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Quadruple π-π-stacking of macrocyclic viologen radical-cations

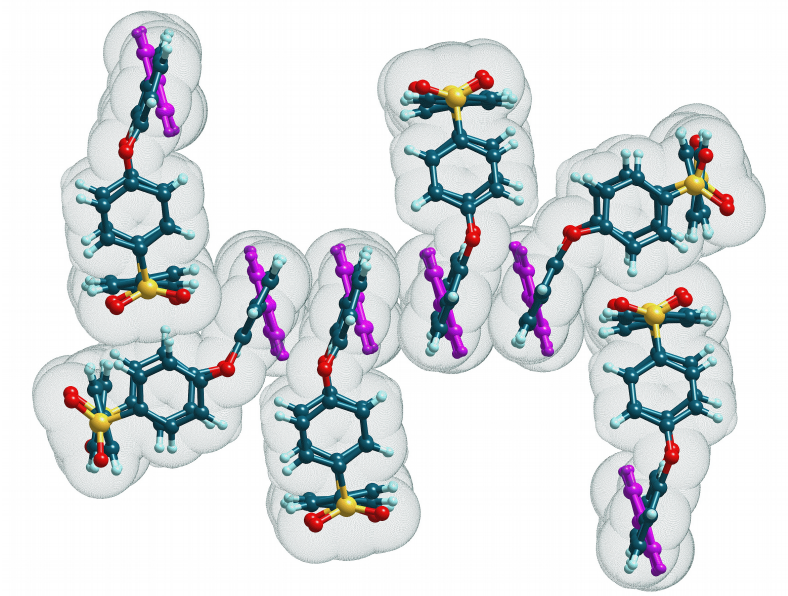
Claire A. Murray,[a] Zhixue Zhu,[a] Christine J. Cardin,[a] Howard M. Colquhoun,[a]* and Barnaby W. Greenland [b]*

[a] Department of Chemistry, University of Reading, Whiteknights, Reading, RG6 6AH

[b] Reading School of Pharmacy, University of Reading, Whiteknights, Reading, RG6 6AH

* email: b.w.greenland@reading.ac.uk; h.m.colquhoun@rdg.ac.uk

Abstract



The solid state structures of the di-cationic (**1a**) and radical mono-cationic (**1b**) redox forms of a 4,4'-bipyridinium (viologen) containing macrocyle have been established by single crystal X-ray analysis. Formation of the radical cation has a dramatic effect on the molecular structure of the macrocycle, both decreasing the diameter of the ring cavity (from 8.5 Å to 7.8 Å) and drastically flattening the torsion angle between the two pyridinium residues in the viologen, reducing it from 40º to 5º. Moreover, a close association of these near-planar radical cation units drives the formation of a tetrameric supramolecular structure in the solid state. The interplanar distances between the heterocyclic radical-cationic residues in the quadruple π-stacks, averaging ca. 3.3 Å, are significantly below a typical Van der Waals separation.

Key Words

Viologen, macrocycle, radical cation, X-ray structure, π–π stacking.

Introduction

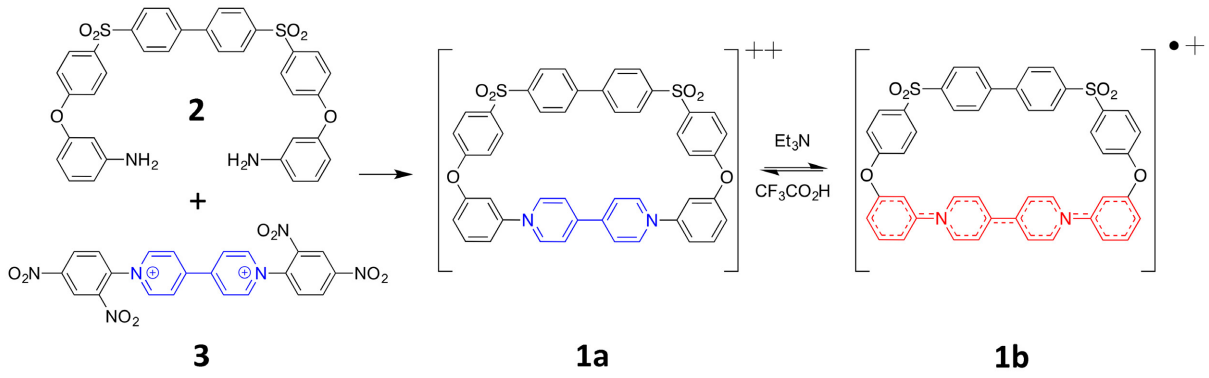
The 4,4'-bipyridinium (viologen) dication has become one of the most versatile building blocks in supramolecular chemistry [1] Many supramolecular structures including catenanes, rotaxanes and inclusion complexes of increasing levels of complexity have been assembled by making use of π-π stacking interactions between the electron-poor viologen residues and π-electron rich molecular components.[2]

