Electron transfer from wheel to axle in a rotaxane. A mass spectrometric investigation†

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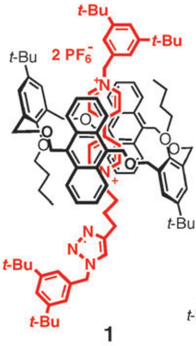
The synthesis and characterization of a new non-symmetrical [2]rotaxane featuring an anthracene-based wheel and an alkylviologen-based axle are reported. The interlocked nature of the isolated adduct is demonstrated through collision-induced decay experiments that were also extended to related model compounds. The observed electron transfer from the wheel to the axle and the fragmentation patterns are discussed.

Introduction

Rotaxanes are molecular assemblies in which a linear component, the axle, is mechanically threaded through one or more cyclic molecules, the wheels, and is endowed with bulky groups at the ends of the rod to prevent the unthreading of the structure.[1] Rotaxane systems have been extensively investigated in recent years, mainly in connection with their use as molecular devices and machines.[2] A precise strategy is needed to obtain the formation of an interlocked system, which may involve self-assembly, self-organization as well as supramolecular assistance to covalent synthesis.[3]



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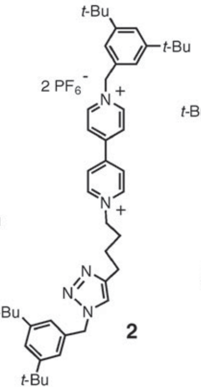

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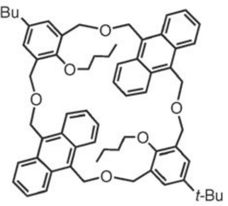

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We recently reported on the synthesis of **3**, on the easily reversible Diels–Alder addition of tetracyanoethylene (TCNE) to its anthracene moieties and on the supramolecular control of the latter reaction by added cationic guests.[4] In particular, the elongated anthracene walls in **3** proved to be suitable for binding alkylviologen ions, with association constants as high as 10^4 M^{-1} being determined in $CHCl_3$–CH_3CN 1 : 1, and with a pseudo-rotaxane arrangement being observed in both solution and solid state.[4] On extending the above research, we planned to obtain fixed threaded structures based on the same host–guest system and here we report on the synthesis of the new [2]-rotaxane **1** featuring the non-symmetrical viologen ion-based axle **2** and the wheel **3**, and on the use of MS techniques to prove its interlocked topology.[5]

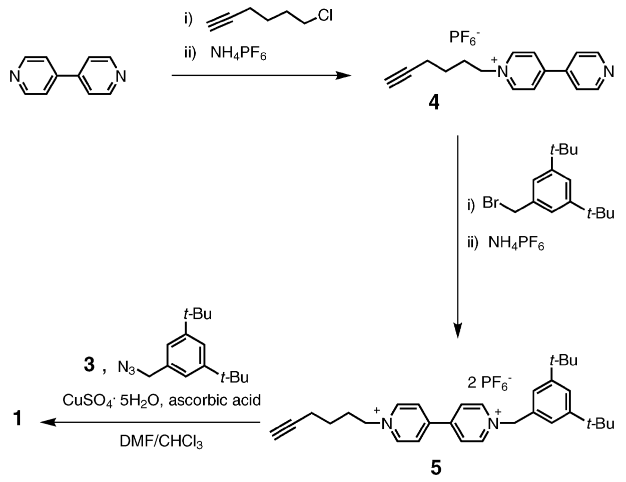
Results and discussion

Synthesis

A capping strategy was chosen to obtain rotaxane **1** (Scheme 1). The key step in the synthesis is the copper(I)-catalyzed 1,3-dipolar cycloaddition[6] between a stoppered azide and the stoppered dication **5** in the presence of the wheel **3**. The non-symmetric rotaxane **1** was eventually obtained in 8% overall yield after recrystallization. On carrying out the last synthetic step in the absence of the wheel **3**, the simple axle **2** was obtained in 92% yield. The latter was used as a model compound that allowed a comparison of threaded and unthreaded adducts.

