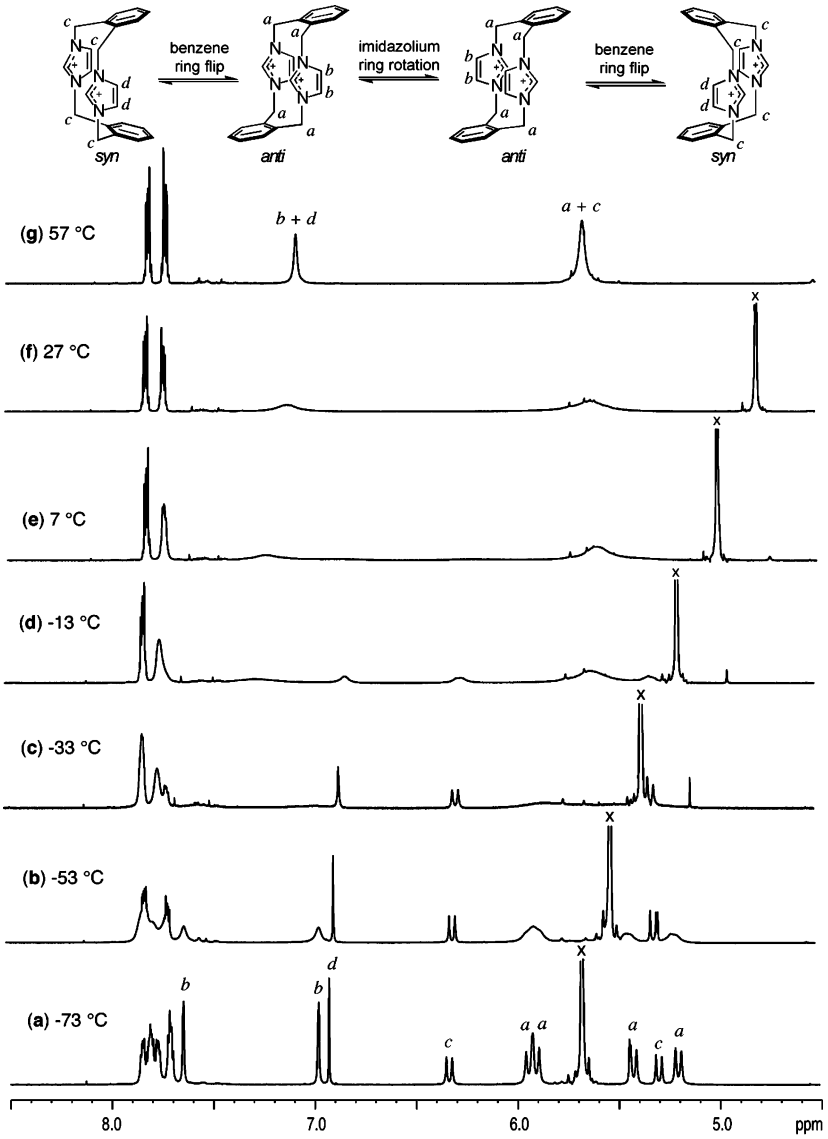


FIGURE 3. Variable-temperature ^{1}H NMR spectra (500.1 MHz, CD_3OD) of *o*-cyclophane **13**. Key (see Scheme 3): *a* = benzylic protons for *anti*-**13**, *b* = imidazolium protons for *anti*-**13**, *c* = benzylic protons for *syn*-**13**, *d* = imidazolium protons for *syn*-**13**, and *x* = solvent (OH) peak.

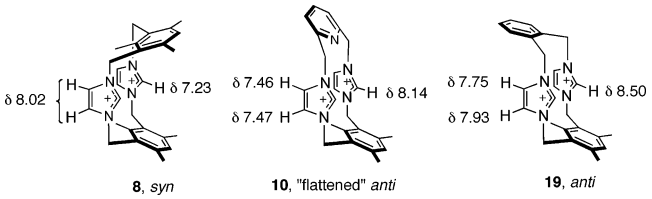
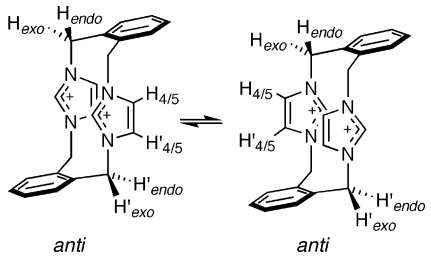


FIGURE 4. Conformations of rigid *m*- and *o*/*m*-cyclophanes. ^{1}H NMR chemical shifts used to assign the conformations are indicated on each conformation.

