Viologen–cucurbituril host/guest chemistry – redox control of dimerization versus inclusion†

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Two calix[4]arene systems, C234+ and C244+ – where 2 corresponds to the number of viologen units and 3–4 corresponds to the number of carbon atoms connecting the viologen units to the macrocyclic core – have been synthesized and led to the formation of [3]pseudorotaxanes when combined with either CB[7] or CB[8]. The [3]pseudorotaxanes spontaneously dissociate upon reduction of the bipyridinium units as the result of intramolecular dimerization of the two face-to-face viologen radical cations. CB[7] and CB[8]-based [2]pseudorotaxanes containing monomeric viologen guest model compounds, MC32+ and MC4+, do not undergo decomplexation and dimerization following electrochemical reduction of their bipyridinium units.

Introduction

The stimuli–responsive properties of a molecule with redox-active units can be advantageously used in a broad range of applications including drug delivery and development, electronic displays, electronic memory, batteries, and multi-state switchable materials.1–11 Among these redox-active molecules, for example metalloccenes, tetrathiafulvalene derivatives, naphthalene diimides, and benzoquinones, bipyridinium derivatives12 (also known as viologens) are of particular interest because of their vibrantly electrochromic properties. Bipyridinium dications (BIPY2+), for example, are typically colorless whereas BIPY+ radical monocations are deep blue in color.14 Furthermore, these radical cations spontaneously undergo π-dimerization, a process known as pimerization15 that is driven by radical–radical interactions that favor the formation of the singlet state (i.e., panchromatic absorption14–16 to afford the (BIPY+)2 dimer in aqueous solution. Pimerization of BIPY+ radical cations has been used in supramolecular and mechano-nostereochemical systems to generate translational and rotational molecular movement in many recently reported mechanically interlocked molecules.17–19 Furthermore, the rich redox chemistry of viologens also makes them attractive for use in electrochromic, catalytic, and bioanalytical applications.20–22

However, one major complication that limits the use of viologen-based pimerization to develop stimuli–responsive materials is that the system suffers from low dimerization constants (e.g., log Kdimer = 2.70).24 This results in loosely associated π-dimers in solution, and thus requires the use of high concentrations of the constituent molecular components to drive the binding. The use of low temperatures, micelle environments,24 or macrocyclic hosts with large cavity sizes such as cucurbiturils (e.g., CB[8]), cyclodextrins (e.g., β-CD), or Stoddart’s Blue Box17,18,25 can help favor the formation of intermolecular π-dimer species. A. E. Kaifer, K. Kim and their coworkers described for the first time the interaction of MV2+ with cucurbit[n]uril hosts such as CB[7] and CB[8],26–28 With CB[8], it was found that MV2+ strongly binds in a 1 : 1 stoichiometry inside the macrocyclic cavity, the major driving force being ion–dipole interactions between the positively charged viologen and the oxygen rich host portals atoms. One electron reduction of methyl viologen MV2+ allowed the formation of a bisradical species ([MV+]2 < CB[8]). The dimerization constant of the MV+ in the presence of the CB[8] was estimated to be ~2 × 109 M−1 which is about 105 times larger than MV+ alone.29,30
Supramolecular assemblies based on CB[8] have been reviewed recently by A. E. Kaifer, M. D. Garcia et al.29

Alternatively, it has been shown that pre-organizing two or more organic radicals with well-tailored anchoring platforms and appropriate chain lengths can strengthen the intramolecular binding of the π-dimers in solution.31 We have previously demonstrated that a hexavalent phosphazene30 fulfilled most of the prerequisites including ease of functionalization, and exhibited efficient and fast pimerization. This compound was applicable towards electrochromic material research and possessed specific recognition properties as a function of the viologen redox state. In addition, alkyl,32–37 porphyrinic,38,39 ferrocenyl,40 aryl,42–44 C60,15 and calixarene46,47 linkers, as well as dendritic48,49 and covalent organic polymeric50,51 viologen-based materials (Scheme S1 in the ESI†) have also been demonstrated to promote intramolecular dimerization of their corresponding bipyridinium radical cations.

In line with our ongoing research on viologen-based systems for generating redox-active devices, we turned our attention to calix[4]arene as an inert anchoring platform. Calix[4]arenes can be easily chemically modified and their structural and conformational properties make for an excellent foundation upon which to build increasingly complex architectures. Calix[4]arene can exist in four conformations in solution, the cone, the partial cone, the 1,2-alternate, and the 1,3-alternate. Furthermore, the alkylation selectivity, in regard to the number of substituted phenols, can be controlled by the reaction conditions, thereby giving rise to a broad range of conformers and cavity sizes.52

Herein, we report the synthesis and physicochemical characterization of a series of host–guest monomeric and calix[4]arene-functionalized dimeric viologen–CB-based pseudorotaxane complexes and the structure–property relationships that enable their electrochemical-triggered decomplexation. Calix[4]arene was functionalized with two terminal viologens using spacers of varying length (Fig. 1).45 The use of synthetic receptors that have both a high affinity and a high selectivity for the binding of guests in water is indeed a very interesting prospect.53–56 The recognition properties of the viologen-based systems (oxidized and reduced) with CB[7] and CB[8] were analyzed using a set of complementary analytical methods which include ESI-MS, square wave and cyclic voltammetry, UV-visible-near infrared (NIR) spectrophotometry, 1H-NMR, and electron paramagnetic resonance (EPR).