Viologens undergo a two-step reversible reduction. Sequential addition of two electrons to the di-cation results firstly in the formation of a radical mono-cation, then subsequently in the generation of a neutral quinoidal system.[3] Each redox event alters the nature of the supramolecular interactions exhibited by the three distinct species (with charges 2+, 1+ and 0), and such redox behaviour has been developed extensively to deliver switch-like behaviour in supramolecular assemblies.[4]

It has been known since the 1960s that radical mono-cationic viologens undergo dimerization (so-called "pimerisation") in solution, with pairing of their π-electron spins increasing as the temperature is reduced.[5] However, it is only relatively recently that this process has been exploited as a tool in the design and synthesis of functioning supramolecular structures, including semiconducting crystals,[6] chain-folding oligomers,[7] and reconfigurable supramolecular polymers,[8] along with more complex mechanically interlocked structures.[9]

One of the most widely studied viologen species for the formation of supramolecular assemblies is the tetracationic macrocycle cyclobis(paraquat-*p*-phenylene) (CBPQT,).[10] A key structural feature underpinning the success of this macrocycle in supramolecular chemistry is the precise separation of the essentially parallel viologen residues which produces a cavity of diameter ca. 6.6 Å.[11] This separation is ideal for the inclusion of planar π-electron rich or radical cationic compounds. However, a structural drawback of CBPQT is that it contains the *N*-benzylbipyridinium moiety which is readily susceptible to cleavage under nucleophilic conditions.

Our previous work in this area has focused on the synthesis of oligomeric[12] and macrocyclic[13] species that contain only *N-arylene*bipyridinium residues and are therefore chemically very much more stable. Specifically, we have synthesised a series of macrocyles that contain either one or two viologen residues suitably positioned to allow the formation of supramolecular assemblies, but which are not susceptible to N-C bond cleavage.[13] This is exemplified by the synthesis of the dicationic, viologen-containing macrocycle **1a**, formed from the all-aromatic diamine **2**[14] and the well known diZincke salt **3**[15] (Scheme 1). The pale yellow macrocycle is chemically stable to many bases and nucleophiles whilst still being able to form *pseudo*-rotaxanes with π–electron rich aromatic compounds.[13] Macrocycle **1a** was also found to be a potent electron acceptor, undergoing addition of a single electron on contact with mild electron donors such as triethylamine. This reduction process results in the formation of an intensely coloured, green, paramagnetic radical mono-cation (**1b)** in which the unpaired electron is delocalised over four aromatic/heterocyclic rings. The presence of paramgnetic spin density leads to the disappearance of the ^{1}H NMR resonances associated with these rings (shown in red in Scheme1) though resonances associated with the rest of the molecule are esentially unaffected. The reduction is reversed on addition of a proton source such as trifluoroacetic acid.



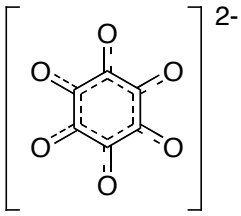
Scheme 1: Synthesis of viologen-containing macrocycle **1a** and its reversible reduction to the radical cation **1b.**

Here we describe the crystal and molecular structures of both the dicationic macrocycle **1a** as its hexafluorophosphate salt, and the same species in its reduced, radical-cationic state (**1b**). The two forms of the macrocycle exhibit dramatically

different structures and crystal packing, with the crystal structure of **1b** being primarily dictated by a close association of the radical-cationic viologen residues.

