JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

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A Noncovalently Reversible Paramagnetic Switch in Water

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Supporting Information

ABSTRACT: We report an organo-paramagnetic switch consisting of a linked bis(viologen) dication diradical that can be cycled reversibly between diamagnetic and paramagnetic states via noncovalent guest−host chemistry with cucurbit[7]uril (CB[7]) in room-temperature water. Computations suggest that the nature of the interaction between the viologen cation radical units is that of a pi dimer (pimer). Molecules with switchable magnetic properties have possible applications in spintronics, data storage devices, chemical sensors, building blocks for materials with switchable bulk magnetic properties, as well as magnetic resonance probes for biological applications.

Organic molecules with magnetic properties hold promise in applications as diverse as molecular electronic devices,[1,2] organic spintronics,[3−5] organic polymers with bulk ferromagnetism,[6−8] and biological probes for magnetic resonance experiments.[9,10] Notable examples of this type include organic spin switching in the solid-state[11−13] and supramolecular organic radical complexes with switchable properties.[14−19] Further, while there has been interest in spin state switching in organometallic complexes,[20,21] organic molecules with switchable spin states and magnetic properties in solution remain elusive. Here, we report that a linked bis(viologen) dication diradical can be reversibly cycled between diamagnetic and paramagnetic forms using noncovalent chemistry in room-temperature water, providing a switch with changes in color and magnetic properties.

Viologen cation radicals are a well-characterized class of spin-unpaired organic species.[22−28] Notably, it has been reported that viologen cation radicals exist in equilibrium with a diamagnetic dimer in solution.[23,24,26] In other studies, it has been shown that viologen dications and viologen cation radicals form noncovalent complexes with CB[7], a supramolecular host consisting of seven methylene-linked glycouril units wrapped into a macrocyclic container.[29−34] Thus, we considered it might be possible to synthesize a viologen cation radical that could be switched between diamagnetic and paramagnetic forms using noncovalent chemistry with CB[7]. While our initial attempts at exploiting the propyl viologen radical cation as a paramagnetic switch were frustrated by its concentration-dependent dimerization (see Supporting Information), it is known that the dimer-free radical equilibrium of viologen and related radicals can be shifted to favor the diamagnetic dimer when the radicals are covalently tethered.[35,36] In particular, a three-carbon tether unit has been shown to lead to efficient intramolecular dimerization for viologen.[23,37,38]

Thus, we synthesized the propyl-tethered bis(viologen) dication diradical **2** that has a concentration-independent intramolecular dimerization switchable between diamagnetic and paramagnetic forms using noncovalent chemistry with CB[7] (see Figure 1). The results of EPR titration studies,

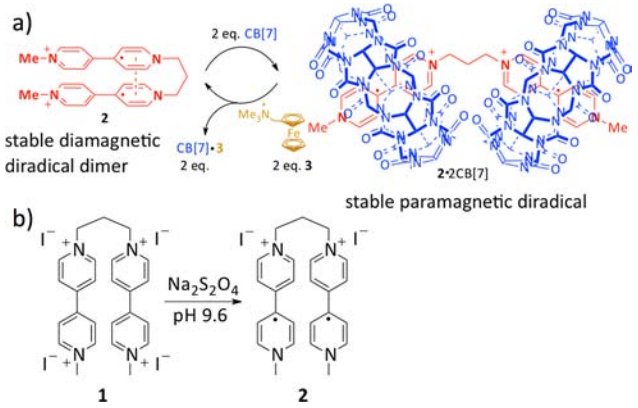

Figure 1. (a) Reversible cycling between diamagnetic and paramagnetic forms of **2** using noncovalent chemistry. (b) Reduction of **1** to diradical dication **2**.

UV−vis switching studies, and computational studies indicate the propyl-linked bis(viologen) dication diradical **2** is a diamagnetic species that can be switched to the paramagnetic form by formation of a ternary complex with CB[7]. The diradical complex can further be switched back to the diamagnetic form by displacement of **2** by a tighter-binding guest, trimethylaminomethylferrocenyl iodide **3**. This switching between diamagnetic and paramagnetic forms can be cycled multiple times without radical decomposition.

Dimer **2** was synthesized by two-electron reduction of the propyl-linked bis(viologen) tetracation **1** using sodium dithionite in buffered water.[39] We detected only a weak signal in the EPR spectrum attributable to the viologen radical cation assignable to a small thermal population of the dissociated paramagnetic diradical. We were unable to see any peaks in the ^{1}H NMR spectrum for this singlet dimer, however, possibly because of a population of the paramagnetic form at room

Received: April 11, 2013
Published: July 5, 2013

temperature (from the EPR data, the equilibrium constant between diamagnetic and paramagnetic forms = 30 at 22 °C).