Characterization

The compound obtained according to Scheme 1 and supposed to be the rotaxane **1** is soluble in $CDCl_3$, while the poor



Scheme 1

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† Electronic supplementary information (ESI) available: ^{1}H NMR and ^{13}C NMR spectra of compounds **4**, **3** and **2**; spectra at low temperatures of compound **1**; fragmentation pattern of the wheel. See DOI: 10.1039/b9nj00501c

solubility of **2** is not significantly increased on addition of an equimolar amount of **3**; moreover, its solutions are coloured red, at variance with solutions of **2** + **3**.

Marked differences between the isolated compound and a mixture of **2** + **3** are also apparent in the ^{1}H NMR spectra in $CDCl_3$–CD_3CN (see ESI†). Some signals of the wheel can be supposed to have shifted, as in the previously investigated reversible inclusion of alkylviologen ions into the wheel **3**, but a large number of superimposed signals and broadened signals are apparent that do not allow the structure of the expected rotaxane to be assigned to the isolated compound. The above complications are likely due to the low symmetry of the system and to dynamic phenomena, with moderately fast interconversion among the possible arrangements in the interlocked system. Spectra taken in CD_2Cl_2 at low temperatures, down to 208 K, did not clarify the picture since the observed large number of peaks could not be safely interpreted (see ESI†).

The picture was somewhat simplified on taking spectra at high temperatures in $CDCl_2CDCl_2$. Complicated patterns were still observed for most signals, but at 333 K the pattern for *t*-Bu protons was as expected for a fast interconversion among the conformations in the rotaxane structure, namely, four peaks in 2 : 2 : 1 : 1 area ratios (Fig. 1).[7]

Although the NMR spectra suggest that the isolated compound is the expected rotaxane, they cannot, by themselves, prove the structure and its interlocked nature.

We were able to obtain what appeared to be good quality single crystals of the compound, but unfortunately, X-ray analysis could not be performed successfully since they diffracted poorly. On the other hand, the melting point indicates that the isolated compound is a well defined and pure species, with mp = 256.6–258.2 °C.

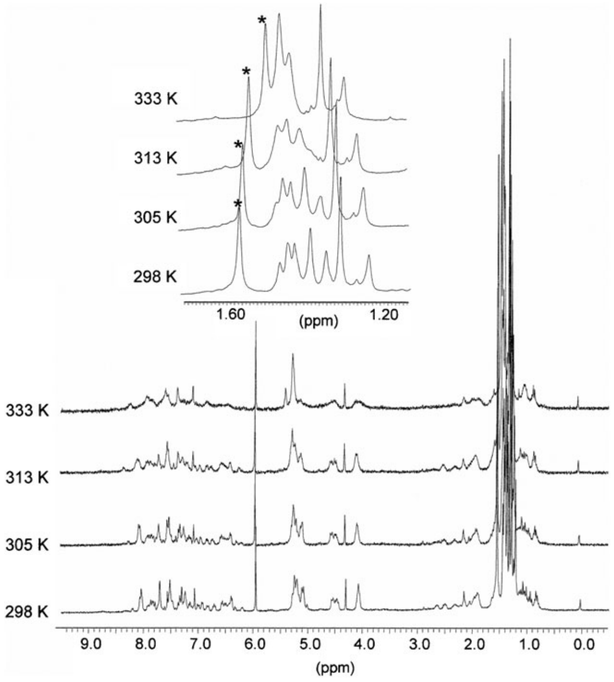


Fig. 1 ^{1}H NMR spectra at high temperature of compound **1** in $CDCl_2CDCl_2$. In the inset, the enlarged region with *t*-Bu signals is shown; water signals are starred.

An unambiguous assignment of the interlocked structure **1** to the isolated compound could, however, be made on the basis of mass spectrometric results.

First of all high-resolution mass spectrometry (HRMS) confirmed the atomic composition of the expected compound: calculated for $C_{110}H_{135}N_5O_6^{2+}$ 811.0206, found 811.0195. Since the same molecular mass is expected for any 1 : 1 adduct of the axle and the wheel, MS/MS collision-induced decay (CID) experiments were carried out to prove the interlocked nature of the isolated adduct.