SCHEME 3



suggestion of an *anti* conformation since, in an *anti* conformation, different shielding effects would be expected for H4 and H5; it may be that the cyclophane adopts a "flattened" *anti* conformation, in which the pyridine ring lies closer to the plane defined by the four N atoms. The ^{1}H NMR spectrum for **19** (see also Figure S4 in the Supporting Information) is similar to that of **10** (four sets of sharp doublets and a signal for H2 downfield to that of **8**), suggesting that, in solution, it also adopts the *anti* conformation (Figure 4). The chemical shifts of the H4 (δ 7.75, d_6-DMSO) and H5 (δ 7.93, d_6-DMSO) imidazolium protons (assignments based on ^{1}H−^{13}C HSQC and ^{1}H−^{13}C HMBC 2D NMR experiments) provide further evidence for an *anti* conformation. The upfield shift of H4 compared to that of H5 is consistent with the H4 protons receiving more shielding than the H5 protons by the *o*-xylyl group. The solution conformations deduced by NMR (*syn* for **8** and *anti* for **10** and **19**)

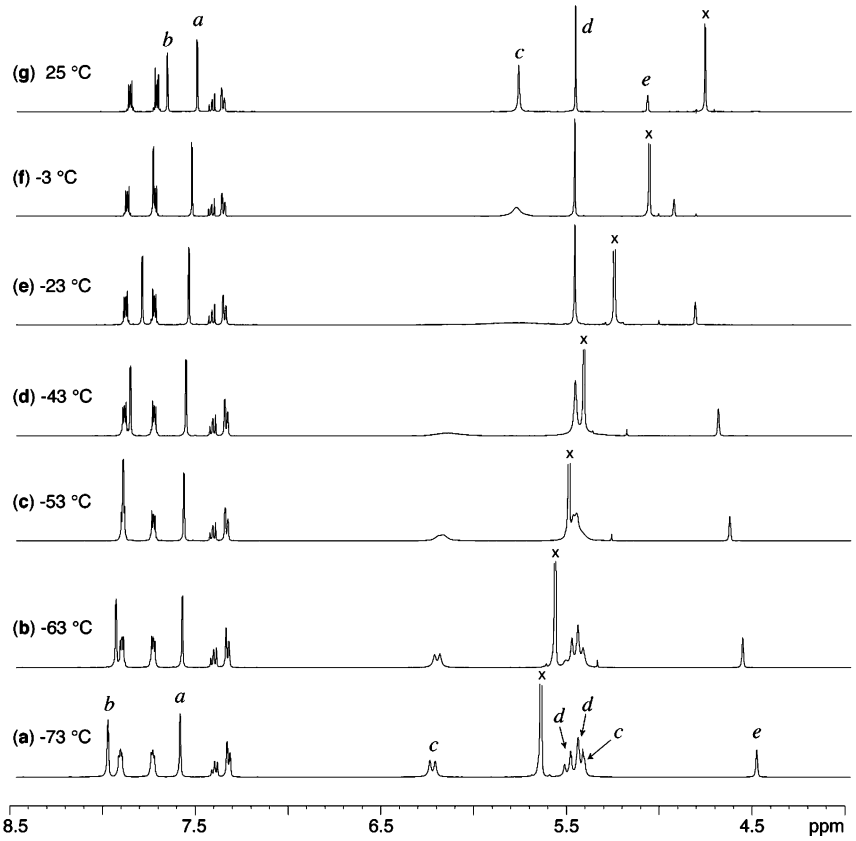
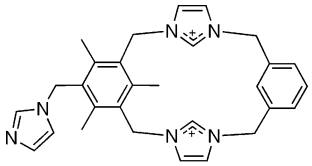


FIGURE 5. Variable-temperature ^{1}H NMR spectra (500.1 MHz, CD_3OD) of *o*/*m*-cyclophane **18**. Key: *a* = imidazolium H4 protons, *b* = imidazolium H5 protons, *c* = *o*-benzylic protons, *d* = *m*-benzylic protons, *e* = *m*-xylyl H2 protons, and *x* = solvent (OH) peak.

are similar to the solid-state conformations identified in X-ray studies (see Structural Studies and Figures 7f, 7c, and 7b, respectively).



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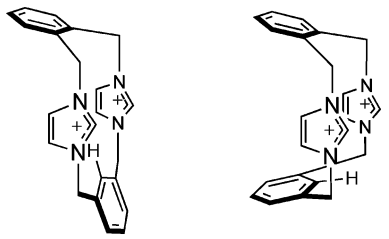
The *m*- and *o*/*m*-cyclophanes that do not contain a mesitylene group (**7**, **9**, **11**, **12**, **18**, and **20**) are all nonrigid on the NMR time scale. The signals for the benzylic protons in the ^{1}H NMR spectra of **7**, **9**, **11**, and **20** appear as singlets at room temperature and also at temperatures as low as 220 K, indicating that these cyclophanes are not conformationally rigid. The conformational lability of **9** has been recently identified by Bitter and coworkers.[12] The chemical shifts of the signals corresponding to the imidazolium H2 protons in **7** (δ 9.42, d_6-DMSO) and **9** (δ 9.20, d_6-DMSO) are much more downfield than those for the rigid cyclophanes **8** and **10**. This result suggests that, in the dominant conformations of these cyclophanes, the imidazolium H2 protons are not magnetically shielded by the benzene rings; the cyclophanes may, for example, adopt *syn* conformations in which the imidazolium H2 protons are *exo* with respect to the cyclophane skeleton (cf. the conformation shown below for *syn*-**18**, Scheme 4), or the benzene rings may simply lie closer to the "plane" of the cyclophane (cf. the *meta*-

SCHEME 4



"flattened" **18** *syn*-**18**

substituted benzene ring in the flattened structure in Scheme 4). For **7**, **9**, **11**, and **20**, exchange processes are rapid on the NMR time scale, even at −53 °C; the ^{1}H NMR spectra for these cyclophanes at −53 °C are similar to those at room temperature. For *o*/*m*-cyclophane **18** and phenol *m*-cyclophane **12**, however, the exchange processes are sufficiently slow at low temperatures that particular conformations can be frozen out.