Results and discussion

Studies of the potential for di-cationic macrocycle **1** to encapsulate a di-anionic aromatic species (the rhodizonate(2-) ion, **4**, as its sodium salt) in acetonitrile led to the isolation of two distinct crystalline species. The crystals could be separated manually owing to their distinct colours: one pale yellow and the other intense, dark green. Surprisingly, neither of these crystal forms were the anticipated complex **1**⊃**4**. However, the disparate colours of these crystals suggested the serendipitous isolation of the native dicationic and radical cationic forms of the macrocycle. Consistent with this, rhodizonic acid is known to act as a reductant towards, for example, cytochrome *c.*[16]



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On inspection of the crystal structures, the two forms of macrocycle **1** exhibited dramatically different molecular structures and packing motifs. Notably, the mean transannular distances in the two macrocyles are very different (Figure 1). Thus, the the "central" carbon atoms on either face of the dicationic macrocycle **1a** are separated by approximately 8.5 Å (pale yellow crystals, Figure 1whilst the equivalent atoms in the radical cation **1b** are singificantly closer at ca. 7.8 Å as shown in Figure 1(b). There are two independent molecules in the unit cell of **1b**, and these have very different conformations (Figure 1), with the 4,4'-bipyridyl residue being orientated either approximately parallel to the mean plane of the macrocycle or essentially perpendicular to it (**1b'** and **1b"** respectively in Figure 1).

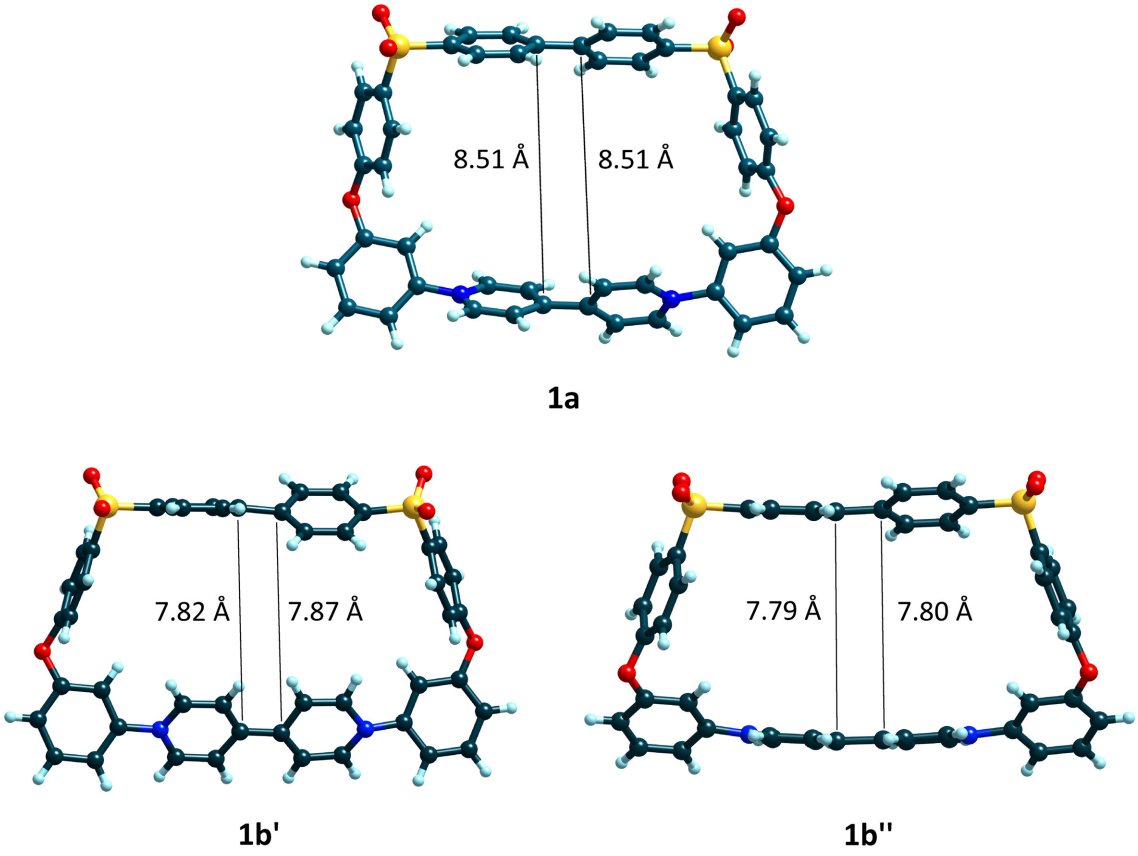
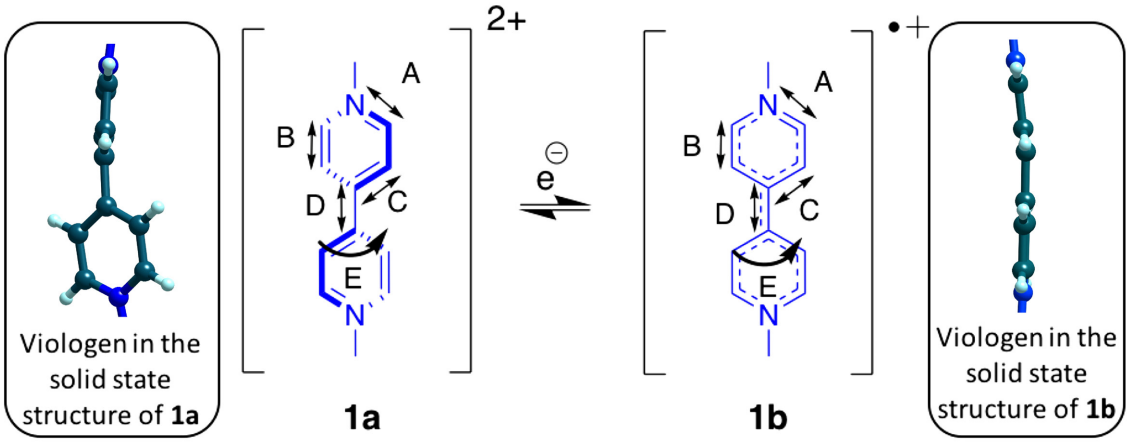