In Fig. 2, the results of three series of MS/MS CID experiments are reported. Spectra (a)–(d) refer to experiments carried out on the dicationic axle, as selected in the analysis of a CH_3CN solution of salt **2**. The symbols are explained in Scheme 2, in which the observed fragmentation pattern of the axle is reported. Moreover, two parallel CID experiments at increasing collision energy were carried out on the mass-selected ions, m/z = 811, obtained from CH_3CN solutions of either a mixture of **2** and **3** or the compound supposed to be the rotaxane **1**; spectra (e)–(h) and spectra (i)–(l) in Fig. 2, respectively. At a collision potential of 5 V, partial fragmentation is apparent only for the simple dicationic axle. On increasing the collision potential, significant differences appear in the behaviour of unthreaded and threaded complexes. So, at 25 V, the signal with m/z = 811 is still important in the spectrum of the supposed rotaxane, while it is no longer detectable in the case of the mixture of **2** + **3**, with only fragment peaks being apparent; spectra (l) and (h). On the basis of the above spectra, the interlocked structure of **1** can be held as proved. Namely, unthreaded adducts are expected to be dissociated by simply breaking non-covalent interactions, with a process requiring relatively low-energy collisions in a MS/MS CID experiment, while breaking a covalent bond is necessary to separate the two components in the case of a rotaxane structure, and the latter process can only occur through higher energy collisions.[5]

Electron transfer processes

Actually, the picture is somewhat more complicated and a deeper analysis is needed. Under suitably high collision-energy conditions the threaded structure can be disassembled through bond breaking at either the axle or the wheel. Most peaks in Fig. 2 are fragment peaks of the axle and correspond to those reported in Scheme 2;[8] on the other hand, the unfragmented axle appears to be very different in the absence and in the presence of the wheel, namely, only a dication (m/z = 342.5) for the analysis of the simple salt and only a monocation (m/z = 685.5) for the analysis of both threaded and unthreaded complexes of the axle and the wheel.

The peak of the singly-charged ion appearing only in the presence of cyclophane **3** can be attributed to the radical cation resulting from an electron transfer process from the wheel to the axle, as induced by suitably energetic collisions (Scheme 3). The two radical cations formed are expected to repel each other in the absence of additional bonds, and to be detected as separated species. Accordingly, in the case of the mixture of **3** + **2**, the signal at m/z = 685.5 is accompanied by a signal at m/z = 936.6 for the radical cation derived from the wheel; spectra (f)–(h) in Fig. 2. On the other hand, in the case

