Solution-Phase Mechanistic Study and Solid-State Structure of a Tris(bipyridinium radical cation) Inclusion Complex

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INTRODUCTION

Noncovalent donor–acceptor charge-transfer (CT) interactions, which occur between π-electron-poor 1,1-dialkyl-4,4′-bipyridinium (BIPY•+) dications and a range of neutral π-electron-rich compounds have been known since at least the 1960s. Since these times, the blossoming of the systematic investigation of noncovalent bonding interactions in general that followed hard on the heels of the discovery of the crown ethers by Pedersen led directly to the development of host–guest chemistry by Cram and the ushering in of chemistry beyond the molecule, later to become known as supramolecular chemistry at the suggestion of Lehn. Both host–guest and supramolecular chemistry have evolved to embrace inclusion complexes of many different types, including those of a donor–acceptor nature where BIPY•+ units fulfill the role of guests in some cases and of components of hosts in others. The large collection of stable donor–acceptor complexes involving

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Supporting Information

ABSTRACT: The ability of the diradical dicatonic cyclobis(paraquat-p-phenylene) (CBPQT2•+,•+) ring to form inclusion complexes with 1,1-dialkyl-4,4′-bipyridinium radical cationic (BIPY•+) guests has been investigated mechanistically and quantitatively. Two BIPY•+ radical cations, methyl viologen (MV•+) and a dibutyl derivative (V•+), were investigated as guests for the CBPQT2•+,•+ ring. Both guests form triradical complexes, namely, CBPQT2•+,•+MV•+ and CBPQT2•+,•+V•+, respectively. The structural details of the CBPQT2•+,•+MV•+ complex, which were ascertained by single-crystal X-ray crystallography, reveal that MV•+ is located inside the cavity of the ring in a centrosymmetric fashion: the 1:1 complexes pack in continuous radical cation stacks. A similar solid-state packing was observed in the case of CBPQT2•+,•+ by itself. Quantum mechanical calculations agree well with the superstructure revealed by X-ray crystallography for CBPQT2•+,•+MV•+ and further suggest an electronic asymmetry in the SOMO caused by radical-pairing interactions. The electronic asymmetry is maintained in solution. The thermodynamic stability of the CBPQT2•+,•+MV•+ complex was probed by both isothermal titration calorimetry (ITC) and UV/vis spectroscopy, leading to binding constants of (5.0 ± 0.6) × 104 M−1 and (7.9 ± 5.5) × 104 M−1, respectively. The kinetics of association and dissociation were determined by stopped-flow spectroscopy, yielding a k and k of (2.1 ± 0.3) × 106 M−1 s−1 and 250 ± 50 s−1, respectively. The electrochemical mechanistic details were studied by variable scan rate cyclic voltammetry (CV), and the experimental data were compared digitally with simulated data, modeled on the proposed mechanism using the thermodynamic and kinetic parameters obtained from ITC, UV/vis, and stopped-flow spectroscopy. In particular, the electrochemical mechanism of association/dissociation involves a biradical tetracation intermediate CBPQT2•+,•+CV•+ inclusion complex; in the case of the V•+ guest, the rate of dissociation (k = 10 ± 2 s−1) was slow enough that it could be detected and quantified by variable scan rate CV. All the experimental observations lead to the speculation that the CBPQT2•+,•+ ring of the biradical tetracation complex might possess the unique property of being able to recognize both BIPY•+ radical cation and π-electron-rich guests simultaneously. The findings reported herein lay the foundation for future studies where this radical–radical recognition motif is harnessed particularly in the context of mechanically interlocked molecules and increases our fundamental understanding of BIPY•+ radical–radical interactions in solution as well as in the solid-state.

Received: September 23, 2011
Published: December 9, 2011

Bipy2+ as π-electron-poor acceptors alongside a suite of π-electron-rich donors has resulted in the use of donor–acceptor interactions to template the formation of the mechanical bond,12 paving the way for the development14 of mechanically interlocked molecules (MIMs) such as catenanes13 and rotaxanes.16 The introduction of bistability into these MIMs has transformed them from being intellectual curiosities into functioning molecular switches, which have been incorporated into integrated systems as disparate as molecular electronic devices17 (MEDs) in addressable memories18 based on crossbar architectures, artificial molecular muscles19 as examples of nanoelectromechanical systems (NEMS), and mechanized mesoporous silica nanoparticles (MSNPs) for drug delivery.20

The radical chemistry of compounds containing Bipy2+ units has been well documented21 in the scientific literature since the 1930s. They have been referred to commonly21b as viologen radicals known22,23 for over 40 years to undergo dimerization, nanes15 and rotaxanes.16 The introduction of bistability into these MIMs has transformed them from being intellectual curiosities into functioning molecular switches, which have been incorporated into integrated systems as disparate as molecular electronic devices17 (MEDs) in addressable memories18 based on crossbar architectures, artificial molecular muscles19 as examples of nanoelectromechanical systems (NEMS), and mechanized mesoporous silica nanoparticles (MSNPs) for drug delivery.20

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Although many examples of donor–acceptor recognition motifs have been described in the literature, relatively few radical–radical interaction complexes have been reported in communications and papers.

The structural formulas (Scheme 2) represent the formation of the [2+pseudorotaxane CBPQT2(+)⊂CMV2+], along with the simplified schematic of the redox-induced complexation processes, are illustrated in Scheme 2. Previously, we have shown26 both experimentally and theoretically in solution that, because only two of the Bipy2+ radical cations of the complex are spin-paired at any given time, there are many possible permutations of interactions that can occur. Hence, to understand how these molecules can function as molecular switches, it is important to understand the nature of the interactions that exist between the radical cation pairs.
given time, the third unpaired BIPY*+ radical cation of the complex is not as strongly engaged in radical–radical interactions. This fact has important repercussions for the redox-induced mechanism of switching, which will be discussed in detail later on in this paper. Reoxidation of the complex results in its dissociation into its constituent components. Overall, the complexation and decomplexation processes are reversible.