**Experimental section**

**Synthesis**

Starting materials and solvents. All commercial reagents were purchased from Sigma-Aldrich and used without further purification. 1-Methyl-[4,4′-bipyridin]-1-ium iodide (I1) was prepared according to literature procedures.7 1-(3-Bromopropoxy)-4-(tert-buty)benzene (I2), 1-(4-bromo-butoxy)-4-(tert-buty)benzene (I3), 1,3-bis(3-bromopropoxy)-p-tert-buty-calix[4]arene (I5) and 1,3-bis(4-bromobutoxy)-p-tert-buty-calix[4]arene (I6) were also prepared according reported procedures with slight modifications.38,39 The dicationic dimethyl viologen MV2+ (Fig. 1) and tetrakis-p-tert-buty-calix[4]arene (ref. 60 and 61) were prepared according to literature procedures. Thin layer chromatography (TLC) was used to follow the reactions and was performed on aluminium sheets bearing silica gel 60 F254 (E. Merck). Column chromatography was performed using silica gel (Merck; 40–63 μm). Nuclear magnetic resonance (NMR) spectra were recorded on a Bruker AC 400 with working frequencies of 400 and 100 MHz for 1H and 13C, respectively. Chemical shifts are reported in ppm relative to the signals corresponding to the residual non-deuterated solvents (CDCl3 (δ = 7.26), CD3OD (δ = 3.34), and d6-DMSO (δ = 2.50). High-resolution electrospray mass (HR-ESI) spectra were measured on a micro Q-TOF (Bruker) spectrometer.

**Fig.1** Chemical structures of the calix[4]arene viologen-based systems C234+ and C244+ and the reference compounds MC32+ and MC44+. The number 2 stands for the number of viologens while 3–4 correspond to the number of carbons of the chain connecting the terminal viologens to the calix[4]arene backbone. Methyl-viologen (MV2+) has been used as a model compound in this work. C224+ (PF6− salt) was not synthesized in this work (see ref. 45) and only considered for DFT calculations.

1-(3-4-(Tert-buty)phenoxo)propyl]-1-methyl-[4,4′-bipyridin]-1,1′-diium bromide iodide (MC32+). 0.8 g (2.95 mmol) of I2 was mixed with 0.88 g (2.95 mmol) of I1 in 30 mL of acetonitrile (CH3CN) and the mixture was refluxed for two days. The reaction mixture was filtered and washed with CH3CN to afford MC32+ as a red-orange solid (yield: 31%). 1H NMR (400 MHz, CD3OD): δ [ppm]: 9.36 [d, 2H, J = 7.26 Hz, Ar-H], 9.23 [d, 2H, J = 7.2 Hz, Ar-H], 8.70 [t, 4H, J = 6.8 Hz, Ar-H], 8.60 [t, 4H, J = 7.2 Hz, Ar-H], 7.30 [d, 2H, J = 8.8
Ar-H], 6.77 [d, 2H, J = 9.2, Ar-H], 5.04 [t, 2H, J = 6.8 Hz, N-CH2-CH2-], 4.57 [s, 3H, N], 2H, J = 5.6 Hz, O-CH2-CH2-], 2.66–2.60 [m, 2H, N-CH2-CH2-CH2-O], 1.29 [s, 9H, C(CH3)3]. 13C NMR (100 MHz, CD3OD): δ [ppm]: 158.08, 152.66, 152.21, 151.75, 148.88, 148.34, 145.96, 129.04, 128.84, 128.20, 124.39, 115.78, 66.58, 62.13, 35.75, 32.72. Melting point: 258–9 °C. HR-MS for C23H30ON2 [MC32+]: calc/m/z = 311.2024 and exp. m/z = 311.2018.

**Physico-chemistry.** The experimental details and related figures are given in the ESI.†

**DFT calculations.** The singlet states of the C232(=C=) with the hybrid meta-GGA approximation with the M06-2X functional and the Gaussian 16 package. The standard 6-311G(d,p) basis set was used throughout. Solvent effects (water) were incorporated with the polarized continuum model (PCM) using default settings and the integral equation formalism.

Frequency calculations were used to confirm that the optimized geometries corresponded to local energy minima on the potential energy surface. The M06-2X/6-311G(d,p) approach in combination with the PCM was found to provide good results for the description of π-stacking interactions of violagen derivatives.**

**EPR spectroscopy.** EPR spectra were recorded on a CAMS 800 EPR spectrometer 8400 and measurements were carried out with solutions of the calixarene-bis-viologen compounds C234+ and C244+, along with their model ligands, namely MC32+ and MC42+, in the absence and in the presence of CB[7]. This study was performed to evaluate whether or not the radical cations were dimerized or segregated depending on the composition of the mixture. The radical cations species were produced chemically by addition of an excess of a reducing agent (e.g., sodium dithionite Na2S2O4). Each solution was prepared at a concentration of ~10−4 M. The EPR data are available in Fig. S17–S20 in the ESI†.