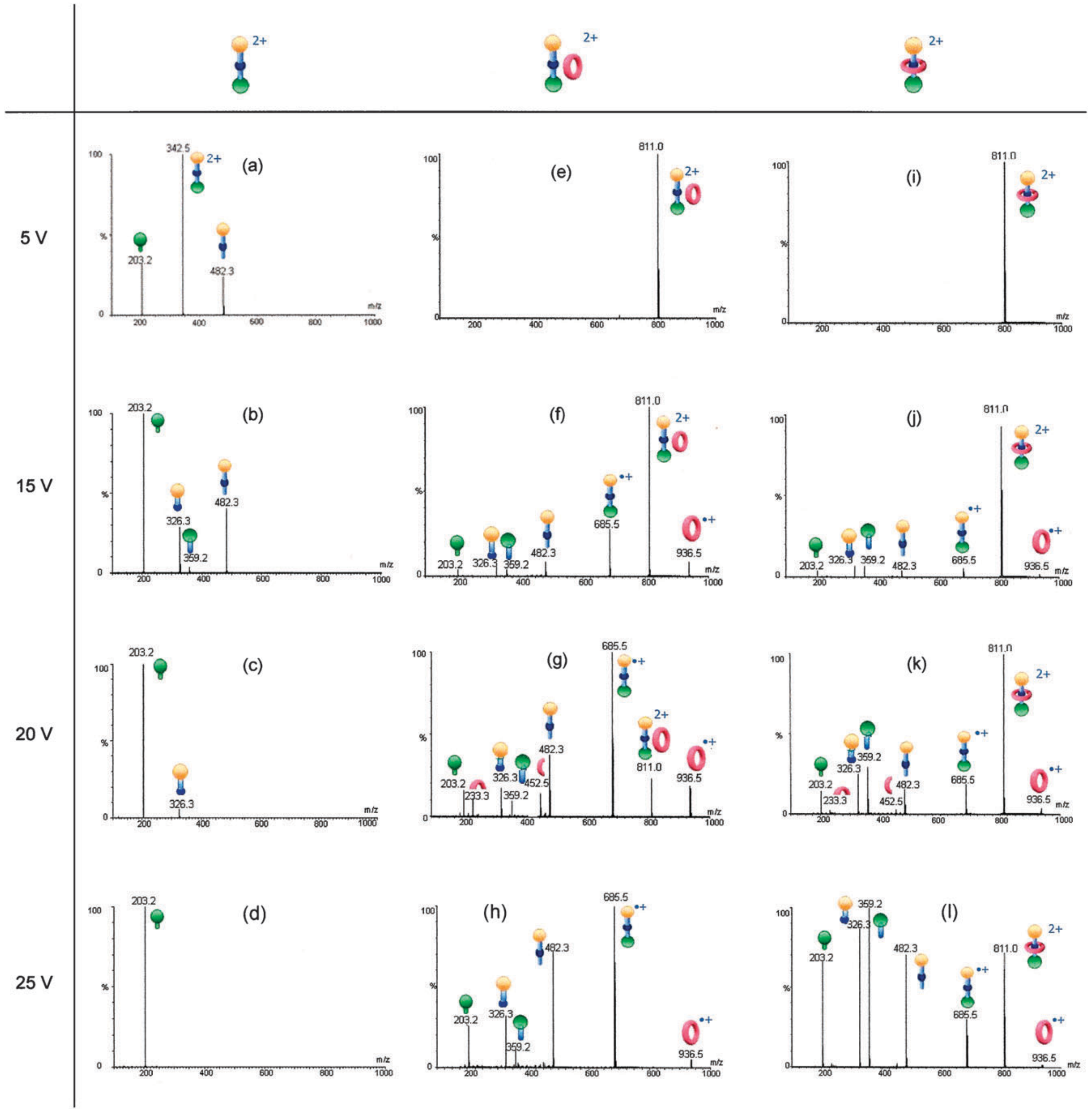
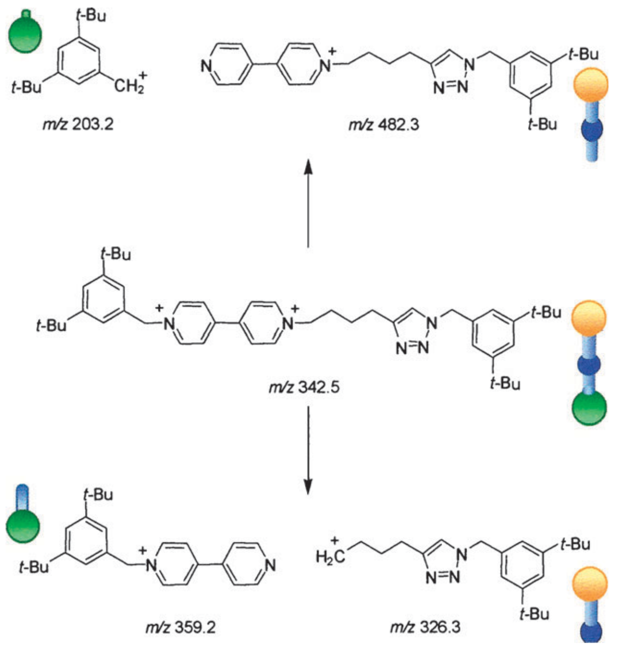
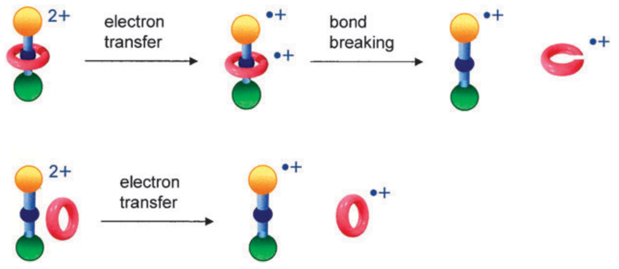