**X-ray Crystallography.** Single crystals of the CBPQT2[2+]⊂MV2+ complex were grown from MeCN using slow vapor diffusion of iPr2O inside a glovebox at room temperature. Zinc dust was used to bring about the reduction of CBPQT4+ and MV2+ to their respective radical cationic forms. (For a general procedure on the use of zinc dust as a reducing agent, see the Experimental Section). The solid-state structure, as determined by X-ray crystallography, demonstrates (Figure 1) the formation of the trisradical tricationic complex. The inclusion complex was observed to be associated with three PF6− counterions in the solid state, supporting the hypothesis that each of the BIPY2+ units indeed has been reduced to their radical cationic form, BIPY*+. The MV2+ radical cation is situated inside the cavity of the CBPQT2[2+]⊂MV2+ ring in a centrosymmetric fashion, with 3.22 Å centroid-to-centroid separation from each of the BIPY*+ radical cation subunits of the cyclophane. The axis defined by the central aryl–aryl C–C bond in the MV2+ radical cation subtends an angle of 14° (Figure 1b) with the axis orthogonal to the plane defined by the four N atoms of the ring. We surmise that this deviation from orthogonality maximizes the amount of π-overlap between MV2+ and CBPQT2[2+]. This deviation from orthogonality observed in the solid state for the CBPQT2[2+]⊂MV2+ complex is in good agreement (vide infra) with that predicted from theoretical calculations. Virtually no torsional twisting of any of the three BIPY*+ units of the complex about their 4,4'-C–C bond is apparent, a phenomenon that is not observed for the CBPQT3+ ring in its fully oxidized form. This almost complete lack of torsional twists is consistent, however, with the solid-state structure of the MV2+ radical cation reported previously. The extended superstructure reveals (Figure 1c) a continuous BIPY*+ radical cation π-stack, with adjacent complexes aligned in register. A centroid-to-centroid separation of 3.28 Å characterizes the distance between the BIPY*+ radical cation subunits of the CBPQT2[2+]⊂MV2+ complex. The PF6− counterions are observed to occupy (Figure 1d) the space between adjacent stacks. In particular, close contact (~2.6 Å) of the fluorines with the hydrogen atoms of the methylene groups and those of the α and β carbons of the CBPQT2[2+] ring are observed. In all, this type of continuous radical cation stack is similar to that reported by Kochi in 1990 for the MV2+ radical cation in the solid state.

We have also investigated the crystal growth of the CBPQT2[2+] diradical dication alone in solution. Crystals were obtained from slow vapor diffusion of iPr2O into a solution of the diradical dication in MeCN all inside of a glovebox. Remarkably, long, dark, opaque needle-like crystals up to three centimeters in length were observed after less than a week of crystal growth. Single-crystal X-ray analyses revealed (Figure 2) that CBPQT2[2+] crystallizes with two PF6− counterions, confirming its diradical dicaticonic nature. Once again, virtually no torsional twisting was observed in the BIPY*+ units of the CBPQT2[2+] ring, an observation that is consistent with that already observed for the trisradical complex. The centroid-to-centroid transannular distance spanning the gap between the planes of the two BIPY*+ units of the ring is 6.92 Å, a remarkably longer distance compared with that (6.43 Å) present in the trisradical complex.
order to accommodate the MV\(^+\) to expand in size in one direction while contracting in the other in

by the inclusion of MV\(^+\) porous channels formed by the diradical dicationic ring

The centroid-to-centroid transannular separation between the phenylene units, which was observed in the solid-state structure of the CBPQT\(^{2(\ast \ast)}\) ring, is 10.2 Å and may be contrasted with the analogous distance of 10.3 Å for the trisradical complex. These observations indicate that the CBPQT\(^{2(\ast \ast)}\) ring is able to expand in size in one direction while contracting in the other in

in order to accommodate the MV\(^+\) guest in such a way that the bowing of the BIPY\(^+\) units of the ring is reduced. The decreased degree of bowing of the BIPY\(^+\) units brought about by the inclusion of MV\(^+\) in the CBPQT\(^{2(\ast \ast)}\) ring serves to increase the distance between the phenylene units of the ring in the complex. Reminiscent of the way the trisradical complex packs in the solid state, the superstructure reveals a continuous

stack of CBPQT\(^{2(\ast \ast)}\) rings. A centroid-to-centroid separation between the BIPY\(^+\) units of adjacent CBPQT\(^{2(\ast \ast)}\) rings of 3.12 Å is observed along with a packing structure that is aligned in register, that is, no angle of offset between adjacently stacked rings is observed. The cavities of the rings arrange themselves in such a way as to form (Figure 2b) continuous porous channels that run the whole length of the crystal, with the PF\(_6^-\) counterions occupying the spaces between the rings. In a fashion similar to that of the trisradical complex, close contact (∼2.6 Å) of the fluorine atoms with the α, β, and methylene protons of the CBPQT\(^{2(\ast \ast)}\) ring is observed (Figure 2c).

Overall, the superstructure is consistent with our understanding of the nature of BIPY\(^+\) radical–radical interactions, which serve to “stitch” the CBPQT\(^{2(\ast \ast)}\) rings together into stacks.