Low-Temperature ^{1}H NMR Studies of *o*/*m*-Cyclophane 18. A ^{1}H NMR study of **18** (Figure 5) indicates that at −73 °C this cyclophane exists in a single conformation, tentatively assigned as a flattened conformation (Scheme 4). This assignment is based on the observations that (i) the signal due to the H2 proton of the *m*-xylyl group (the proton between the benzylic substituents on the *m*-xylyl unit) appears at unusually high field (δ 4.51), consistent with the *m*-xylyl unit being oriented so that this proton is in a region of shielding between the imidazolium groups, and (ii) the downfield chemical shift

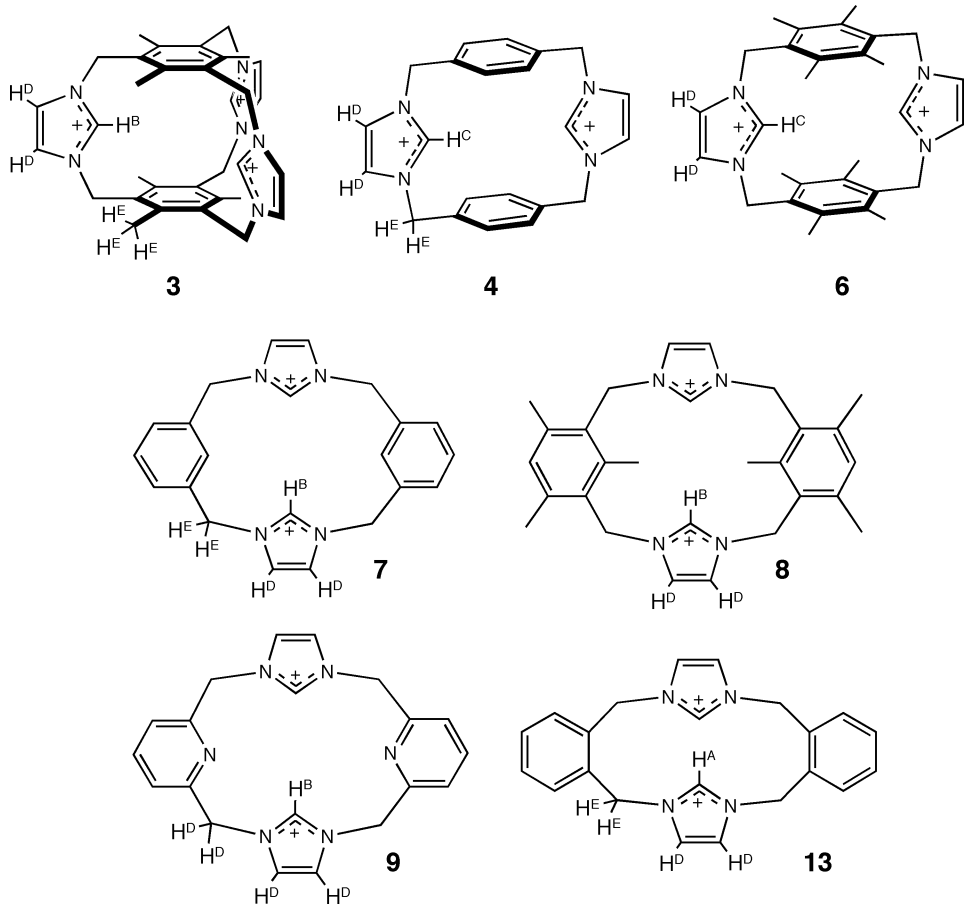


FIGURE 6. H/D exchange in imidazolium-linked cyclophanes. The H/D exchange was monitored by ^{1}H NMR spectroscopy. Spectra were recorded using ~0.04 M solutions of cyclophane bromide salts in D_2O at 300 MHz and ambient temperature. Conditions required for complete exchange of the protons: $H^A = D_2O$, room temperature, <10 min; $H^B = D_2O$, 100 °C, 1 h; $H^C = D_2O$, 2 equiv of NaOH, room temperature, <10 min; $H^D = D_2O$, 2 equiv of NaOH, 100 °C, 1 h; and $H^E = D_2O$, 2 equiv of NaOH, 100 °C, >24 h. Exchange was not detectable for protons attached to benzene or pyridine rings or methylene protons in **3**, **6**, and **8**.

of the signal due to the imidazolium H2 protons (δ 9.11) is indicative of these protons not experiencing shielding by the benzene rings. The imidazolium H4/H5 protons resonate at δ 7.61 and 8.00, consistent with the existence of a conformation where the upfield signal corresponds to protons shielded by the *o*-xylyl ring. At low temperatures, the benzylic protons appear as two pairs of doublets, and these pairs coalesce to two singlets at higher temperatures, indicative of a process that interconverts two equivalent (mirror image) conformations. Interestingly, however, these coalescences in the NMR spectra are accompanied by marked shifts in the signals due to the *m*-xylyl H2 proton (downfield) and the imidazolium H5 protons (upfield). It may be that as the temperature is increased, the conformation becomes more *syn*-like (Scheme 4) so that the imidazolium H5 protons experience increased shielding due to the proximity of the *m*-xylyl group (thus the H5 ^{1}H NMR signal moves upfield) and the H2 protons of the *m*-xylyl group move out of the region of shielding between the imidazolium groups (thus the ^{1}H NMR signal moves downfield).