Figure 1. Structures of the macrocycles **1a** and **1b**/**1b'** from single crystal X-ray analysis. Transannular C.....C distances between the central atoms of the biphenyl and bipyridyl residues show that the macrocycle contracts very markedly on reduction.

Examining the bond *lengths* in the viologen residues in **1a** and **1b'/1b''** reveals only minimal differences between the three macrocycles (Table 1) suggesting that reduction leads to no sigificant changes in bond order within the viologen residue. However, the torsion angle between the two pyridinium rings changes dramatically on reduction, from ca. 48º in **1a** to just 3°/9º degrees in **1b'/1b''**. The near-coplanarity of the pyridyl residues in radical cations **1b** and **1b'** clearly enables the delocalisation of the unpaired π-electron density within the reduced viologen unit that was evident from a previous NMR study of this macrocycle.[13] That study also suggested delocalisation of unpaired spin density into the phenylene rings attached directly to the viologen unit. The crystal structure of **1b** indeed shows a marked reduction of the torsion angles between these rings and their associated viologen residues, consistent with delocalisation via increased overlap of the coresponding π-systems. A flattening of the bipyridine torsion angle in viologen radical cations has been observed in the solid state structures of the radical cations of diphenylviologen[16] and

of dimethylviologen[17] and has more recently been described by Stoddart and co-workers in their studies of the di-radical, di-cationic macrocyclic form of CBPQT,[18] confirming our assignments of the two redox forms of macrocycle **1**.

Table 1. Mean bond lengths and ring/ring torsion angles from the crystal structures of **1a** and **1b**



	A (Å)	B (Å)	C (Å)	D (Å)	E (deg)
1a	1.35	1.38	1.39	1.49	48
1b'	1.34	1.38	1.38	1.41	9.0
1b"	1.34	1.38	1.38	1.51	3.0

[a] The illustration shows selected views from the crystal structures of **1a** and **1b**, highlighting the difference in torsion angles between viologen fragments in the two macrocycles. The table also shows the relative constancy of bond lengths between **1a** and **1b'/1b"** and the very substantial change in viologen ring-ring torsion angles between **1a** and **1b'/1b"**.

The di-cationic and radical-cationic forms of the macrocycle show very different packing motifs in the crystal. Thus, the hexafluorophosphate salt **1a**, in space group P-*1* (*Z* = 2) contains macrocycles that form infinite π-stacks parallel to the *a* axis, with the viologen residue of each macrocycle packing against the biphenylene-disulfone residue of its neighbour (Figure 2).