Fig. 2 CID experiments at increasing collision energy carried out on selected peaks of the dicationic axle (from CH_3CN solutions of **2**), of the dicationic unthreaded adduct (from CH_3CN solutions of a mixture of **2** and **3**) and of the dicationic threaded adduct (CH_3CN solutions of **1**). Charge is indicated only in the case of dications and in the case of radical cationic axle and wheel.

of the rotaxane **1**, the simple electron transfer process does not allow the two radical monocations to fly apart and to be detected as separated species. Even if the excited state does not immediately undergo back electron transfer, the rotaxane with interlocked radical cations cannot be distinguished from the ground state featuring an almost dicationic axle and an almost neutral wheel. The paired radical monocations can be detected as separate species only provided a covalent bond is also broken before back electron transfer occurs. In particular, the observed peak for the unfragmented radical cationic axle necessarily requires that the ring is opened (Scheme 3). On the other hand, fragmentation of either a dicationic or a radical monocationic axle can be considered for both threaded and unthreaded complexes with the wheel. The dicationic axle may fragment according to the paths reported in Scheme 1 for the simple salt **2**, with a neutral wheel that cannot be detected apparently being released. Fragmentation of the radical monocationic axle can also be conceived to occur—with the release of a radical cationic wheel in the case of the threaded pair of radical cations, and after the radical cation wheel flies apart in the case of the unthreaded complex. No new fragments of the axle are actually detected besides those reported in Scheme 2.



Scheme 2



Scheme 3

When a comparison is made with spectra (a) and (b) in Fig. 2, complexation with the wheel appears to reduce fragmentation of the axle at the lower values of collision energy.[9] On the other hand, in the case of **1**, both signals at m/z = 685.5 and m/z = 936.6 are rather small; both radical cations appear to be largely fragmented at the high collision energy required to break a covalent bond and separate the two topologically-bound species. The peaks of the two radical cations are more intense in the case of the unthreaded complex, in particular at a collision potential of 20 V.

Redox processes can well be expected to occur in compounds such as **3**,[10] while electron transfer processes have been guessed to take place in MS/MS CID experiments on such easily reducible species as alkylviologen dications.[11] However, to the best of our knowledge, in no previous investigation of systems of this type could both the reduced and the oxidized partners be detected in the mass spectra.

Further evidence for electron transfer in the MS experiments was gained by investigating dications **6–8** that can be considered as axles in unlocked, namely pseudo-rotaxanic, complexes with the wheel **3**. Also in these cases, 1 : 1 mixtures of a dihexafluorophosphate salt and the wheel **3** were investigated and MS/MS CID experiments at increasing collision energy were carried out on the selected dication corresponding to the complex with the wheel. Electron transfer appears to take place in the cases of **6** and **7**, as shown in the spectra taken at a collision potential of 20 V and reported in Fig. 3. The radical cations of the axle and of the wheel are detected as an intense and a small peak, respectively, with significant fragment peaks formed from the wheel also being observed. On the other hand, in the case of **8**, which is a less reducible species,[12] intense peaks are only observed for the selected complex ion **8** + **3** (m/z = 599.3) and the simple dication **8** (m/z = 131.1),