**Electrochemistry.** All the solutions used for the electrochemical experiments were prepared from 0.1 M TBACl aqueous solution with following concentrations of each species: MC24+ (C = 6.3 × 10−5 M), MC34+ (C = 6 × 10−5 M), and C244+ (C = 5 × 10−5 M) with CB[7] (C = 2 × 10−3 M). The setup comprises a Gamry Multipurpose instrument (Reference 600) interfaced to a PC. The experiments were performed using a glassy carbon working electrode (0.071 cm2, BASI). The electrode surface was polished routinely with 0.05 μm alumina–water slurry on a felt surface immediately before use. The counter electrode was a Pt coil and the reference electrode was a Ag/AgCl electrode. Cyclic voltammetry (CV) and square wave (SW) differential pulse voltammetry were carried out at room temperature in an argon-purged H2O solution between 0 V (initial potential) and −1.2 V (final potential). Chronocoulometry experiments were performed upon stepping from 0 to −0.7 V for 10 s before measuring the response signal corresponding to a radical-cation. Then the potential is stepped from −0.7 V to 0 V allowing measurement of the response signal corresponding to the fully oxidized species. The experimental errors on the potential values are ±10 mV.
Results and discussion

Synthesis

Two calix[4]arene systems, namely C23+ and C24+, whereby 2 stands for the number of viologens and 3–4 correspond to the number of carbons of the chain connecting the viologens to the calix[4]arene core (Scheme 1), were synthesized. For a deeper understanding of the host–guest complexation properties of the viologen derivatives with either CB[7] or CB[8], two model compounds, namely MC3+ and MC4+, were also prepared. 4,4′-bipyridine was first monomethylated using 1 equivalent of methyl iodide in acetonitrile leading to 11 with 63% yield. tert-Butyl-phenol was reacted either with 1,3-dibromo-propane or 1,4-dibromo-butane in acetonitrile in the presence of 1 equivalent of potassium carbonate to provide intermediates I2 or I3, respectively. The synthesis of MC3+ and MC4+ was then achieved following the reaction of I2 or I3 with 1-methyl-4,4′-bipyridinium (I1) in CH3CN. The synthesis of the tetrakis-p-tert-butyl-calix[4]arene I4 (63% yield) was achieved by reaction of p-tert-butyl phenol with excess of formaldehyde in the presence of NaOH. As described above, I4 was then reacted with 1,3-dibromo-propane and 1,4-dibromo-butane to lead to intermediates I5 (92% yield) or I6 (65% yield), respectively. Reacting these two calix[4]arene intermediates with I1 then leads to the targeted bis-viologen systems C23+ (85% yield) and C24+ (67% yield). All these viologen derivatives were isolated in the form of mixed iodide/bromide salts.

Characterization of the thread/CB[7] [n]pseudorotaxanes

Recognition of MC3+ and MC4+ by CB[7]. The UV-vis absorption spectrophotometric binding titration of MC3+ (Fig. S1 and S2 in the ESI†) and MC4+ (Fig. S3 and S4 in the ESI†) with CB[7] and their corresponding Job plots provided evidence that MC3++CB[7] and MC4++CB[7] exist as 1:1 stoichiometric host–guest complexes. Both MC3+ and MC4+ are characterized by two main absorptions at ~225 nm and 260 nm (Table 1) that are attributed to the π−π* transitions of the tert-butyl-phenyl and BIPY* chromophoric units, respectively. It was observed that complexation with CB[7] induces a hypochromic shift of the absorption band attributed to the BIPY* transitions, while those of the tert-butyl-phenyl units remain almost unaltered. This suggested that CB[7] is bound to the BIPY* subunit rather than the apparently more hydrophobic alkoxy-tert-butyl-phenyl group. This binding behavior is most likely explained by the weaker affinity of the alkoxy-tert-butyl-phenyl moiety for CB[7] and steric hindrance of its bulky tert-butyl group. The calculated binding constants (log KMC3+:CB[7] = 4.51(6) and log KMC4+:CB[7] = 4.68(5) determined in 0.1 M phosphate buffer, pH 7.0) were found to be lower than that determined for MV2+, most likely as a consequence of statistical effects. In this case, the two pyridinium aromatic faces of MV2+ are not sterically blocked to CB[7], while one side of the bipyridinium units of MC3+ and MC4+ are capped with a tert-butyl-phenyl bulky stopper. Consequently, the KMC3+/KMV2+ (0.16) and KMC4+/KMV2+ (0.24) ratios are close to the statistical value of 0.25. At the higher concentrations that were used for 1H NMR (Fig. S12 and S13 in the ESI†) and the higher CB[7]/MC3+ or CB[7]/MC4+ host–guest titrations provided for ESI-MS measurements (Fig. S8 and S9 in the ESI†), other host–guest complexes were observed, namely the [3]pseudorotaxanes, MC3+⊂(CB[7])2 and MC4+⊂(CB[7])2. For these complexes, the 1H NMR titrations suggested that the second CB[7]...
macrocycle is sitting in close proximity to the tert-butyl-phenyl unit (Fig. 2a). Binding of the first CB[7] indeed mainly affects the β and β’ protons of the BIPY2+ unit, while recognition of the second CB[7] macrocycle influences the protons of the tert-butyl-phenyl residue (Fig. S12 and S13 in the ESI†). The inability to quantify the second recognition event leading to the formation of MC32+(CB[7])2 or MC42+(CB[7])2 by absorption spectrophotometry likely resulted from weak spectral variations and their much lower stability constants.