The radical cationic form (**1b**) of the macrocycle also exhibits P−*1* symmetry, but examination of the structure reveals that the crystal is assembled from an

unpredented, tetrameric, supramolecular unit. This consists of a stack of four closely-packed, near-parallel radical-cationic viologen residues, the interactions of which evidently dictate the solid-state structure (Figure 2B). The nature of the counterions could not be established in this structure owing to extensive positional disorder, even though the atomic positions of the macrocyles themselves are relatively well-defined. The electron density representing the counterions was therefore accounted for using the SQUEEZE routine in PLATON.

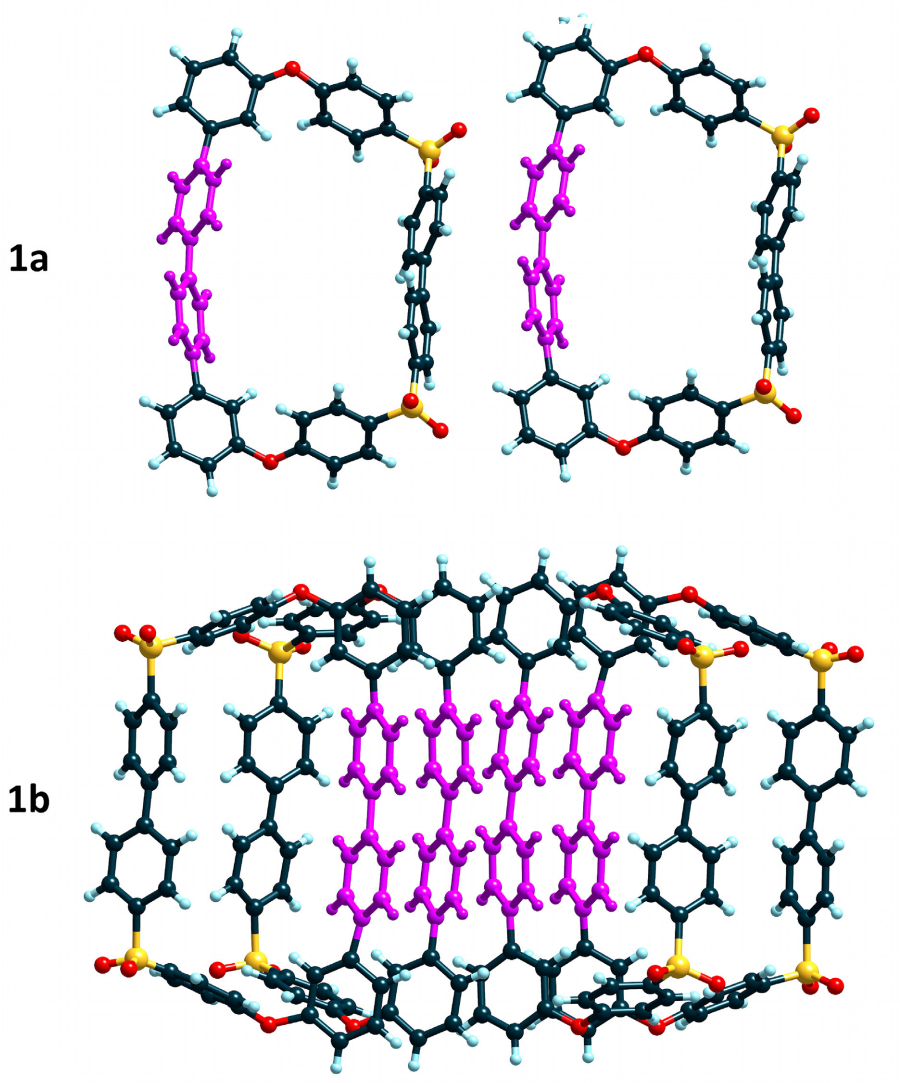


Figure 2. Packing of nearest-neighbour macrocycles in crystals of **1a** and **1b**. In each case the viologen residue or radical-cationic viologen is highlighted in magenta.