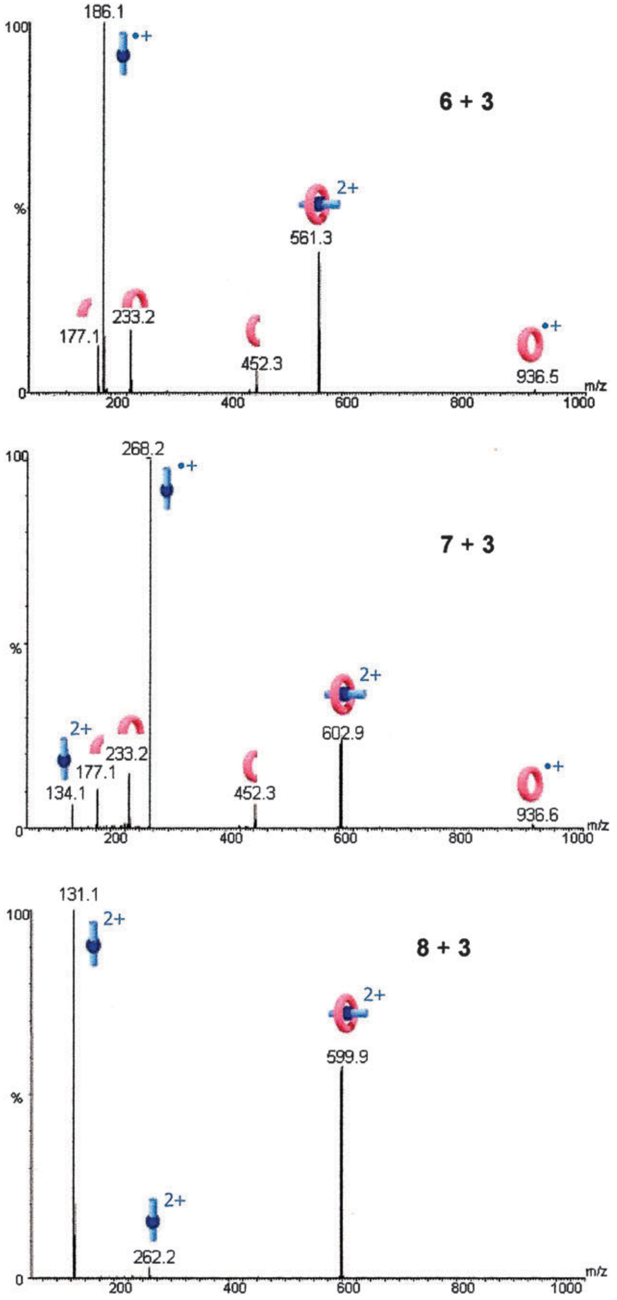
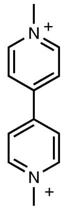


Fig. 3 CID experiments at a collision potential of 20 V as carried out on selected peaks of the pseudo-rotaxanic adducts of **3** with dicationic axles of varying structure.

while a signal corresponding to the radical monocationic axle can be barely detected.



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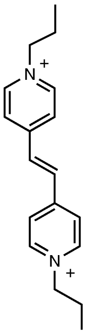

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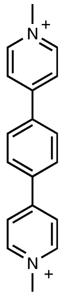

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Conclusions

The non-symmetrical [2]-rotaxane **1** has been synthesized and MS/MS CID experiments allowed us to distinguish between the threaded and the corresponding unthreaded adduct. Peculiar features are apparent in the present system, namely that electronic excitation caused by suitably energetic collisions gives rise to a pair of radical cations that can be directly detected as separate species in the case of the unthreaded adduct, while still being interlocked in the case of the rotaxane structure and only able to be separated on cleaving a covalent bond. The latter process appears to be more energy demanding and the different topologies of the two adducts can be confirmed on tuning the collision potential. Ring opening of the radical cation wheel accounts for the detection of the radical cationic axle. MS/MS CID experiments have also been carried out on a third type of adduct, namely the pseudo-rotaxanic one. The latter resembles the rotaxane in the inclusion geometry, but also resembles the **2** + **3** adduct in the absence of covalent bonds between the partners. Also in these cases, detection of axle and wheel radical cations and of their fragments indicates that electron transfer takes place, provided the axle is an easily reducible species.