To gain further insight into the molecular recognition properties, diffusion coefficients were determined by 1H NMR-DOSY for MC32+ and MC42+ both in the absence and in the presence of increasing amounts of CB[7] (Table 2). Firstly, a comparison of the diffusion coefficients of the free MC32+ and MC42+ revealed similar values, which indicated that both model systems share common structural properties (i.e., comparable volume of 303 cm³ mol⁻¹ for MC32+ and 318 cm³ mol⁻¹ for MC42+ estimated with DFT) notwithstanding the slightly elongated carbon spacer for MC42+. Secondly, the values of the diffusion coefficients decreased as a function of the number of equivalents of CB[7], demonstrating the successive formation of host–guest species of increasing volume and weight (e.g., volume of 928 cm³ mol⁻¹ obtained with DFT for MC32+ ⊂ CB[7]). Lastly, the diffusion coefficients measured for MC32+ and MC42+ using the same amount of CB[7] are comparable to one another, which suggested that the [2]pseudorotaxanes, MC32+ ⊂ CB[7] and MC42+ ⊂ CB[7], and the [3]pseudorotaxanes, MC33+ ⊂ (CB[7])2 and MC43+ ⊂ (CB[7])2, are roughly structurally equivalent. The inability to determine the stability constant of [3]pseudorotaxane prevents the evaluation of the diffusion coefficients specific to each inclusion complex (i.e., [2]- and [3]pseudorotaxanes).

Recognition of C23 4+ and C24 4+ by CB[7]. Altogether, absorption binding titrations (Fig. S6 and S7 in the ESI†), 1H-NMR data (Fig. S14 and S15 in the ESI†), and ESI-MS experiments (Fig. S10 and S11 in the ESI†) demonstrated that the [3]pseudorotaxanes, C23 3+ ⊂ (CB[7])2 and C24 4+ ⊂ (CB[7])2, formed predominantly. Hypochromic and bathochromic shifts of the absorption bands which correspond to the π–π* transitions of the BIPY2+ cores were observed in both cases (Table 1) as a consequence of the encapsulation of the terminal BIPY2+ chromophores within the hydrophobic macrocyclic cavity of CB[7]. The absorption bands which correspond to the π–π* transitions for the calix[4]arene core remained unaffected by CB[7] complexation. As previously shown with the model systems, MC32+ and MC42+, the presence of a hydrophobic alkoxy substituent did not alter the molecular recognition properties. As a result, the two CB[7] macrocycles remained bound to the middle of each of the two BIPY2+ terminal electrophores as evidenced by 1H NMR spectroscopy (Fig. S14 and S15 in the ESI†). The apparent stability constants (log Kavo(CB[7])) = 4.5(1) and log Kavo(CB[7]) = 4.44(8) were found to be close

![Image](https://via.placeholder.com/150)

**Fig. 2** Schematic representation of (a) the [2]pseudorotaxanes MC32⊂CB[7] and MC42⊂CB[7] (CB[7] mainly resides on the bipyridinium group) and of MC32⊂(CB[7])2 and MC42⊂(CB[7])2 (i.e., the hydrophobic cavity of the second CB[7] is sitting close to the terminal phenyl group); and (b) the [3]pseudorotaxanes C234⊂(CB[7])2 and C244⊂(CB[7])2 (i.e., the CB[7] mainly resides on the bipyridinium groups). n = 2, or 3. CB[7] is represented with the grey cylinder.

| Viologen V | log Kvos(CB[7]) | V (λ) nm (10⁴ M⁻¹ cm⁻¹) | V⊂CB[7] (λ) nm (10⁴ M⁻¹ cm⁻¹) |
|------------|----------------|--------------------------|-------------------------------|
| MV2+       | 5.30 (2)       | 227 (2.96)/257 (2.06)     | 266 (3.13)/281 (sh)           |
| MC32+      | 4.51 (6)       | 224 (2.29)/259 (2.17)     | 223 (2.49)/255 (1.51)         |
| MC42+      | 4.68 (5)       | 223 (2.17)/260 (2.29)     | 224 (2.48)/252 (1.40)         |
| C234+      | 4.5 (1)        | 223 (4.72)/262 (3.20)     | 223 (5.70)/275 (2.10)         |
| C244+      | 4.44 (8)       | 220 (7.16)/263 (2.99)     | 220 (7.29)/280 (1.83)         |

* Solvent: water buffered at pH 7.0 with 0.1 M Na₂H₂PO₄/NaH₂PO₄; l = 1 cm; T = 25.0(1) °C. The error (indicated in brackets) on the stability constants correspond to 3σ with σ = standard deviation. sh = shoulder.
to those evaluated for the corresponding models, MC32+ and MC42+ (Table 1). Again, these stability constant values were found to be lower than those measured for MV2+ (log $K_{MV^{2+} \rightarrow CB^{+}} = 5.30(2)$) as a consequence of the presence of the bulky calix[4]arene core (Fig. 2b).

Diffusion coefficients were also determined for C234+ and C244+ both in the absence and the presence of CB[7]. In contrast to the values measured for the model ligands, the $D$ value measured for C234+ was found to be lower than that of C244+. One would expect that the extended spacer of C244+ should increase the global volume of the molecule (i.e., DFT calculated volumes of 824 cm$^3$ mol$^{-1}$ for C244+ and 873 cm$^3$ mol$^{-1}$ for C244+), thereby causing it to diffuse slower in solution. This unexpected result thus might be explained by the slightly more flexible arms of C244+ which should minimize the steric interactions of the viologen units with the bulky calix[4]arene core, thereby resulting in markedly different solvation properties with respect to C234+. As a consequence, the diffusion coefficient decreases in the presence of CB[7] for C244+, while it increases for C234+, so that both converge to a comparable value, the volumes of host–guest species with C234+ and C244+ being then globally equivalent in the presence of CB[7].