Low-Temperature ^{1}H NMR Studies of Phenol *m*-Cyclophane 12. At −73 °C in methanol solutions, phenol *m*-cyclophane **12** exists in two frozen out *syn* conformations, assigned as *syn* A and *syn* B (Scheme 5) on the basis of the following observations (see also Figure S5 in the Supporting Information): (i) the number and multiplicity of ^{1}H NMR signals observed for each conformation are consistent with the imidazolium groups mutually *syn* and the phenol groups being mutually *syn* in each case; (ii) for each conformation, the benzylic protons (*exo* and *endo*) appear as a pair of doublets; and (iii) the signals due to the imidazolium H2 protons appear at δ 9.19 (major conformation, ~67%) and 8.20 (minor conformation, ~33%). The upfield position of the latter is consistent with the H2 protons of the minor conformation being shielded by the magnetically anisotropic benzene rings. The dominant conformation (*syn* A, Scheme 5) is the same as that characterized in the solid state (see Figure 7g).

As the temperature is increased, the ^{1}H NMR signals for the two conformations coalesce so that, in the ^{1}H NMR spectrum at room temperature, all signals are singlets. This result indicates the existence of exchange processes that interconvert the two equivalent forms of *syn* A and interconvert the two equivalent forms of *syn* B and also interconvert *syn* A with *syn* B. The *anti* conformations were not detected at any temperature but are presumably transient intermediates in the exchange pathways. The NMR behavior exhibited by **12** is reminiscent of that of calix[4]arenes in that, at low temperatures, the 1,3 alternate conformation is frozen out for calix[4]arene, but

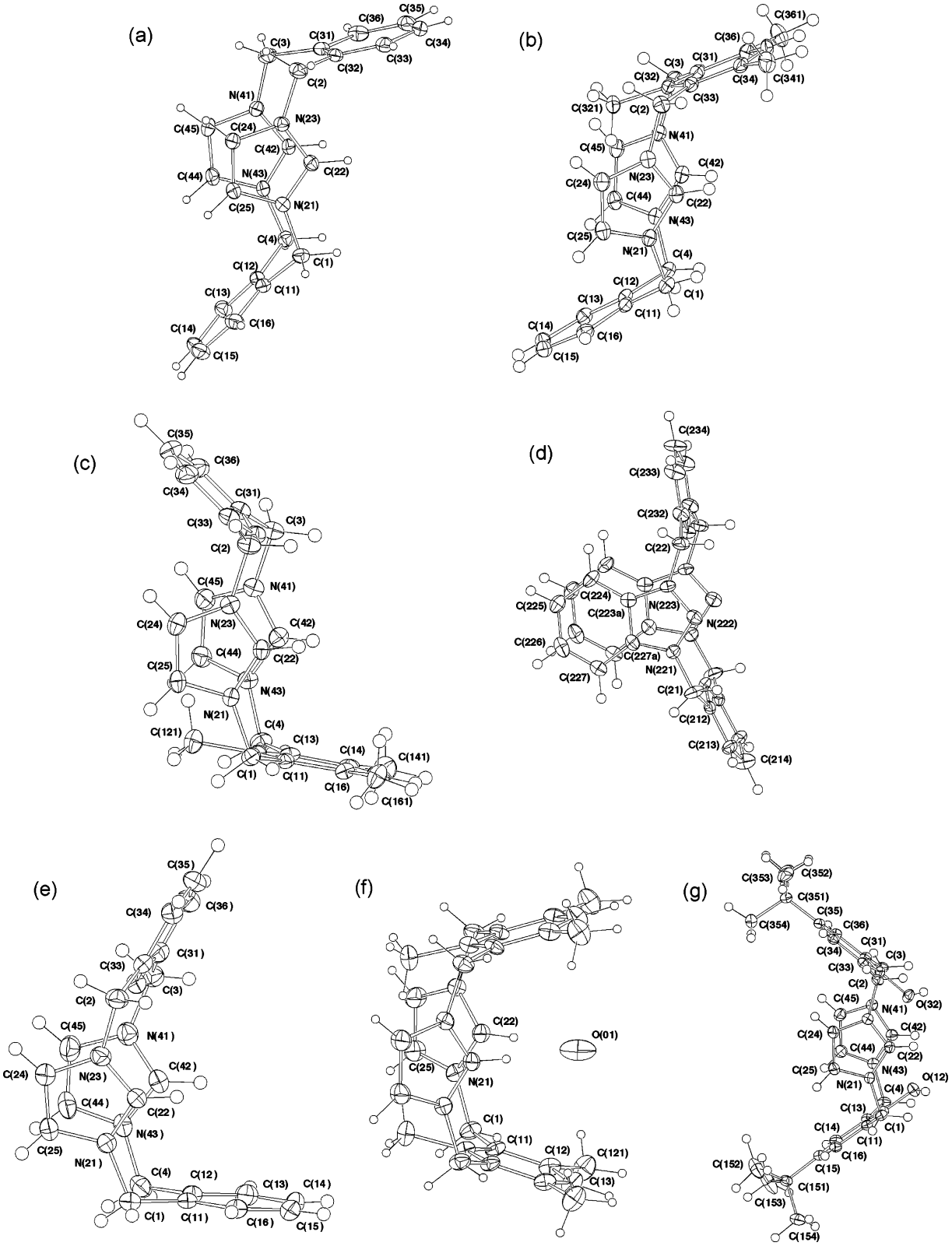
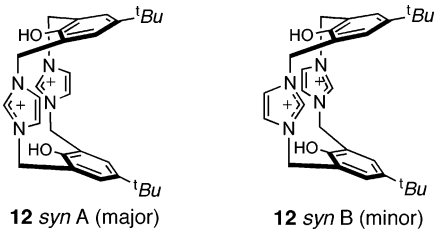