Experimental

General methods

NMR spectra were recorded at 298 K on a 300 MHz spectrometer. Deuterated halogenated solvents were stored over activated molecular sieves. ES mass spectra and MS/MS spectra were recorded on a Q-TOF mass spectrometer. In CID experiments, argon (1 mbar) was used as the collision gas and the acceleration voltage was varied in the range 5–25 V, with 200 V being the maximum value for the instrument used.

Synthesis of the materials

1-(5-Hexyn-1-yl)-4,4′-bipyridinium bis(hexafluorophosphate) 4. A mixture of 4,4′-dipyridyl (1.00 g, 6.40 mmol) and 6-chloro-1-hexyne (2.00 g, 21.5 mmol) in DMF (10 ml) was reacted for 3 weeks at 70 °C. The crude solid obtained on removing the solvent was washed several times with hot acetonitrile, the combined extracts were evaporated and water (about 1 cm^3) and NH_4PF_6 (400 mg, 2.45 mmol) were added to the solid residue. The white crystals obtained were filtered, washed with water and then with diethyl ether to yield **4**, (1.7 g, yield 66%): mp 149.2–151.8 °C; δ_H (300 MHz, CD_3CN) 1.52–1.62 (2 H, m), 2.04–2.29 (5 H, overlapped m), 4.56 (2 H, t, *J* 7.7), 7.77 (2 H, d, *J* 6.2), 8.30 (2 H, d, *J* 6.2), 8.76 (2 H, d, *J* 6.6), 8.84 (2 H, d, *J* 6.6) ppm; δ_C (75 MHz, CD_3CN) 18.8, 26.0, 31.4, 62.5, 71.0, 79.6, 123.3, 127.6, 146.4, 145.9, 152.6 ppm; *m*/*z* $(ES)^+$ 237.1 $[M^+]$.

1-[3,5-Di-*tert*-butylphenyl)methyl]-1′-(5-hexyn-1-yl)-4,4′-bipyridinium bis(hexafluorophosphate) 5. A mixture of **4** (0.60 g, 0.82 mmol) and 3,5-di-*tert*-butylbenzyl bromide (0.67 g, 2.4 mmol) in acetonitrile (10 ml) was refluxed for 60 h. The cooled mixture was filtered and the solid was washed three times with chloroform, once with acetonitrile and once with diethyl ether. The resulting white powder was added to NH_4PF_6 (140 mg, 0.86 mmol) dissolved in a few drops of water. The mixture was filtered and the white solid was washed with water and then with diethyl ether to give **5**, (0.284 g, yield 52%): mp 237.0–240.4 °C; δ_H (300 MHz, CD_3CN) 1.34 (18 H, s), 1.55–1.66 (2 H, m), 2.08–2.33 (5 H, overlapped m), 4.66 (2 H, t, *J* 7.3), 5.79 (2 H, s), 7.43 (1 H, apparent d, *J* 1.8), 7.61 (2 H, apparent s), 8.39 (4 H, d, overlapped), 8.92 (2 H, d, *J* = 6.6 Hz), 9.02 (2 H, d, *J* = 7.0 Hz) ppm; ^{13}CNMR, 75 MHz, CD_3CN: δ 18.8, 26.0, 32.0, 36.2, 63.1, 66.8, 71.1, 79.6, 84.7, 125.3, 125.8, 128.8, 128.9, 133.4, 146.9, 147.0, 154.0 ppm; *m*/*z* $(ES)^+$ 237.1 $[M^{2+} - t\text{-}Bu_2(C_6H_3)CH_2{}^+]$, 220.2 $[t\text{-}Bu_2(C_6H_3)CH_2{}^+]$.