### Characterization of the radical cations

**Intermolecular versus intramolecular dimerization of the radical cations.** We have demonstrated that MC32+ and MC42+ rapidly pimerize (Fig. S21 and S22 in the ESI†) in aqueous solution with a log $K_{dim}$ value of 3.4. This value is very similar to the value previously determined for the benzyl methyl viologen radical cation BMV+ (log $K_{dim} = 3.46(5)$), but much higher than that reported for the methyl viologen radical cation MV+ (log $K_{dim} = 2.5$).69,70 The values of $K_{dim}$ are also similar to those measured for viologens decorated with hydrophobic alkyl substituents.69 This suggested that increasing the hydrophobicity around the BIPY2+ unit with aryl/alkyl substituents favors the intermolecular pimerization in aqueous solution. Moreover, we could again demonstrate that the extended spacer for MC42+ does not drastically alter its pimerization since similar $K_{dim}$ values were calculated for MC32+ and MC42+. These two radical cations are characterized by intense and structured absorption bands in the visible region (MC32+: $\lambda_{max} \sim 602$ nm, $\varepsilon_{602} = 1.01 \times 10^4$ M$^{-1}$ cm$^{-1}$; MC42+: $\lambda_{max} \sim 602$ nm, $\varepsilon_{602} = 9.56 \times 10^4$ M$^{-1}$ cm$^{-1}$, Fig. S21 and S22 in the ESI†), in agreement with the spectroscopic parameters determined for MV+ (600–606 nm)$^{15,23,67,71}$ and BMV+ (600 nm).30 Formation of the radical cations induced a significant hypsochromic shift of the absorption band at ~600 nm ($\Delta \lambda \sim 50$ nm) and gave rise to intense absorption bands corresponding to radical–radical transitions in the NIR region ($\lambda_{max} > 850–900$ nm).15 These UV-vis absorption studies also demonstrated that no significant pimerization occurs unless the concentration of the radical cations is high enough (>10$^{-3}$ M, Fig. S21 and S22 in the ESI†). As previously reported,11–17 preorganization of the BIPY2+ electron donors to within close proximity of one another around a robust and inert molecular platform can enhance their pimerization, leading to very stable $\pi$-dimers in aqueous solution.

Upon chemical generation of the radical cations, C232(+) and C242(+) (Fig. S27 and S28 in the ESI†), intense absorption bands appeared at ~530 nm (Fig. 3). An additional intense absorption band centered at 1072 nm for C232(−) and at 925 nm for C242(−) were observed and are unambiguously assigned to the intramolecular charge resonance that occurs in the dimerized viologen radical cation species. This feature indicated that a two-electron reduction of C234+ and C244+ leads to two radical dvalent cations, C232(±) and C242(±), that spontaneously pimerize intramolecularly, leading to a stable radical dimeric species.

The NIR absorption spectroscopic signatures of the $\pi$-dimerized complexes were demonstrated to be closely related to the extent of overlapping between both $\pi$-orbitals of the BIPY+ radicals.45 When a propyloxy chain links the viologens to the calix[4]arene moiety (C232(±)): $\lambda_{max} \sim 960$ nm in CH$_3$CN and $\lambda_{max} \sim 1070$ nm in water), DFT calculations at the BLYP-D3/
DZVP level suggested that only one pyridinium ring per viologen radical is involved in the intramolecular \( \pi \)-dimerization process. This result, which is imposed by geometric constraints that is inherent to the length and structure of the propyl chain, is not observed with the ethyloxy-derived calix[4]arene-bis-viologen (C\( _{22} \)\( _{2} \)\( ^{2+} \)), \( \lambda_{\text{max}} \sim 860 \) nm in CH\( _{3} \)CN\( ^{+} \)), which affords a fully face-to-face stacked arrangement. DFT calculations performed at the M06-2X/6-311G(d,p) level (Fig. 4) provided a minimum energy conformation for C\( _{22} \)\( _{2} \)\( ^{2+} \) in which the two BIPY\( ^{+} \) units display an almost perfect face-to-face interaction. Similarly, the BIPY\( ^{+} \) units in C\( _{23} \)\( _{2} \)\( ^{2+} \) are twisted with respect to each other by an angle of \( \sim 78^{\circ} \), reducing the overlap between the corresponding \( \pi \)-orbitals. Increasing the length from 3 to 4 carbons (butyloxy derivative, C\( _{24} \)\( _{2} \)\( ^{2+} \)), \( \lambda_{\text{max}} \sim 925 \) nm in water) does not completely reinstate the face-to-face dimerized \( \pi \)-stacking orientation, but it does increase the overlap of the \( \pi \)-orbitals with respect to C\( _{23} \)\( _{2} \)\( ^{2+} \) with a twist angle of \( \sim 60^{\circ} \). Thus, the nature and size of the linker between the calix[4]arene platform and the terminal BIPY\( ^{+} \) radical cations, as well as the nature of the platform, with the calix[4]arene displaying a cone conformation, appear to be crucial factors that govern the arrangement of the \( \pi \)-dimers. It is noteworthy that preorganization of the designed systems apparently allows for efficient intramolecular dimerization of the two viologens upon reduction in a range of solvents (e.g., water and CH\( _{3} \)CN\( ^{+} \))