Quantum Mechanical Calculations. In order to gain a better understanding of the nature of the binding in CBPQT\(^{2(\ast \ast)}\)•CMV\(^+\), we have previously used\(^{26a}\) density functional theory\(^{35}\) of the M06 flavor\(^{34}\) to provide a quantum mechanical description of the binding in the superstructure. The superstructure for [CBPQT\(^{2(\ast \ast)}\)•CMV\(^+\)]\([3PF_6^-]\) was minimized at the M06/6-31G** level, as depicted in Figure 3a. The calculated superstructure (Figure 3a) agrees well with that determined experimentally from X-ray crystallography, namely, that MV\(^+\) resides inside the cavity of the CBPQT\(^{2(\ast \ast)}\) ring at an angle offset to the axis perpendicular to the plane defined by the four nitrogen atoms of the ring. Natural population analysis\(^{35}\) of the inclusion complex shows that the charges on the CBPQT\(^{2(\ast \ast)}\) and MV\(^+\) fragments are +1.71 and +1.18, respectively, which suggests some degree of charge transfer from the guest to the host. The asymmetry of the complex is also corroborated by the singly occupied molecular orbital (SOMO) being preferentially distributed (Figure 3b) over one of the two BIPY\(^+\) units of the CBPQT\(^{2(\ast \ast)}\) ring. This electronic asymmetry in the SOMO supports our hypothesis (vide infra) that, as a consequence of radical pairing, one BIPY\(^+\) unit of the CBPQT\(^{2(\ast \ast)}\) ring is not interacting as strongly with the MV\(^+\) guest. As a result, this weaker interaction of one BIPY\(^+\) unit of the CBPQT\(^{2(\ast \ast)}\) ring leads to a bisradical tetracationic CBPQT\(^{2(\ast \ast)}\)•CMV\(^+\) intermediate in the electrochemical mechanism of formation. In addition, the MV\(^+\) guest in the

![Figure 2](image1)

**Figure 2.** Solid-state superstructure of the diradical dication CBPQT\(^{2(\ast \ast)}\) ring obtained by single-crystal X-ray crystallography. (a) In common with the trisradical CBPQT\(^{2(\ast \ast)}\)•CMV\(^+\) inclusion complex, the CBPQT\(^{2(\ast \ast)}\) solid-state superstructure reveals a stack of CBPQT\(^{2(\ast \ast)}\) rings along the α crystallographic axis maintained by interactions between its BIPY\(^+\) constituent subunits. The counterions, PF\(_6^-\), have been omitted for clarity. (b) A wireframe representation of the solid-state superstructure of CBPQT\(^{2(\ast \ast)}\), depicting the porous channels formed by the diradical dicationic ring’s unoccupied interiors. (c) Side-on view of the X-ray structure of the CBPQT\(^{2(\ast \ast)}\) revealing the superstructure and relative positioning of the PF\(_6^-\) counterions.

![Figure 3](image2)

**Figure 3.** Results from quantum mechanical calculations of the trisradical CBPQT\(^{2(\ast \ast)}\)•CMV\(^+\) complex minimized at the M06/6-31G** level of DFT. (a) Calculated structure (side view) of the trisradical CBPQT\(^{2(\ast \ast)}\)•CMV\(^+\) complex with the PF\(_6^-\) counterions omitted for clarity. (b) Character of the singly occupied molecular orbital (SOMO), where positive and negative phases are shaded blue and red. The SOMO is asymmetrically distributed toward the top BIPY\(^+\) radical cation subunit of the CBPQT\(^{2(\ast \ast)}\) ring component, a distribution of which is likely exaggerated by the asymmetry in the locations of the PF\(_6^-\) counterions. In the ball-and-stick representation of the framework, C is black, N is blue, F is green, and P is purple.
calculated structure is located ~0.14 Å closer to one of the BIPY\(^{+}\) units in the CBPQT\(^{2(+)}\) ring. Additional polarization affects brought about by the asymmetric positioning of the three \(\text{PF}_{6}^{-}\) counterions may act to further exacerbate this distribution of electron density in the SOMO as well as influence the location of the guest within the host. The fact that the crystal structure reveals that the MV\(^{+}\) guest resides equidistant from either side of the BIPY\(^{+}\) units of the CBPQT\(^{2(+)}\) ring is most likely a consequence of the continuous radical–radical packing superstructure, with the \(\text{PF}_{6}^{-}\) counterions symmetrically placed on either side of each complex, which probably serves to "wash-out" this asymmetry in the solid state. We hypothesize that the electronic asymmetry predicted by theory continues to live-on in the solution phase, where no such stacking of complexes is occurring.

**Isothermal Titration Calorimetry.** Thermodynamic parameters governing the stability of the trisradical complex in solution have been obtained by performing ITC experiments at room temperature in MeCN under the inert conditions provided by a glovebox. Solutions of CBPQT\(^{2(+)}\) and MV\(^{+}\) were prepared individually using zinc dust as the reducing agent. The results (Figure 4) confirm the 1:1 stoichiometry of the complex and reveal an association constant \((K_a)\) of \((5.0 \pm 0.6) \times 10^9 \text{ M}^{-1}\). As expected, the binding is enthalpically driven by a \(\Delta H\) value of \(-15.2 \pm 0.5 \text{ kcal mol}^{-1}\) for an entropic cost of \(-29.3 \pm 1.6 \text{ kcal mol}^{-1} \text{ K}^{-1}\) in \(\Delta S\). The free energy of formation \(\Delta G\) at 298 K is \(-6.41 \pm 0.07 \text{ kcal mol}^{-1}\). By comparison with the free energies of formation determined\(^{36}\) under identical conditions for classical donor–acceptor complexes involving the fully oxidized tetracationic CBPQT\(^{4+}\) ring and the \(\pi\)-electron-rich guests, 1,5-bis-[2-(2-hydroxyethoxy)ethoxy]-naphthalene (BHEEN) \((\Delta G = -6.26 \pm 0.04 \text{ kcal mol}^{-1}\) and 2-[2-[2-[2-(2-hydroxyethoxy)ethoxy]methyl]-1,3-dithiol-2-ylidene]-1,3-dithiol-4-y]methoxy[ethoxy][ethoxy]ethanol (a bis(diethylene glycol)|tetrafluorovulene derivative) \((\Delta G = -7.66 \pm 0.07 \text{ kcal mol}^{-1}\) ), one finds that the binding energy is on a par with these complexes. In these donor–acceptor complexes, a significant amount of the binding energy comes\(^{37}\) from [C–H–O] interactions involving particularly the terminal oxygen atoms of the oligo(ethylene glycol) chains to the hydrogen atoms of the \(\alpha\) carbons in the ring. The additional affinity gained from these [C–H–O] interactions is lost when the glycol chains are not present. It is worth noting that, in the case of the trisradical complex in MeCN, [C–H–O] interactions are not necessary in order to achieve binding constants of similar orders of magnitude. The binding affinities for the CBPQT\(^{3+}\) ring, as measured previously\(^{36}\) by ITC in MeCN at 298 K, for tetrathiafulvalene and 1,5-dihydroxynaphthalene, both of which lack oligo(ethylene glycol) chains, were determined to be \((6.9 \pm 0.18) \times 10^3 \text{ M}^{-1}\) and \(440 \pm 130 \text{ M}^{-1}\), respectively.