Compound 2. 110 μl of a 0.074 M solution of $CuSO_4{\cdot}5H_2O$ (8.2 μmol) in DMF and 110 μl of a 0.15 M solution of ascorbic acid (0.017 mmol) in DMF were added to a mixture of compound **5** (0.060 g, 0.082 mmol) and 3,5-di-*tert*-butylbenzylazide[13] (0.021 g, 0.082 mmol) in DMF–$CHCl_3$ 3 : 1 and stirred for 18 h at room temperature. After solvent evaporation under vacuum, addition of water and filtration, the solid was washed with chloroform and then with diethyl ether to yield **2** as a white solid (0.055 g, yield 92%): mp 221.8–225.8 °C; δ_H (300 MHz, CD_3CN) 1.26 (18 H, s), 1.31 (18 H, s), 1.66–1.76 (2H, m), 2.01–2.11 (2 H, m), 2.72 (2 H, t, *J* 11.4), 4.63 (2 H, t, *J* 7.3), 5.44 (2 H, s), 5.75 (2 H, s), 7.16 (1H, apparent d, *J* 1.1), 7.41 (2H, overlapped), 7.58 (4H, s), 8.34 (4 H, d, *J* 6.2), 8.9 (2 H, d, *J* 6.2), 9.01 (2 H, d, *J* 6.6) ppm; ^{13}CNMR, 75 MHz, CD_3CN: δ 25.3, 26.4, 31.5, 31.6, 35.5, 35.8, 37.3, 54.8, 62.8, 66.4, 79.1, 95.7, 122.6, 123.3, 123.4, 124.8, 125.4, 128.3, 128.4, 132.9, 146.4, 146.5, 152.5, 153.6 ppm; *m*/*z* $(ES)^+$ 342.7 $[M^{2+}]$.

Compound 1. Compound **1** was obtained by the same procedure reported for compound **2** on reacting 3,5-di-*tert*-butylbenzylazide (11 mg, 0.015 mmol), **5** (4.0 mg, 0.016 mmol), cyclophane **3** (0.015 g, 0.016 mmol), $CuSO_4{\cdot}5H_2O$ (8.2 μmol) and ascorbic acid (0.017 mmol). Work-up was as above, then slow diffusion of vapours of diethyl ether into a solution of the product in $CHCl_3$–CH_3CN afforded pure **1**, yield 24%, mp: 256.4–258.0; *m*/*z* [HRMS $(ES)^+$] calculated for $C_{110}H_{135}N_5O_6{}^{2+}$ 811.0206, found 811.0195.

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7 The 2 : 2 : 1 : 1 area ratios are expected for the "alternate" arrangement of the wheel, whilst the 2 : 2 : 2 area ratios are expected for the "cone" arrangement. In previous investigations, both free and complexed **3** appeared to be present in the former conformation, both in solution and in the solid state; moreover, the intercon version between the two "alternate" conformations appeared to be fast both in the free wheel and in the presence of simple alkylviologen ion guests (see ref. 4). On the other hand, molecular models suggest that conformational interconversion is somewhat hindered, but still possible, in the case of **1**.

8 In some cases, fragment ions derived from the wheel have also been detected. Their guessed structure and the used symbols are reported in ESI†.

9 Complexation with molecular tweezers has been reported to stabilize viologen dications which are intrinsically unstable in the high vacuum of a mass spectrometer and are not detected at all as unfragmented "naked" species, see: C. A. Schalley, C. Verhaelen, F.-G. Klärner, U. Hahn and F. Vögtle, *Angew. Chem., Int. Ed.*, 2005, **44**, 477. Interestingly, in the spectrum of compound **5** we also detected only fragment monocations (see Experimental).

10 Oxidation potentials for 9,10-dimethylanthracene and 2,4,6-trimethylanisole, suitable models for the system at hand are 1.2 V (CH_3CN, 25 °C) and 1.7 V (CH_2Cl_2, −50 °C) respectively; see: V. D. Parker, Y. T. Chao and G. Zheng, *J. Am. Chem. Soc.*, 1997, **119**, 11390; O. Hammerich, V. D. Parker and A. Ronlán, *Acta Chem. Scand., Ser. B*, 1976, **30b**, 89.

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12 The reduction potentials are −0.92 V, −0.59 V, −0.43 V for **8**, **7** and **6**, respectively, in CH_3CN at 298 K, see: K. Takahashi, T. Nihira, K. Akiyama, Y. Ikegami and E. Fukuyo, *J. Chem. Soc., Chem. Commun.*, 1992, 620.

13 See ref. 6, third citation.