Reduction of the [\( n \)]pseudorotaxanes with CB\( ^{7} \)

Monocationic monoradicals MC\( _{3} \)\( ^{2+} \) and MC\( _{4} \)\( ^{2+} \). Cyclic voltammetry (Fig. S16 in the ESI†), square-wave voltammetry (Fig. 5), and EPR (Fig. S17 and S18 in the ESI†) measurements in phosphate-buffered solutions at pH 7 were performed on the model systems, MC\( _{3} \)\( ^{2+} \) and MC\( _{4} \)\( ^{2+} \), in the absence and presence of CB\( ^{7} \). Both systems were characterized by two successive one-electron reversible redox waves: \( E_{1/21} (\text{MC} \ _{3} \ ^{2+} / \text{MC} \ _{3} \ ^{+}) = -0.56 \) V and \( E_{1/22} (\text{MC} \ _{3} \ ^{+} / \text{MC} \ _{3} \ ^{0}) = -0.83 \) V; \( E_{1/21} (\text{MC} \ _{4} \ ^{2+} / \text{MC} \ _{4} \ ^{+}) = -0.56 \) V and \( E_{1/22} = -0.83 \) V. In the presence of three equivalents of CB\( ^{7} \), where it is assumed that MC\( _{3} \)\( ^{2+} \)\( _{3} \)CB\( ^{7} \) and MC\( _{4} \)\( ^{2+} \)\( _{3} \)CB\( ^{7} \) predominate, both redox waves shifted slightly to more negative potentials (Table 3) while retaining their reversible shapes.

These shifts corresponded to the signatures of the relative affinities of CB\( ^{7} \) for the different redox states of the model systems. Assuming a \( K_{\text{MC} \ _{3} ^{2+} \text{CB} \ ^{7}} \) value of 4.51(6) for MC\( _{3} \)\( ^{2+} \)\( _{3} \)CB\( ^{7} \) (Fig. S1 in the ESI†), a \( K_{\text{MC} \ _{4} ^{2+} \text{CB} \ ^{7}} \) of \( \sim 4 \)–4.2

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Fig. 4 Geometries obtained with DFT (M062X/6-311G(d,p)) (left panel), the corresponding HOMOs (central panel) and detail of the arrangements of the redox-active BIPY\( ^{+} \) units within the two electrons reduced calix[4]arene-bis-viologens C\( _{22} \)\( _{2} \)\( ^{2+} \), C\( _{23} \)\( _{2} \)\( ^{2+} \) and C\( _{24} \)\( _{2} \)\( ^{2+} \) that undergo intramolecular pimerization.
and a $K_{MC3^{+}\text{CB}[7]}$ of $3.5$–$3.9$ values were accordingly calculated. Similarly, using a $K_{MC4^{+}\text{CB}[7]}$ value of 4.68(5) (Fig. S3 in the ESI†), a $K_{MC4^{+}\text{CB}[7]}$ of $3.8$ was calculated. Using an electrochemical approach, these calculated values were in reasonably good agreement, within error, with those derived from direct absorption binding titrations ($K_{MC3^{+}\text{CB}[7]} = 3.8$ (Fig. S24 in the ESI†) and $K_{MC4^{+}\text{CB}[7]} = 4.54(5)$ (Fig. S26 in the ESI†). In contrast to BMV$^{2+}$, where translational motion of the CB[7] macrocycle occurred upon electrochemical reduction of the bipyridinium unit, the CB[7] macrocycle remained firmly bound to the BIPY$^{2+}$ electroactive units of the MC$^{4+}$ derivatives regardless of their oxidation state.

Assuming that only the first one-electron reduction process dominates from 0 V to $-0.7$ V (Fig. S16 in the ESI† and Fig. 5), the diffusion coefficients of MC3$^{2+}$ and MC4$^{2+}$ in the absence and in the presence of CB[7] (Table 4) can be evaluated by chronocoulometric experiments. The differences observed between the values of the diffusion coefficients of MC3$^{+}$/MC3$^{2+}$ and MC4$^{+}$/MC4$^{2+}$ could be an indication of the dimerization of the model systems upon the one-electron reduction reactions. Addition of CB[7] suppresses the pimerization process in favor of the inclusion complexes. As a consequence, the inclusion complexes with CB[7] have lower diffusion coefficients than the corresponding free viologens.

Investigations of the UV-vis-NIR absorption spectra of MC3$^{2+}$ and MC4$^{2+}$ in water at pH 7.0 in the absence or in the presence of a reducing agent were carried out to evaluate the effect of CB[7] addition (Fig. S23 and S25 in the ESI†). MC3$^{+}$+CB[7] and MC4$^{+}$+CB[7] both clearly exhibited a significant hypochromic shift of the visible absorption band associated with the radical cation with increasing concentration of CB[7], strong evidence for the inclusion of the BIPY$^{2+}$ radical cation within the hydrophobic cavity of CB[7]. This binding event effectively hampers radical cation pimerization.

Bisradicals C23(4+)$ and C24(2+)$, Cyclic (Fig. S16 in the ESI†) and square wave (Fig. 6) voltammetry studies were undertaken to evaluate the impact of CB[7] addition on the intramolecular pimerization of the BIPY$^{2+}$ radical cations of the calix[4]arene-viologens, C23$^{4+}$ and C24$^{4+}$. The electrochemical data clearly showed two distinct and reversible redox waves. The relative amplitudes and shapes of the peaks for each wave at the anode (oxidation) are similar to those observed at the cathode (reduction). Such a pattern is an indication of the redox reversibility of the system.