**UV/Vis and Stopped-Flow Spectroscopy.** The absorption spectra of the radical cation MV\(^{+}\) and of the diradical dication CBPQT\(^{2(+)}\) were first of all recorded alone in MeCN at concentrations in the range of \(\sim 5 \times 10^{-5}\) to \(10^{-4}\) M in order to verify the absence of intermolecular radical–radical interactions\(^{38}\) between like species under the experimental conditions employed. The absorption spectra of MV\(^{+}\) and of CBPQT\(^{2(+)}\) are both characterized (Figure 5a) by two sets of finely structured absorptions (vibronic coupling) centered on 390 and 600 nm, respectively. No absorption was observed in the near-IR region, an observation that confirms the absence\(^{39}\) of intermolecular radical–radical interactions, namely, BIPY\(^{+}\) dimerization, in MeCN.

The electronic spectrum of CBPQT\(^{2(+)}\) was compared (Supporting Information) to the sum of the electronic spectra of 2 equiv. of MV\(^{+}\) in order to further investigate the ability of the two BIPY\(^{+}\) units in CBPQT\(^{2(+)}\) to interact with each other in a noncovalent bonding fashion. The larger extinction coefficients (Supporting Information) of the CBPQT\(^{2(+)}\) diradical dication, compared to the sum of two MV\(^{+}\) radical cations, suggest an intramolecular dipole–dipole interaction in the ground state between the CBPQT\(^{2(+)}\) ring’s two BIPY\(^{+}\) radical cationic units. This observation is in good agreement\(^{40}\) with EPR results obtained previously, data from which support the hypothesis of intramolecular dipole–dipole interactions.

The strength of the association between CBPQT\(^{2(+)}\) and the MV\(^{+}\) was then probed (Supporting Information) in MeCN using UV/vis absorption spectrophotometry, allowing us to assess the spectroscopic and thermodynamic parameters associated with the formation of the CBPQT\(^{2(+)}\)\text{CMV}^{+}\) trisradical trication inclusion complex. The recognition of MV\(^{+}\) by CBPQT\(^{2(+)}\) occurs (Figure 5a) with a significant broadening of the absorption band centered around 604 nm, resulting effectively in the concomitant observation of a new band appearing at 550 nm, as well as the emergence\(^{11}\) of an intense absorption band straddling\(^{260}\) the near-IR region.
Table 1. Thermodynamic Parameters Associated with the Formation of the Trisradical Inclusion Complex between the Diradical Dication CBPQT$^{2(+)\_2}$ Ring and the Radical Cation MV$^{+\_4}$

<table>
<thead>
<tr>
<th>$K_a$ 10$^4$ M$^{-1}$</th>
<th>$\Delta G$, kcal mol$^{-1}$</th>
<th>$\Delta H$, kcal mol$^{-1}$</th>
<th>$\Delta S$, cal mol$^{-1}$ K$^{-1}$</th>
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<tr>
<td>5.04 ± 0.63$^b$</td>
<td>−6.41 ± 0.07$^b$</td>
<td>−15.2 ± 0.3$^b$</td>
<td>−29.3 ± 1.6$^b$</td>
</tr>
<tr>
<td>7.9 ± 5.5$^c$</td>
<td>−6.7 ± 0.4$^c$</td>
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$^a$Solvent, MeCN; $T = 298$ K. $^b$Determined by ITC. $^c$Determined by UV/vis spectroscopy.

The processing of these spectrophotometric data made it possible to carry out an independent determination of the stability constant ($K_a$) for the trisradical trication inclusion complex, in addition to affording (Figure 5a) the corresponding electronic spectrum of the 1:1 trisradical tricationic CBPQT$^{2(+)\_2}$ CMV$^{+\_4}$ complex. It displays the characteristic spectroscopic features of BIPY radical–radical interactions (pimerization), namely a broad near-IR band, as well as an increase in the intensities of the absorption bands in the 500–600 nm region compared with the free components dissolved on their own in solution. The results from this titration reveal a $K_a$ value of (7.9 ± 5.5) × 10$^4$ M$^{-1}$, an association constant that is consistent within experimental error of that (5.0 ± 0.6) × 10$^4$ M$^{-1}$ determined from the ITC experiments. The thermodynamic parameters obtained from both the ITC and UV/vis spectroscopic data are summarized in Table 1.