A view along the *b* axis of the tetrameric assembly clearly shows that the interactions between the essentially coplanar radical cationic viologen species are driving the formation of the tetramer in the solid state (Figure 3A). A view perpendicular to this,

looking down the tetramer stack (Figure 3B), shows that each viologen radical cation is virtually superimposable on the residue below. In addition, the face to face separation between each radical cation averages approximately 3.32 Å, significantly below a typical van der Waals π-π contact distance for aromatic molecules.

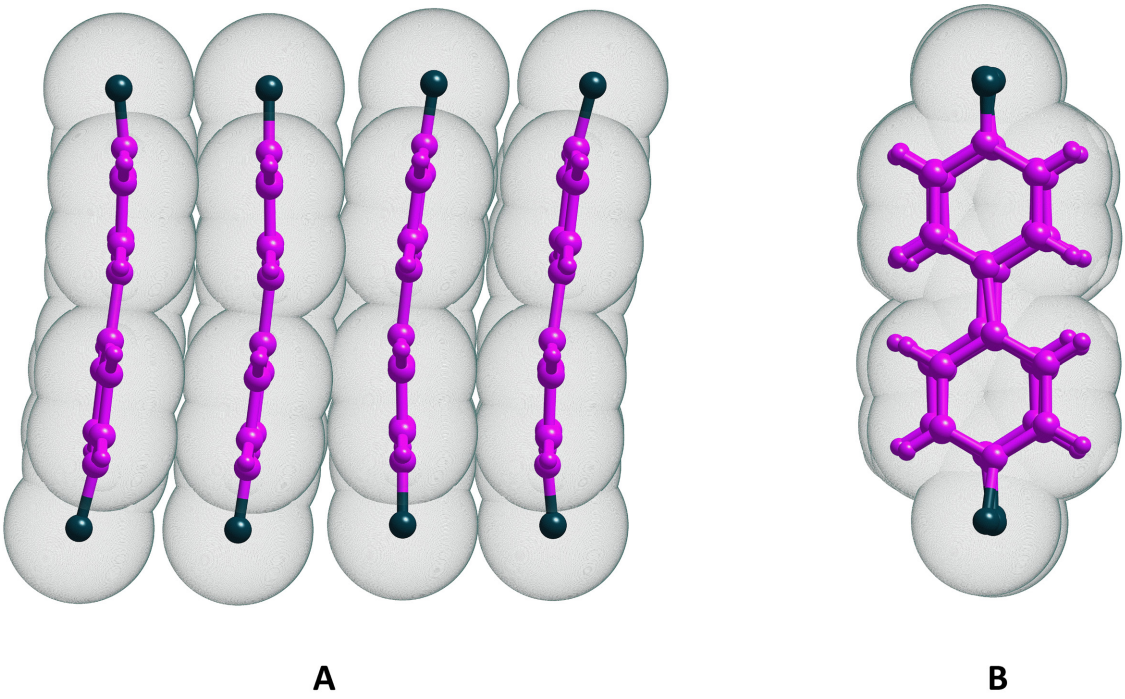


Figure 3. Stacking of the viologen units in the crystal of 1b, viewed (A) down the *b* axis of the unit cell, with van der Waals surfaces showing the close π-π interactions within the quadruple stack, and viewed (B) perpendicular to this axis, showing the near-exact overlap of all four viologen residues in the stack.

From Figure 3(A) it might be assumed that the π-stacking of reduced viologen units would extend indefinitely through the crystal, but this is certainly not the case. Each group of four "stacked" macrocycles, containing two **1b'** and two **1b"** types, comprises a discrete structural unit. As shown in Figure 4, this unit is terminated at each end by a 4,4'-biphenylenedisulfone unit of a **1b'**-type macrocycle from a different quadruple stack.