**Table 3** Values of $E_{1/2}$ (in V) for MC3$^{2+}$ (0.05 mM), MC4$^{2+}$ (0.063 mM), C23$^{4+}$ (0.05 mM) and C24$^{4+}$ (0.05 mM) measured by cyclic voltammetry (CV) and square wave voltammetry (SWV) in the absence and in the presence of 3 equivalents of CB[7] for MC3$^{2+}$, MC4$^{2+}$ and C23$^{4+}$, and 4 equivalents of CB[7] for C24$^{4+}$.

| Species | $E_{1/2}$ (CV) | $E_{1/2}$ (SW) |
|---------|---------------|---------------|
| MC3$^{2+}$ | $-0.56$ V | $-0.56$ V |
| MC3$^{2+}$+3 eq. CB[7] | $-0.60$ V | $-0.59$ V |
| MC4$^{2+}$ | $-0.56$ V | $-0.56$ V |
| MC4$^{2+}$+3 eq. CB[7] | $-0.58$ V | $-0.58$ V |
| C23$^{4+}$ | $-0.42$ V | $-0.43$ V |
| C23$^{4+}$+3 eq. CB[7] | $-0.44$ V | $-0.46$ V |
| C24$^{4+}$ | $-0.45$ V | $-0.47$ V |
| C24$^{4+}$+4 eq. CB[7] | $-0.50$ V | $-0.51$ V |

**Table 4** Diffusion coefficients $D$ ($\text{cm}^2 \text{s}^{-1}$) of MC3$^{2+}$, MC4$^{2+}$, C23$^{4+}$ and C24$^{4+}$ measured by chronocoulometry in H$_2$O (0.1 M TBACl) in the absence and the presence of CB[7]. The errors on these values are 10%.

| No CB[7]/D | +CB[7]/D |
|------------|----------|
| MC3$^{+}$/0.7 $\times$ 10$^{-5}$ | MC3$^{+}$/2 eq. CB[7]/1.9 $\times$ 10$^{-5}$ |
| MC3$^{2+}$/5.4 $\times$ 10$^{-5}$ | MC3$^{2+}$/2 eq. CB[7]/14.2 $\times$ 10$^{-5}$ |
| MC4$^{+}$/3.1 $\times$ 10$^{-5}$ | MC4$^{+}$/2 eq. CB[7]/6.2 $\times$ 10$^{-5}$ |
| C23$^{4+}$/1.41 $\times$ 10$^{-5}$ | C23$^{4+}$/3 eq. CB[7]/2.9 $\times$ 10$^{-5}$ |
| C23$^{4+}$/7.58 $\times$ 10$^{-5}$ | C23$^{4+}$/3 eq. CB[7]/3.91 $\times$ 10$^{-5}$ |
| C24$^{4+}$/8.01 $\times$ 10$^{-5}$ | C24$^{4+}$/4 eq. CB[7]/0.16 $\times$ 10$^{-5}$ |
| C24$^{4+}$/20.1 $\times$ 10$^{-5}$ | C24$^{4+}$/4 eq. CB[7]/42.1 $\times$ 10$^{-5}$ |

Fig. 5 Square wave voltammograms of (a) MC3$^{2+}$, [MC3$^{2+}$] = 0.05 mM and b) MC4$^{2+}$, [MC4$^{2+}$] = 0.06 mM in the absence (orange) and the presence of CB[7] (blue, 3 equivalents of CB[7]). All voltammograms were recorded in argon-purged phosphate buffer solutions (pH 7) at 298 K (E versus Ag/AgCl).
The square wave voltammograms of C234+ and C244+ (Fig. 6) displayed two reversible two-electron reduction processes: \( E_{1/2}^{\text{i}} (C23^{4+} \rightarrow C23^{2+}) = -0.43 \text{ V} \) and \( E_{1/2}^{\text{j}} (C23^{2+} \rightarrow C23^{0}) = -0.85 \text{ V} \). Interestingly, for the [3]pseudorotaxanes, C234+ ↔[CB[7]]2 and C244+ ↔[CB[7]]2, no shifts were observed for the second reduction wave (Table 3), which would have corresponded to the following electrochemical processes: C234+ ↔[CB[7]]2 \( \Rightarrow C23^{0} ↔[CB[7]]_{2} \). Rather, our observations indicated that after the first two-electron reduction process, the threads behave as if they are unbound C232(c) and C242(c). In other words, the first reduction of C234+ ↔[CB[7]]2 and C244+ ↔[CB[7]]2 induced dethreading of the [CB[7]] macrocycles, which is spontaneously followed by intramolecular dimerization of the two terminal BIPY+ groups, leading to the formation of intramolecular dimeric species, C232(c) and C242(c). These results were consistent with the absorption spectrophotometric analyses (Fig. S27 and S28 in the ESI†) and EPR behavior (Fig. S19 and S20 in the ESI†) of the C234+/[CB[7]] and C244+/[CB[7]] [3] pseudorotaxanes.