Stopped-flow UV/vis spectroscopy was performed to evaluate the kinetic parameters controlling the association and dissociation of the trisradical tricationic CBPQT$^{2(+)\_2}$ CMV$^{+\_4}$ inclusion complex. The absorption at 505 nm was used as a measure of the concentration of the inclusion complex as a function of time, employing pseudo-first-order experimental protocols. A monoexponential increase of the absorbance at 505 nm in the millisecond time range was recorded for the formation of the trisradical trication from these experiments, a single rate-limiting step (Figure 5b), governing the formation of the inclusion complex, was deduced. The experimental data indicate that the formation of the 1:1 complex proceeds in a single, very fast rate-limiting step. The concentration of MV$^{+\_4}$ was varied and the corresponding pseudo-first-order rate constant ($k_{obs}$) was shown to depend linearly on [MV$^{+\_4}$]$_{tot}$ according to the following equation:

$$k_{obs} = a[\text{MV}^{+\_4}]_{tot} + b$$

The experimental data led us to suggest the following concerted mechanism:

$$\text{CBPQT}^{2(+)} + \text{MV}^{+\_4} \overset{k_f}{\rightarrow} \text{CBPQT}^{2(+)} \subset \text{MV}^{+\_4}$$

where

$$k_{obs} = k_f[\text{MV}^{+\_4}]_{tot} + k_b$$

and $k_f$ = a (M$^{-1}$ s$^{-1}$), the bimolecular association rate constant, and $k_b$ = b (s$^{-1}$), the monomolecular dissociation rate constant.

The fact that the formation of the CBPQT$^{2(+)\_2}$ CMV$^{+\_4}$ complex proceeds very rapidly ($k_f = (2.1 ± 0.3) × 10^6$ M$^{-1}$ s$^{-1}$) in a single rate-limiting step indicates the absence of either strong electrostatic repulsions or steric hindrance at play during this process. A plot of $k_{obs}$ versus the concentration of MV$^{+\_4}$ yielded (Figure 5c) a rate of association $k_f$ of (2.1 ± 0.3) × 10$^6$ M$^{-1}$ s$^{-1}$, and a rate of dissociation $k_b$ of 250 ± 50 s$^{-1}$. The ratio of $k_f/k_b$ (0.84 × 10$^6$ M$^{-1}$) is reasonably consistent with the thermodynamic equilibrium constants determined by ITC [(5.04 ± 0.63) × 10$^4$ M$^{-1}$] and UV/vis [(7.9 ± 5.5) × 10$^4$ M$^{-1}$] spectroscopy. The $k_f$ value obtained for the formation of the trisradical CBPQT$^{2(+)\_2}$ CMV$^{+\_4}$ complex is an order of magnitude smaller compared with the threading rate constant ($k_b = 250 ± 50$ s$^{-1}$) for the CBPQT$^{2(+)\_2}$ CMV$^{+\_4}$ complex is comparable to that ($k_b = 530 ± 50$ s$^{-1}$, MeCN, 293 K) of the CBPQT$^{4+}$ CBHEEN.
complex dissociation rate constant. Although the rate constant for formation of the trisradical CBPQT\(^{2(+*+)}\)⊂MV\(^+\) complex is an order of magnitude less than that for the formation of CBPQT\(^{4+}\)⊂BHEEN, we have shown previously for the formation\(^{46}\) of [2]pseudorotaxanes with threads containing 1,5-dioxynaphthalene units together with terminal BIPY\(^{2+}\) units flanking either side that the threading of the CBPQT\(^{4+}\) ring is slowed \((k = (7.0 \pm 0.7) \times 10^{-3} \text{M}^{-1} \text{s}^{-1}, 0.1 \text{ M NaCl in H}_2\text{O}, 298 \text{ K})\) by many orders of magnitude as a consequence of the BIPY\(^{2+}\) units serving the role of electrostatic barriers.

**Cyclic Voltammetry and Digital Simulations.** In a 1:1 mixture of CBPQT\(^{4+}\) and MV\(^{2+}\), both in their fully oxidized forms, no binding between the two charged species is observed, presumably as a consequence of their similar \(\pi\)-electron-poor electronic characteristics, not to mention electrostatic repulsion. Upon a three-electron reduction, wherein two electrons contribute to the formation of the CBPQT\(^{2(+*+)}\) ring and one to the formation of the MV\(^{+}\) guest, production of the trisradical CBPQT\(^{2(+*+)}\)⊂MV\(^+\) inclusion complex ensues as a result of favorable radical–radical interactions, all of which can be stimulated electrochemically. The nature of these radical–radical interactions is largely a consequence of radical pairing, a phenomenon that has been studied\(^{42}\) in considerable detail in the case of the classical viologen radical cation dimers and violenes in general.\(^{48}\) When viologen radical cations dimerize, at distances defined by van der Waals contacts, the dimers become radially paired and hence EPR silent (inactive), while the viologen radical cation monomer results in a characteristic signal. This mechanism involving radical pairing has important implications when considering the electrochemical behavior of the trisradical CBPQT\(^{2( +*+)}\)⊂MV\(^+\) complex. Consider the hypothesis where only two of the BIPY\(^{•}\) radical cation subunits of the complex are paired at any one time, leaving one BIPY\(^{•+}\) radical cation subunit of the CBPQT\(^{2(+*+)}\) ring unpaired. One might anticipate that this unpaired BIPY\(^{•+}\) unit would not be as strongly engaged in radical–radical interactions as the other two paired BIPY\(^{•+}\) units. Theoretical investigations, based on DFT to calculate the SOMO of the trisradical CBPQT\(^{2(+*+)}\)⊂MV\(^+\) complex, support\(^{60}\) this hypothesis (vide supra), by revealing that orbital overlap of the MV\(^+\) guest occurs predominantly with only one of the BIPY\(^{•+}\) units in the CBPQT\(^{2(+*+)}\) ring. The fact that one of the two BIPY\(^{•+}\) radical cations in the ring is not as strongly interactive with the MV\(^+\) guest mandates, from a thermodynamic perspective, that this unpaired BIPY\(^{•+}\) unit undergoes reduction to its neutral BIPY\(^{0}\) form at a less negative potential, that is, it should be easier to reduce in comparison with the two radially paired BIPY\(^{•+}\) units. The corollary to this argument is that the reoxidation of the unpaired BIPY\(^{•+}\) radical cation unit should also occur at less positive potentials, that is, it should be easier to oxidize, compared with the two paired BIPY\(^{•+}\) radical cation units. It follows therefore that the formation of a tetracationic CBPQT\(^{2( +*+)}\)⊂MV\(^+\) bisradical inclusion complex must appear in any discussion of the electrochemical switching mechanism.