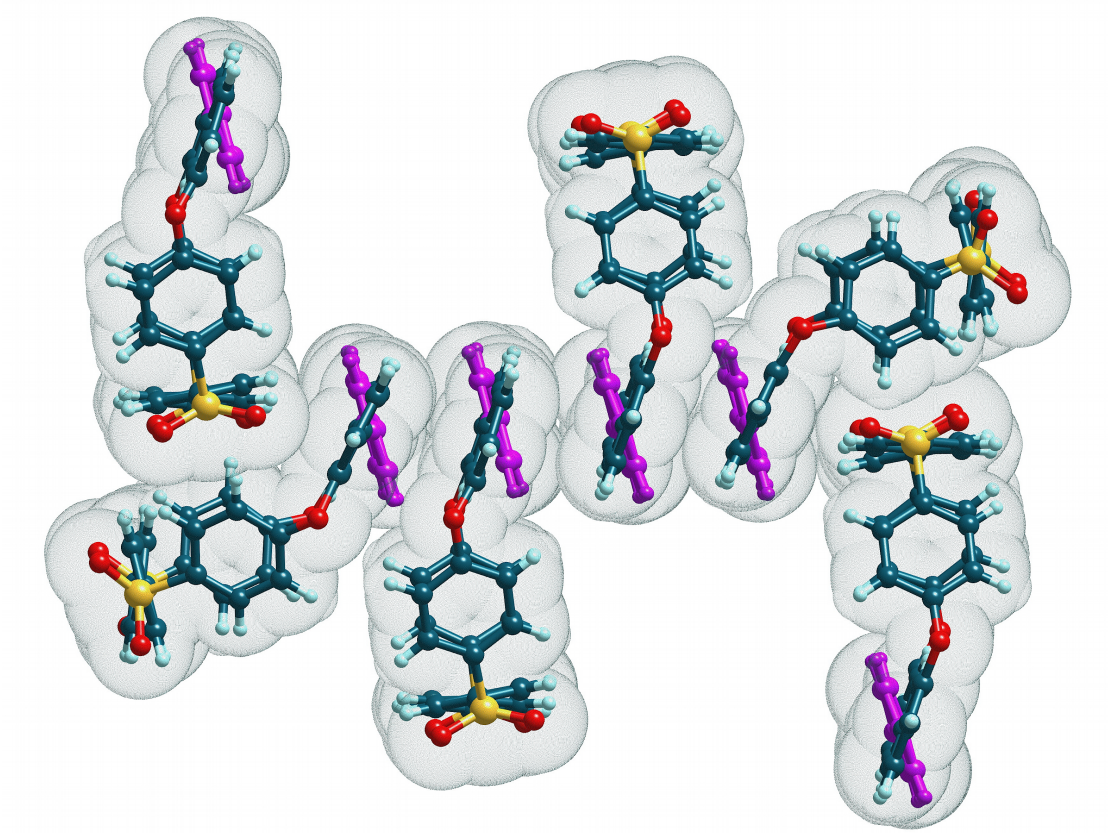


Figure 4. Termination of the quadruple π-stack motif in the crystal of the macrocyclic radical-cation **1b**, showing van der Waals surfaces. Viologen units are highlighted in magenta. Each "terminating" macrocycle is itself a component of a further quadruple π-stack.

Conclusions

Exploiting the interactions between viologen radical cations is an increasing valuable method for the formation of functional and/or mechanically interlocked molecules and supramolecular structures. In this paper we demonstrate the solid state structures of a dicationic and radical cationic macrocyclic receptor. Formation of the radical cation has a substantial influence on the conformation of the macrocycle, specifically by reducing the cavity size (from ca. 8.51 to 7.85 Å) and flattening the torsion angle between the two pyridinium residues from 48° to 9° (**1b'**) or 3° (**1b"**). The formation of radical cationic dimers results in the formation of a highly unusual tetrameric supramolecular unit in the solid state. By comparing the crystal structures of the same macrocycle in two redox states this work expands our structural understanding of these remarkable species.

Crystal data

Single crystal X-ray data were measured on an Oxford Diffraction X-Calibur CCD diffractometer using Cu-Ka radiation. Structure solution and refinement were carried out using the CRYSTALS suite of programmes.[1]

Single crystals of **1a** were isolated from acetonitrile solution by slow evaporation. Crystal data: $C_{46}H_{32}F_{12}N_2O_6P_2S_2.(H_2O).(CH_3CN)_{1.5}$, M_r = 1142.42, triclinic, *P*-1. *a* = 12.8487(6), *b* = 14.4974(7), *c* = 15.0149(7) Å, α = 112.141(4), β = 98.180(4), γ = 95.153(4)°. *V* = 2532.69(12) Å^3, *T* = 150 K, *Z* = 2, D_c = 1.498 g cm^{-3}, μ(Mo-Ka) = 0.267 mm^{-1}, *F*(000) = 1166. Independent measured reflections 10954. R_1 = 0.0737, wR_2 = 0.1100 for 6029 independent observed reflections [2θ ≤ 29.12°, $I > 2\sigma(I)$]. CCDC No.