FIGURE 7. Different cyclophane types that were structurally characterized and their observed conformations. (a) Bis(*o*-phenylene) cation **13**. This *anti* conformation was also observed in both of the two independent cations of the bis(*o*-tetramethylphenylene) array (**14**), (b) *o*-phenylene(*sym*-trimethyl-*m*-phenylene) cation **19**, (c) *m*-phenylene(*sym*-trimethyl-*m*-phenylene) cation **10**, and (d) bis(*sym*-*m*-pyridyl) cation **11**. (e) The *syn*-type conformation was found in the *o*-phenylene(*sym*-*m*-pyridyl) cation **20**, (f) bis-(*sym*-*m*-mesityl) cation **8**, and (g) bis(1-hydroxyl-4-*tert*-butyl-2,6-*m*-phenylene) cation **12**. All structures are at ~153 K and shown with 50% probability amplitude displacement ellipsoids (except for a, at 300 K and 20% probability ellipsoids).

SCHEME 5



the calixarene structure becomes labile at higher temperatures.[25]

Of the cyclophanes that have *meta*-type aromatic groups (derived from benzene, mesitylene, or pyridine), only those that contain at least one mesitylene unit never show conformational mobility on the NMR time scale. This result presumably arises because interconversion of conformations in a mesitylene-based system would require the passage of a methyl group through the cyclophane macrocycle between the imidazolium rings, with greater steric hindrance than that of the analogous processes in non-mesitylene-based cyclophanes. Interestingly, the ^{1}H NMR signal for the C2 methyl group in all of the mesitylene-based cyclophanes lies significantly upfield of the signals due to the other mesitylene methyl groups, a result that may reflect the C2 methyl group being in an environment shielded by the ring currents of the imidazolium units.

H/D Exchange Reactions in D_2O. Studies of the 1,3,5-cyclophane salt (**3**·3Br) in D_2O solutions revealed some interesting H/D exchange reactions (Figure 6). The ^{1}H NMR spectra of freshly prepared D_2O solutions containing **3**·3Br show singlets due to the four different types of protons: the imidazolium H2 protons, the imidazolium H4/H5 protons, the methylene protons, and the methyl protons. When a sample was allowed to stand for a few days at room temperature or 1 h in a steam bath, the ^{1}H NMR signal due to the imidazolium H2 protons at δ 5.64 disappeared due to the H/D exchange. The presence of ^{2}H bonded to the imidazolium C2 was confirmed by ^{13}C NMR; in the ^{13}C NMR spectrum, the signal due to C2 was split into a 1:1:1 triplet ($^1J_{C,D} = 29$ Hz). Addition of a small amount of NaOH to the sample resulted in the rapid H/D exchange of the imidazolium H4/H5 protons (δ 7.83), and when the sample was heated in a steam bath for a few days, the protons of the methyl groups were also exchanged. Similar H/D exchange reactions were observed for other azolium-linked cyclophanes, as exemplified in Figure 6.

Some trends in the ease of H/D exchange are apparent. In all cases, the imidazolium H2 protons exchange most readily, followed by the less-acidic imidazolium H4/H5 protons. The ability of imidazoles and imidazolium ions to undergo the H/D exchange of H2 and H4/H5 is well-known.[26−29] Exchange of the methylene protons in **9** is also quite facile,[6] a result that is presumably a consequence of the enhancement of acidity of these protons by the pyridine group.[30] Exchange of methylene protons in **7** (isostructural to **9**) and **4** occurred more slowly than for **9**. In **3**, **6**, and **8**, no exchange of methylene protons was detected, perhaps, because the exchange reactions are slowed by the steric hindrance associated with the methyl groups in these cyclophanes. The exchange of methyl protons in **3** is surprising since the methyl groups are several bonds removed from the imidazolium units. Base-catalyzed exchange of the methyl protons might occur via an *o*-xylenyl intermediate (Scheme 6). If this mechanism were to operate in the case of **5**, H/D exchange of the methyl protons could be accompanied by equilibration of pseudo-*ortho*-**5b** and pseudo-*geminal*-**5a** isomers. This possibility could not be tested, however, because when H/D exchange experiments were conducted starting with pure pseudo-*geminal*-**5a**, no exchange of methyl protons was observed. As an additional test, H/D exchange studies were performed on the non-cyclophane salt **22**·3Br under the same conditions as detailed in Figure 6. H/D exchange occurred readily at the imidazolium H2 and H4/H5 positions in **22**·3Br, without complication, under conditions similar to those for the exchange of the corresponding protons in the cyclophane salt **3**·3Br. However, in contrast to the situation for **3**·3Br, exchange of the benzylic methyl protons in **22**·3Br was slow (25% exchange after 24 h at 100 °C in the presence of 2 equiv of NaOH for **22**, compared to 90% exchange within 1 h under similar conditions for **3**). In further contrast to the situation for **3**, H/D exchange of the benzylic methyl protons in **22** was accompanied by partial (but not complete) decomposition of the cation, as indicated by the appearance of extra signals in the benzylic, *N*-methyl, and benzylic/methyl regions of the ^{1}H NMR spectrum (see the Supporting Information). These decomposition products did not include *N*-methylimidazole, a product which would be expected if H/D exchange of the benzylic/methyl protons in **22** proceeds via an *o*-xylylene intermediate analogous to that shown in Scheme 6. Although the absence of *N*-methylimidazole among the decomposition products counts against the possibility of an *o*-xylylene intermediate for **22**, the significant differences between the course of H/D exchanges for **22** and **3** make us reluctant to exclude the possibility of such an intermedi-