The CV of an equimolar mixture of the CBPQT\(^{4+}\) ring and MV\(^{2+}\) is presented in Figure 6a. The first reduction peak \((-0.32 \text{ V, peak potential})\) is a three-electron process with two electrons going to CBPQT\(^{4+}\), forming the diradical dication CBPQT\(^{2(+*+)}\), and one electron going to MV\(^{2+}\), forming the radical cation MV\(^•\). As a consequence of this three-electron process, formation of the trisradical tricationic CBPQT\(^{2(+*+)}\)⊂MV\(^+\) inclusion complex ensues spontaneously. The result of this inclusion is that only one of the BIPY\(^{•+}\) radical cations of the complexed CBPQT\(^{2(+*+)}\) interacts strongly with the MV\(^+\) radical cation, leading to the fact that the second reduction of this weakly interacting, unpaired BIPY\(^{•+}\) occurs at a less negative potential \((-0.76 \text{ V, peak potential})\), roughly at the same potential as the second reduction of CBPQT\(^{4+}\) alone in solution. The reduction of the paired BIPY\(^{•+}\) units of the complexed CBPQT\(^{2(+*+)}\) and the MV\(^+\) radical cation, occur

![Figure 6.](image-url)
CBPQT4+ ring cannot escape the influence of the BIPY2+ unit the mechanical bond. The mechanical bond dictates that the 1,3-dipolar cycloaddition in the final reaction step, thus forming upon radical process that generates the trisradical tricationic R3+ complex. The presence of the BIPY2+ unit in the ring CBPQT2+V+ ring leads to dissociation of the complex observable on the time scale of the CV experiments. When the experimental data were fitted to the digital simulations, the free energy barrier, ΔG°‡, to dissociation of the bisradical CBPQT2+V+ complex was determined to be 16.1 kcal mol−1. Blue trace = 200 mV s−1; purple trace =10 V s−1. IR compensation was applied and an Ag/AgCl reference electrode was used.

Question: What is the significance of the bisradical tetracationic intermediate in the CV experiments observed in Figure 7?

Answer: The bisradical tetracationic intermediate in the CV experiments observed in Figure 7 is significant because it represents a stable species that can undergo further oxidation or reduction processes. This intermediate allows for the observation of multiple redox events, which can be used to study the electronic properties and reactivity of the complexes involved.
dramatically shifted two-electron process can be assigned to the simultaneous two-electron oxidation of the radically paired BIPY⁺⁺ units of CBPQT(2⁺)(MV⁺⁺)⊂CV⁺⁺, leading to the fully oxidized and highly unstable hexacationic CBPQT⁴⁺ CV²⁺ complex, which quickly dissociates on the time scale of the CV experiment.

Because of the dissociation of the CBPQT(2⁺)(MV⁺⁺)⊂CV⁺⁺ inclusion complex, we hypothesize that the reoxidation potentials for both separated components become shifted toward less positive potentials, resembling those of the free components alone in solution, than the first one-electron oxidation of the unpaired BIPY⁺⁺ radical cation in the scan, resulting in a single broad reoxidation peak. Mechanistically, we propose a first-order rate law for the dissociation of the CBPQT(2⁺)(MV⁺⁺)⊂CV⁺⁺ inclusion complex into its individual components that is proportional to a rate constant and the concentration of the bisradical species.

Digital CV simulations of the proposed mechanism were performed (Figure 7) based on the results obtained from ITC and stopped-flow spectroscopy and are in good agreement with the experimental data. Comparisons between digital simulations and the experimental data using a X² fitting algorithm or by employing a relative integration analysis (see Supporting Information) of the reoxidation waves as a function of time (scan rate) establish the barrier ΔG‡ governing the first-order dissociation of the bisradical tetracationic complex to be 16.1 or 16.5 kcal mol⁻¹, respectively, at room temperature. Table 2 summarizes the kinetic parameters obtained from stopped-flow UV/vis spectroscopic and CV data. It is worth noting that, since the kinetic reoxidation pathway of the trisradical tricationic complex is scan-rate dependent, it represents an example of a bilabile system.