Single crystals of **1b** were isolated from acetonitrile solution by slow evaporation. $C_{46}H_{32}N_2O_6S_2$, M_r = 772.90, triclinic, *P*-1. *a* = 12.768(2), *b* = 17.357(3), *c* = 22.570(5) Å, α = 104.465(16), β = 105.548(17), γ = 102.734(15)°. *V* = 4439.3(17) Å^3, *T* = 150 K, *Z* = 2, D_c = 1.156 g cm^{-3}, μ(Mo-Ka) = 0.166 mm^{-1}, *F*(000) = 1608. Independent measured reflections 10405. R_1 = 0.1517, wR_2 = 0.2660 for 3262 independent observed reflections [2θ ≤ 23.98°, $I > 2\sigma(I)$]. CCDC No.

1. Betteridge, P. W., Carruthers, J. R., Cooper, R. I., Prout, K., Watkin, D. J. (2003). *J. Appl. Cryst.* **36**, 1487.

Supporting Information

Cif files, structure factors and Checkcif reports for **1a** and **1b,**

Acknowledgements

This work was supported by EPSRC (EP/F013663/1).

Disclosure Statement

The authors declare no conflict of interest.

References

1 Atwood, Jerry L.; Steed, Jonathan W. (2013). *Supramolecular chemistry*. Wiley, Hoboken, N.J.

2 Fang, L.; Olson, M.A.; Benítez, D.; Tkatchouk, E.; Goddard III, W.A.; Stoddart, J.F. *Chem. Soc. Rev*., **2010**, *39*, 17–29.

3 Monk, P. M. S. *The viologens: physicochemical properties, synthesis and applications of the salts of 4,4'-bipyridine*, Wiley, Chichester, 1998.

4

5 Kosower, E. M.; Cotter, J. L. Stable Free Radicals. II. The Reduction of 1-Methyl-4-cyanopyridinium Ion to Methylviologen Cation Radical. J. Am. Chem. Soc. 1964, 86, 5524– 5527.

6 Fahrenbach, A. C.; Sampath, S.; Late, D. J.; Barnes, J. C.; Kleinman, S. L.; Valley, N.; Hartlieb, K. J.; Liu, Z.; Dravid, V. P.; Schatz, G. C.; Van Duyne, R. P.; Stoddart, J. F. ACS Nano 2012, 6, 9964.

7 Yuping Wang, Marco Frasconi, Wei-Guang Liu, Zhichang Liu, Amy A. Sarjeant, Majed S. Nassar, Youssry Y. Botros, William A. Goddard III, and J. Fraser Stoddart J. Am. Chem. Soc., 2015, 137 (2), pp 876–885

8 Sahnawaz Ahmed, Nilotpal Singha, Bapan Pramanik,a Julfikar Hassan Mondala and Debapratim Das, Polym. Chem., 2016,7, 4393-4401

9 Michael T. Colvin, Karla K. Cotí, Diego Benítez, Ekaterina Tkatchouk, John-Carl Olsen, Matthew E. Belowich, Raanan Carmielli, Hussam A. Khatib, William A. Goddard III Michael R. Wasielewski, J. Fraser Stoddart Nature Chemistry 2010, 1, 42-49

10 Odell, B.; Reddington, M. V.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 1547-1550.

11 Philp, D.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Williams, D. J. The Complexation of Tetrathiafulvalene by Cyclobis(Paraquat-p-phenylene). J. Chem. Soc., Chem. Commun. 1991, 1584–1586

12 Chen, L.; Willcock, H.; Wedge, C. J.; Hartl, F.; Colquhoun, H. M.; Greenland, B. W. Org. Biomol. Chem. 2016, 14, 980. L. Chen, F. Hartl, H. M. Colquhoun and B. W. Greenland, Tetrahedron Lett., 2017, 58, 1859–1862.

13 Colquhoun, H.M.; Greenland, B.W.; Zhu, Z.; Shaw, J. S.; Cardin, C.J.; Burattini, S.; Elliott, J.M.; Basu, S.; Gasa, T.B.; Stoddart, J. F. *Org. Lett.*, **2009**, *11*, 5238-5241

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