SCHEME 6. Possible H/D Exchange Mechanism for the Methyl Groups of 3

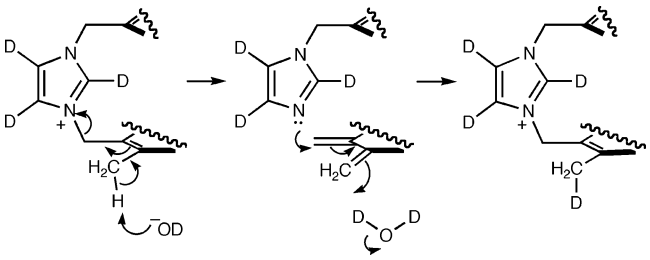


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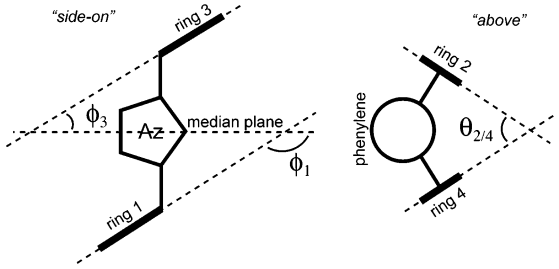
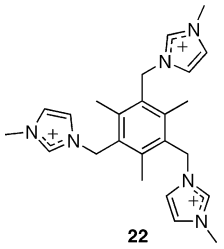
TABLE 3. Cyclophane Descriptors[a] (see text)



	$\theta_{2/4}$	ϕ_1	ϕ_3	$\chi_{1/2}$	$\chi_{1/4}$	$\chi_{3/2}$	$\chi_{3/4}$	C(22)···(C42)	H(22)···H(42)	N(23)···N(41)	N(21)···N(43)
						o-Cyclophane Systems					
13·2Br	14.9(1)	136.3(1)	12.2(1)	87.2(1)	83.3(1)	89.8(1)	88.3(1)	3.047(3)	2.84(4)	3.210(3)	3.227(3)
14·2Br (1)	15.1(2)	132.4(1)	3.5(1)	80.7(1)	87.1(3)	89.5(1)	87.2(1)	3.033(4)	2.83[b]	3.232(4)	3.177(4)
(2)	21.7(2)	132.4(1)	3.8(1)	80.7(1)	83.0(1)	85.7(1)	86.4(1)	3.002(5)	2.68[b]	3.276(4)	3.248(4)
23	7.84(6)	119.51(8)	119.51(8)	80.2(1)	86.8(1)	86.8(1)	80.2(1)	3.120(3)	3.119(3)[c]	3.132(3)	3.132(3)
						o/*m*-Cyclophane Systems[d]					
20·2Br	28.0(1)	5.07(9)	60.29(9)	76.8(1)	75.2(1)	78.5(1)	89.4(1)	3.922(3)	3.97(3)	4.427(3)	3.363(3)
19·2Br	63.54(7)	157.01(6)	16.23(6)	70.36(6)	63.01(6)	70.15(6)	68.39(6)	3.888(2)	2.95(2)	5.073(2)	4.194(3)
						m-Cyclophane Systems					
11·2Br (1)	18.0(1)	17.1(3)	86.9(2)	85.9(3)	85.9(3)	81.2(2)	81.2(2)	4.944(9)[e]	(n/a)	4.696(8)	4.636(9)
(2)	15.7(1)	68.2(2)	92.9(3)	83.0(2)	83.0(2)	82.2(2)	82.2(2)	4.848(8)		4.607(8)	4.627(8)
10·2Br	53.88(9)	8.94(7)	136.83(7)	86.83(7)	84.85(7)	71.36(8)	72.08(8)	4.660(3)	3.86(3)	5.351(2)	5.378(2)
8·2Br	70.6(6)	16.7(5)	16.4(5)	80.5(5)	80.5(5)	80.5(5)	80.5(5)	4.542(2)	3.5[b]	5.402(2)	5.402(2)
12·2Br	40.1(1)	146.58(8)	140.01(8)	81.7(1)	88.58(8)	81.4(1)	82.7(1)	4.990(3)	4.38(5)	5.518(3)	5.989(3)

[a] In degrees and Å. [b] Estimated value. [c] The equivalent O···O distance; details for this compound from a local 150 K redetermination deposited with this paper (see also ref 21). [d] Ring 1, *ortho*; ring 3, *meta*. [e] The equivalent N···N distance.

ate in the very facile H/D exchange of benzylic/methyl positions in **3**.