**EXPERIMENTAL SECTION**

**General Methods.** The tetracationic cyclophane, cyclobis(parquat-p-phenylene) tetrakis(hexafluorophosphate) (CBPQT-4PF₆), the dimethyl viologen⁻²⁺ (MV-2PF₆), and the dibutynyl viologen⁻²⁺ (V₂PF₆), as well as the single-station [2]rotaxane 26b (R-6PF₆) were all prepared according to literature procedures. Zinc dust was activated by stirring it with dilute HCl during 10–15 min and then washing it several times with distilled H₂O, EtOH, and absolute Et₂O before drying rigorously. This procedure removes oxides, which form slowly upon standing in air from the surface of zinc. All the physicochemical investigations were carried out with spectroscopic grade MeCN (Acros Organics ≥99.9% for spectroscopy). The stock solutions of CBPQT-4PF₆ and MV-2PF₆ were prepared by weighing using an AG 245 Mettler Toledo analytical balance (precision 0.01 mg). Complete dissolution of CBPQT-4PF₆ and MV-2PF₆ in MeCN was achieved using an ultrasonic bath (Bandelin Sonorex RK102 Transistor). The concentrations were thus obtained by weighing the appropriate amounts. Reduction of CBPQT⁺⁺ and MV⁺⁺ into the corresponding diradical dication CBPQT⁺⁺⁺⁺ and radical cation MV⁺⁺⁺⁺ was achieved under argon (CO₂- and O₂-free argon using a Sigma Oxiclear cartridge) in less than 1 h by vigorous stirring with activated zinc dust. The formation of the radicals were monitored (see Supporting Information) by absorption spectrophotometry. Isothermal titration calorimetry (ITC) experiments were performed on a MicroCal system, VP-ITC model. Cyclic voltammetry (CV) was carried out at room temperature in argon-purged MeCN solutions with a Gamry Multipurpose instrument (reference 600) interfaced to a PC. The CV experiments were performed using a glassy carbon working electrode (0.071 cm², BAS). 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, unless otherwise noted. The concentrations of the sample and supporting electrolyte, tetrabutylammonium hexafluorophosphate (TBA-PF₆), were 1.0 × 10⁻³ M and 0.1 M⁺⁺⁺⁺ respectively. Experimental error of potential values was ±0.1 mV. All simulations of electrochemical data were performed using DigiSim.

**UV/Vis Absorption Spectrophotometric Titration.** A solution (50 mL) of CBPQT-4PF₆ (4.36 × 10⁻⁵ M) was introduced into a

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### Table 2. Kinetic Parameters Associated with the Formation of the Trisradical Inclusion Complex between the Diradical Dication CBPQT²⁺(MV⁺⁺) and the Bisradical Complex of CBPQT⁻⁻⁻⁻ with V⁺⁺⁺⁺

<table>
<thead>
<tr>
<th>Complex</th>
<th>kᵢ [10⁸ M⁻¹ s⁻¹]</th>
<th>kₒ [s⁻¹]</th>
<th>ΔGᵢ⁺⁺ [kcal mol⁻¹]</th>
<th>ΔGₒ⁺⁺ [kcal mol⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBPQT⁻⁻⁻⁻(MV⁺⁺)</td>
<td>210 ± 30b</td>
<td>250 ± 50b</td>
<td>8.8 ± 0.1b</td>
<td>14.2 ± 0.1b</td>
</tr>
<tr>
<td>CBPQT⁻⁻⁻⁻(MV⁺⁺)⊂CV⁺⁺</td>
<td>3.6 ± 1c</td>
<td>10 ± 2c</td>
<td>11.0 ± 0.7c</td>
<td>16.1 ± 0.5c</td>
</tr>
</tbody>
</table>

*Solvent, MeCN, T = 298 K. b, Determined by stopped-flow spectroscopy. c, Determined by cyclic voltammetry using a relative integration analysis.*
jacketed cell (Metrohm) maintained at 25.0(2) °C (Lauda E200/011 thermostat) while being deoxygenated continuously by CO2- and O2-free argon. In the first instance, an absorption spectrum was recorded using a Varian Cary 50 spectrophotometer, fitted with Hellina optical fibers (Hellina, 041.002-UV), and an immersion probe made of quartz suprasil (Hellina, 661.500-QX). Activated zinc dust was then added, and the formation of the diradical dication CBPQT(4+) was monitored by recording the absorption spectra as a function of time until complete reduction was achieved (∼1 h). Concomitantly, a stock MeCN solution of MV(+) (3.35 × 10−3 M, 10 mL) was prepared from MV·2PF6 under the same conditions, that is, continuous deoxygenation with CO2- and O2-free argon and vigorous stirring in the presence of activated zinc dust. Microvolumes of concentrated MeCN solutions of the radical cation MV(+) were added to a MeCN solution of CBPQT(4+), and the reaction was allowed to stand for 15 min with vigorous stirring in the presence of activated zinc dust and under anaerobic conditions to ensure that both the complete reduction of the BIPY2+ derivatives and the host–guest association equilibration were attained. After each addition, a UV/vis spectrum was recorded from 230 to 900 nm on the Cary 50 (Varian) spectrophotometer maintained at 25(2) °C. The ratio [MV(+)]tot/[CBPQT(4+)]tot was varied (see the Supporting Information) from 0 to 4.38. The spectrophotometric data were analyzed with the Specfit program, which adjusts the absorptivities and the stability constants of the species formed at equilibrium. Specfit uses factor analysis to reduce the number of species formed at equilibrium. Specfit uses factor analysis to reduce the absorbance matrix and extract the eigenvalues prior to the multiwavelength fit of the reduced data set according to the Marquardt algorithm.