Chromocoulometry was also used to evaluate the diffusion coefficients of the fully oxidized and radical cationic states of the different species in aqueous solution. During the two electron reduction process \( (0 \text{ V} \rightarrow -0.7 \text{ V}) \) the fully oxidized species predominate and diffuse to the electrode surface where they are reduced. By measuring the reduction rates, the diffusion constants for C234+ and C244+ species can be calculated in the absence and in the presence of [CB[7]] (Table 4). Alternatively, by setting the voltage to \(-0.7 \text{ V}\) and performing the oxidation process, the rates of oxidation and the diffusion coefficients of the corresponding radical cationic states can be measured as well. In the absence of [CB[7]], larger diffusion coefficients were observed for C234+ and C244+ than for their corresponding fully reduced forms. This could be explained by the ability of higher charged species to diffuse faster towards or away from an electrode. In the presence of [CB[7]], larger diffusion coefficients were measured for the [3]pseudorotaxanes C234+ ↔[CB[7]]2 and C234+ ↔[CB[7]]2 than the corresponding reduced species (i.e., upon reduction, a dethreading of the [CB[7]] occurs as a consequence of favored intramolecular pimerization with respect to the recognition process). Here also, one would expect that the [3]pseudorotaxanes C234+ ↔[CB[7]]2 and C234+ ↔[CB[7]]2 display larger hydrodynamic size by comparison with C233(c) or C24(c). Markedly different solvation of the latter species is suggested to explain these peculiar properties. The close diffusion coefficients of the radical cation species in the absence and the presence of [CB[7]] indicate that the dimerization of the viologen radical cations induce a dethreading of the [CB[7]] macrocycles.

Recognition of the viologen derivatives by [CB[8]]. The characterization of the host–guest complexes formed between MC32+, MC42+, C234+, and C244+ with [CB[8]] was investigated by absorption spectrophotometry (Fig. S29 to S32 in the ESI†) and ESI-MS measurements (Fig. 7). Due to the limited solubility of [CB[8]], we were not able to perform 1H NMR titrations of the corresponding viologens. Similarly to the [n]pseudorotaxanes formed with [CB[7]], we were able to observe evidence for the formation of [2]pseudorotaxanes with MC32+ and MC42+ (namely MC32+ ↔[CB[8]] and MC42+ ↔[CB[8]]), and [3]pseudorotaxanes with C234+ and C244+ (namely a C234+ ↔[CB[8]]2 and C244+ ↔[CB[8]]2).

For the latter [3]pseudorotaxanes, chemical reduction of the BIPY2+ electroactive units led to dethreading of the [CB[8]] macrocyclic host despite its larger cavity size (Fig. S31 and S32 in the ESI†). This suggests significant steric constraints with the calix[4]arene platform and/or poor flexibility of the designed systems even though longer and apparently more flexible spacers were introduced. However, the MC32+ and MC42+ models clearly led (Fig. S29 and S30 in the ESI†) to the expected [3]pseudorotaxanes (MC32+ ↔[CB[8]] and MC42+ ↔[CB[8]]) thus emphasizing the detrimental role of the anchoring platform rather than the length of the spacers. The occurrence of [3] pseudorotaxanes (MC32+ ↔[CB[8]] and MC42+ ↔[CB[8]] upon reduction is in agreement with the published reports the stability of methyl viologen dimer (MV2+)2 ↔[CB[8]] was significantly increased in the presence of [CB[8]].
following the formation of a 2 : 1 (MV+)=CB[8]) supramolecular complex in water.

Conclusions

Two calix[4]arene-bis-viologen systems, namely C23+ and C24+, were synthesized. The host–guest properties were extensively studied using a large set of analytical methods and led to the characterization of [3]pseudorotaxanes in combination with either CB[7] or CB[8]. For each of these host–guest species, CB[7] or CB[8] was demonstrated to reside in the middle of the BIPY2+ cations as a result of steric interactions with the anchoring platform. Upon reduction of the terminal BIPY2+ cations, these [3]pseudorotaxanes spontaneously dissociate as the result of a strong intramolecular dimerization of the two face-to-face viologen radical cations. The arrangement of the BIPY2+ radical cations within the dimeric species seemingly relies on the length of the spacer that links the electroactive units to the anchoring moiety. Dethreading and dimerization do not occur in experiments involving CB[7] (or CB[8]) and either of the two monomeric viologen guests MC32+ and MC42+, which were used as models. On the other hand, the model compounds provided unexpected and valuable properties. Thanks to the presence of a alkoxy-phenyl substitution, [3] pseudorotaxanes spontaneously dissociate as the result of a strong intramolecular dimerization of the two face-to-face viologen radical cations. The arrangement of the BIPY2+ radical cations within the dimeric species seemingly relies on the length of the spacer that links the electroactive units to the anchoring moiety. Dethreading and dimerization do not occur in experiments involving CB[7] (or CB[8]) and either of the two monomeric viologen guests MC32+ and MC42+, which were used as models. On the other hand, the model compounds provided unexpected and valuable properties. Thanks to the presence of a alkoxy-phenyl substitution, [3] pseudorotaxanes spontaneously dissociate as the result of a strong intramolecular dimerization of the two face-to-face viologen radical cations.

Acknowledgements

M. E. thank the CNRS (LIMA, UMR 7042) and the University of Strasbourg for funding this research work. C. P.-I. acknowledges Centro de Supercomputación de Galicia (CESGA) for providing access to supercomputing facilities. A. T. thank NYUAD for its generous support of the research program at NYUAD.

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