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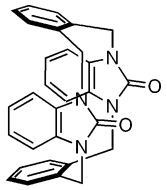
Structural Studies. General. A number of cyclophane salts have been characterized (mostly solvated, with the solvent being modeled as water and/or methanol) by single-crystal X-ray structure determinations; for example, the complexes take the form (cyclophane)Br_2·*n*(solvent). In most cases, one formula unit, devoid of crystallographic symmetry, comprises the asymmetric unit of the structure, but in **14**·2Br, there are two such independent formula units; in **8**·2Br, it is a quarter of the formula unit, with the cation here reaching its highest potential symmetry (2 mm), and in **11**·2Br, it is half, with the cation having *m* symmetry. In general, the crystal packing is far from haphazard, a prime determinant being the considerable planar components of the cations which pack against adjacent cations, frequently related by inversion or other symmetry operations. The bromide anions and solvent molecules appear to be secondary in their influence in this respect, filling interstices and hydrogen bonding with each other, although where the cation form is favorable, inclusion may occur (e.g., **8**·2Br, Figure 7f). The cation conformations may be parametrized in diverse ways. Taking the highest symmetry array of **8**·2Br as a convenient datum, prime descriptors are (a) the interplanar dihedral angle between the two imidazole C_3N_2 rings, θ [the imidazolium C(*n*2)H groups pointing "inward", as here, representing a positive angle; see Table 3], and (b) the interplanar dihedral angles, ϕ, between the pair of six-membered aromatic rings and a median plane through the C(*n*2) atoms and the midpoints of the two C(*n*4)−C(*n*5) bonds; a further distortion may be indicated by the difference in "equivalent" angles between the phenylene and imidazole planes, χ. We now discuss the individual members and types in more detail.

Individual Examples. One extreme cation form in the present arrays may be taken as that presented when the linking six-membered rings are both bound *ortho*. Here, these are represented by the unsubstituted *o*-cyclophane cation **13** (Figure 7a) and the heavily substituted octamethyl *o*-cyclophane cation **14**. In both cases, the disposition of ring 3, with respect to the median plane of the cation, is much flatter than the disposition of ring 1, with the latter being limited in this respect by the emergence of contacts between H(25,44) (imidazolium H4/H5 protons) and the phenylene units. The nature of the array, with one ϕ being acute and the other obtuse (i.e., an *anti* conformation), may be characteristic of species with a pair of *o*-phenylene bridges because of either mechanical or statistical necessity. In the previously studied diazolone (**23**),[21] however, both phenylene groups have an obtuse ϕ (i.e., a *syn* conformation, with the phenylene groups lying away from the diazolone oxygen atoms). The packing of **13**·2Br is of a common type found herein, where in projection down the short

cell axis, the macrocycle plane lies quasi-normal to the axis, with aromatic planes confronting inversion-related counterparts and with anions and solvent disposed between the planes. The packing found in **14**·2Br is of a different type; the cations are arranged in sheets perpendicular to *a*, with the anions and solvents in interleaving sheets, here, about $x = 0, {}^1/_2$.



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When the bridges between the imidazole rings are expanded, the next form is the *o*-phenylene/*m*-phenylene (*ortho*/*meta*) type. The simplest example of this type is the pyridine-derived **20**·2Br, in which the position between the azolylmethyl substituents (the pyridyl nitrogen) is devoid of any substituent. In **20**·2Br, we now find that both phenylene rings lie over C(*n*2) ($n = 2$ and 4) with the imidazolium C(*n*2)H atoms pointing into the cavity between the arene rings. The arene rings have quite different pitches to the median plane of the cation, with that of the *o*-phenylene ring being closely parallel, as in the above bis(*o*-phenylene) examples, and that of the *m*-pyridyl being steeply pitched (Figure 7e). The cell packing here is similar to that of **13**·2Br, the macrocycles lying side by side, inclusive of inverses, and aromatic planes confronting, with anion and solvent molecules between them. A variation on this form is the cation of **19**·2Br, where the pyridine is replaced by a mesitylene unit so that a bulky methyl substituent (methyl 321) now supplants the pyridine nitrogen (Figure 7b). The dihedral angle between the pair of imidazolium rings is now greatly enlarged, possibly to accommodate the steric requirements of methyl 321, which can only lie here [rather than over H(22,42)], and it may be in response to this change in dihedral angle that ϕ_1 for the *o*-phenylene moiety is now obtuse once more. The crystal packing for **19**·2Br appears to be primarily dictated by bromide−water hydrogen bonding: Br(1)···H(016),O(01) = 2.61(2), 3.496(2) Å; Br(2)···H(02a),O(02) ($1 - x$, $2 - y$, $1 - z$) = 2.49(3), 3.314(2) Å; and H(02)···H(01a),O(01) ($1 - x$, $y - {}^1/_2$, ${}^1/_2 - z$) = 2.08(3), 2.811(2) Å.