**Formation Kinetics.** The formation kinetics of the trisradical inclusion complex CBPQT(4+)·CMV(−) were measured on a SX-18MV stopped-flow spectrophotometer from Applied Photophysics. The temperature was maintained at 25.0(2) °C with the help of a Lauda E200/RE220 cryothermostat, and the formation kinetics of the trisradical species was monitored at λ = 505 nm (l = 1 cm), a wavelength that corresponds to the maximum of absorbance difference between the reactants (MV(+) and CBPQT(4+)) and the product (CBPQT(4+)·CMV(−)) within the spectroscopic window employed under the experimental conditions. The CBPQT(4+) concentration was fixed at 1.13 × 10−3 M, and the range of MV(+) concentrations was varied from 1.47 × 10−4 to 2.78 × 10−4 M by dilution of a concentrated stock solution. At least 10 times more concentrated solutions of MV(+) with respect to CBPQT(4+) were used in order to impose pseudo-first-order conditions. Each solution, namely, the CBPQT(4+) and the MV(+) samples, was reacted with activated zinc dust during more than 1 h to ensure complete reduction into CBPQT(4+) and MV(+) species. The data sets, averaged out of at least three replicates, were recorded and analyzed with the commercial software Bioikine.54 This program fits up to three exponential functions to the experimental curves with the Simplex algorithm55 after initialization with a Padé–Laplace method.56

**ASSOCIATED CONTENT**

5 Supporting Information

Further details and characterization by 1H DOSY NMR, CV, digital CV simulations, X-ray crystallography, ITC, and UV/vis spectroscopy. This material is available free of charge via the Internet at http://pubs.acs.org.

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**ACKNOWLEDGMENTS**

We (A.C.F., J.C.B., H.L., A.C., J.J.G., Z.L., and J.F.S.) at Northwestern University acknowledge support from the Air Force Office of Scientific Research (AFOSR) under the Multidisciplinary Research Program of the University Research Initiative (MURI) Award FA9550-07-1-0534 on "Bioinspired Supramolecular Enzymatic Systems" and the National Science Foundation (NSF) under the auspices of Award CHE-0924620. We (W.A.G. and J.F.S.) also acknowledge support by the Microelectronics Advanced Research Corporation (MARCO) and its Focus Center Research Program (FCRP) on Functional Engineered NanoArchitectonics (FENA) as well as support from the Non-Equilibrium Energy Research Center (NERC), which is an Energy Frontier Research Center (EFRC) funded by the U.S. Department of Energy, Office of Basic Sciences (DOE-BES), under Award DE-SC0000989. W.A.G., J.F.S., A.C.F., and J.C.B. were supported by the WCU Program (NRF R-31-2008-000-10055-0) funded by the Ministry of Education, Science and Technology, Korea. A.C.F. acknowledges support from an NSF Graduate Research Fellowship. This work was also supported (M.E. and D.A.L.) by the Centre National de la Recherche Scientifique (CNRS) and the University of Strasbourg (UMR 7509 CNRS-UdS) in France.

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In both cases, the crystals obtained were purple/black needles that were handeled under ambient conditions and in the presence of atmospheric oxygen. Crystal data for [CBPQT2(2+)PF62-]•C12H14N2•2PF6 contained diffuse, disordered solvent void volume was 319 Å3, and the electron count per cell is 73. As the crystal symmetry may be disordered, the electron count per cell may be underestimated.

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(38) This phenomenon of dimerization is indeed a common feature characterizing most types of radical cations including the viologen radicals ($K_{D_{\text{Dim}}} = 1.25 \times 10^3 \text{ M}^{-1}$ for $\text{MV}^{\text{+}+}\text{MeSO}_4$ in water) and is associated with significant spectroscopic changes, for example, the formation of new bands in the range of $\sim 550$–$570 \text{ nm}$ as well as at approximately $900 \text{ nm}$. See: Monk, P. M. S.; Hodgkinson, N. M.; Ramzan, S. A. Dyes Pigm. 1999, 43, 207.
(39) By contrast with aqueous solutions, the monomer–dimer equilibrium is indeed usually not observed in polar organic solvents such as MeOH, MeCN, or DMF except at relatively high concentrations or low temperatures.
(40) EPR investigations, which were performed in MeCN on the CBPQT2(\textsuperscript{1+}\textsuperscript{+}) diradical cation, reveal a lack of hyperfine splitting in the spectrum, while the 1,1\'-dibutyl-4,4\'-bipyridinium V\textsuperscript{+} radical cation displays the hyperfine splitting typically observed for these types of viologen derivatives. The lack of hyperfine splitting observed in the case of the CBPQT2(\textsuperscript{1+}\textsuperscript{+}) diradical cation is most likely a result of intramolecular dipole–dipole interactions between its two BIPY\textsuperscript{+} radical cation units. For more details, see ref 26a.
(41) Although only the tail of this near-IR band has been observed because of the instrumental limitations (200–900 nm) of the absorption spectrophotometer employed during this investigation, we have reported previously using another spectrometer the spectrum (550 nm as well as at $\sim 1075 \text{ nm}$). For more details, see ref 26a. In addition, there are conflicting rationalizations in the literature as to the nature of this near-IR absorption band typical of BIPY\textsuperscript{+} radical dimers. We are of the belief that this near-IR band is a result of through-space intermolecular charge transfer similar to that observed for mixed-valent radical cation dimers. For further discussion, see: (a) Lü, J.-M.; Rosokha, S. V.; Kochi, J. K. J. Am. Chem. Soc. 2003, 125, 12161. (b) Sun, D.-L.; Rosokha, S. V.; Lindeman, S. V.; Kochi, J. K. J. Am. Chem. Soc. 2003, 125, 15950.
(45) Despite the inappropriate solvent conditions, that is, aqueous solutions favor pimerization processes, these thermodynamic data are comparable with those determined for pimerization of MV\textsuperscript{+} as its methosulfate salt in H\textsubscript{2}O ($K_{D_{\text{Dim}}} = 1.25 \times 10^3 \text{ M}^{-1}$; log $K_{D_{\text{Dim}}} = 5.09$). For further details, see the publications cited in ref 21.
(49) This scan rate of 30 V s\textsuperscript{-1} is approaching the upper limit of our experimental capabilities, which is constrained by our use of a glassy carbon working electrode with a relatively large 0.071 cm\textsuperscript{2} surface area.
(56) Yeramian, E.; Claverie, P. Nature 1987, 326, 169.