In **11**·2Br, we now find a bis(*m*-phenylene)-bridged-type system, albeit, with both arenes being 2,6-pyridyl units. Despite the underlying symmetry of the array, expressed in the asymmetric unit being made up two half-formula units, each cation being bisected by a vertical mirror plane, the result is quite unsymmetrical. The two molecules of the asymmetric unit are of the same basic type, but there are profound degrees of differences among the various parameters. The central five-membered rings are now triazoles (rather than imidazoles) with a consequent lack of central hydrogen atoms and, peripherally, a different profile as a consequence of the fused aromatic rings, with projecting hydrogen atoms at their 4 and 7 positions, which may inhibit folding back of the six-membered bridging rings, inhibiting acute ϕ. The increased content of the azolium planes is reflected in the crystal packing (the cations forming a loose web) with the anion/solvent component, considerably disordered, occupying tunnels within. In **10**·2Br, with one of the pyridine nitrogens supplanted by a methyl substituent and reversion to a bis(imidazolium) system, the resulting conformation is consistent with previous expectations, the pyridyl being bent back with obtuse ϕ, while the mesitylene unit, as elsewhere, has ϕ acute; the angle θ between the imidazolium planes is large. The crystal packing, again, is dominated by an array of macrocycle planes normal to the short axis of the cell, including solvent hydrogen bonded to Br(1) [Br(1)···H,O(0) = 2.42(3) and 3.278(2) Å], with the other anions [Br(2)] between them. Finally, in **8**·2Br, a system with two intrusive methyl substituents, these lie out of the macrocycle cavity, which now includes a water molecule [O(01)···H(22) = 2.4 Å (estimated)], with the inclination of the imidazolium rings being extremal. The cations are disposed about the cell diagonals with other solvent molecules and anions between them. A final variant on the latter is found in **12**·2Br, where, with methyl substituents replaced by hydroxyl, the pitch of the bridges is reversed; phenolic oxygen···H(22,42) (imidazolium H2 protons) contacts range between 2.61(5) and 3.10(3) Å. "Hermaphroditic self-inclusion" is found in the packing, the cup of the molecule including a *tert*-butyl group from an adjacent molecule. Anion/solvent strings fill the remaining voids [Br(1)···H,O(01) = 2.30(7), 3.217(3) Å; H,O(02) = 2.56(5), 3.312(3) Å; H,O(03) = 2.37(5), 3.271(3) Å]. Br(2)···H,O(32) = 2.36(4), 3.150(2) Å is an anion··· phenolic group contact, the other phenolic interaction being to one of the water molecules [O(02)···H,O(12) = 1.92(4), 2.667(3) Å].

Conclusion

We have reported the synthesis of a variety of azolium-linked cyclophanes and used NMR and X-ray diffraction methods to characterize their conformational behavior. Most of the cyclophanes are conformationally labile in solution at room temperature, but at lower temperatures, the exchange processes could be slowed sufficiently to enable particular conformations to be characterized for many of the cyclophanes. In these studies, the effects of magnetically anisotropic aromatic rings on the ^{1}H NMR chemical shifts of various protons in the cyclophane structures were useful indicators of the conformation of the cyclophane skeleton. In all *o*- and *m*-cyclophanes characterized, the azolium groups were mutually *syn*, whereas the benzenoid rings were mutually *syn* in some cases and mutually *trans* in others; in some cases (e.g., the *o*-cyclophane **13**) both conformations coexist. Analysis of variable-temperature ^{1}H NMR spectra recorded for solutions of *o*-cyclophane **13** enabled the estimation of rate constants for two different processes involved in the interconversion of the different conformations, namely, (a) rotation of the imidazolium rings and (b) ring flip of the benzenoid rings. Invariably, the dominant conformation detected in solution by NMR studies was also the conformation shown by X-ray studies to exist in the solid state. The cyclophanes also exhibited interesting H/D exchange phenomena in D_2O solutions, most notably a surprisingly facile exchange of benzylic/methyl protons in the case of 1,3,5-cyclophane cation **3**.

Many of the azolium-linked cyclophanes examined in this work, in particular the *o*-cyclophanes, are precursors of structurally interesting transition-metal complexes of *N*-heterocyclic carbenes in which the carbene units are part of a cyclophane skeleton. The conformations of the cyclophane skeletons in the carbene complexes[5,7] frequently resemble those seen for the parent azolium-linked cyclophanes in this work. Studies of the synthesis, structure, and reactivity of azolium-linked cyclophanes and cyclophane−carbene complexes are ongoing in our laboratory, and we will report further results in due course.

Experimental Section

Cyclophane salts were synthesized by reaction of poly(azol-1-ylmethyl)arenes and poly(bromomethyl)arenes in acetone or acetonitrile. A typical example is given below.

19·2Br. α,α′-Dibromo-*o*-xylene (113 mg, 0.428 mmol) in acetone (100 mL) was added to a stirred solution of 2,4-bis-(imidazol-1-ylmethyl)mesitylene (120 mg, 0.428 mmol) in acetone (100 mL). The mixture was stirred for 3 days, and the precipitate was collected and recrystallized from methanol. The cyclophane salt (**19**·2Br) was obtained as a colorless powder (164 mg, 71%). (See the Supporting Information for full characterization.)

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Supporting Information Available: Experimental details for the synthesis of bis(bromomethyl)arenes, bis(azol-1-ylmethyl)arenes, and azolium-linked cyclophanes, and spectroscopic characterization, structure determinations (see also CCDC:239647−239655), determination of rate constants for exchange processes involving **13**, and selected ^{1}H NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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