To test whether **2** could be switched to the paramagnetic form, we added varying amounts of CB[7] to prepared solutions of **2** and monitored the change by EPR spectroscopy. Addition of 3 equiv of CB[7] leads to an increase in the integrated EPR signal intensity of the viologen cation radical (referenced relative to a TEMPONE external standard). The signal is enhanced further by addition of 3 more equiv of CB[7] and still further by adding a total of 9 equiv of CB[7], clearly demonstrating a switch-on EPR behavior for a >12-fold increase in the integrated EPR intensity upon addition of 9 equiv of CB[7] (Figure 2a). We did not pursue additions above 9 equiv of CB[7] because of practical difficulties associated with the solubility limit of CB[7] in H_2O.

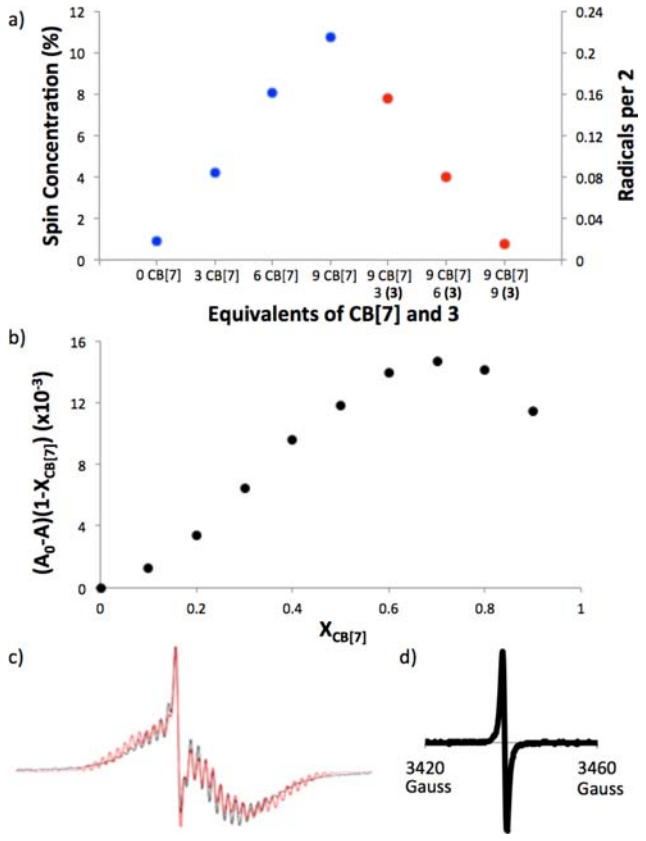

Figure 2. (a) Plot of EPR spin concentration (as double-integrated intensity) of **2** (1 mM) with 0, 3, 6, and 9 equiv of CB[7] added (blue). Switch-off of spin concentration (red) is demonstrated by mixing **2** with 9 equiv of CB[7] and with 3, 6, and 9 equiv of **3**. Spin concentrations are the average of two separate experiments. (b) UV–vis Job Plot titration of **2** (30 μM) with CB[7] (513 nm). (c) Experimental (black) and simulated (red) EPR (X-Band) spectrum of **2** and dithionite (R^2 = 0.980). (d) Experimental spectrum of dithionite.

The lack of complete switching of the dimer **2** by 2 equiv of CB[7] suggests a small association constant. A Job plot was performed, giving a maxima corresponding to a 1:2 **2**·CB[7] stoichiometry (Figure 2b), indicating the formation of a ternary complex. Binding studies by UV–vis were performed to obtain a binding isotherm and fitted with a 2:1 binding equation to obtain the two macroscopic association constants (see Supporting Information for details). A Hill coefficient of 0.59 was obtained for **2** with CB[7], suggesting a negative cooperativity of binding. A macroscopic K_{a1} of 3.0 × 10^4 M^{-1}, with an error of less than 15%, for **2** with CB[7] was obtained, which is within error of other values for unlinked viologen radical cations with CB[7].[34] It should be noted that we also detect by EPR the single-line spectrum of the radical anion of SO_2 in addition to **2**. This impurity signal is attributable to the known equilibrium[40] of dithionite with its two dissociated SO_2 anion radicals. Since identical amounts of dithionite are added in each run, we subtracted the background signal attributable to this radical impurity by measuring the spin concentration of the dithionite in neat buffer, which accounted for ~1.5% spin concentration.

To test whether the paramagnetic ternary complex could be switched back to the diamagnetic form, we added **3** to the paramagnetic ternary complex solution. **3** is known to form a tight complex (K_a ~ 10^{12} M^{-1}) to CB[7] in water and thus would be expected to displace the weaker-binding **2** within the cavity of CB[7], returning **2** to its dimeric diamagnetic form.[41] Indeed, solutions of the dimer containing 9 equiv of CB[7] and 3 equiv of **3** leads to reduction of the EPR signal back to the same intensity as addition of 6 equiv of CB[7] in the absence of **3**. (See Figure 2). Addition of 6 equiv of **3** under the same conditions reduces the signal to that of 3 equiv of CB[7] and 9 equiv reduces it to the starting signal. These experiments demonstrate the switchable nature using noncovalent host–guest chemistry.

Cycling can also be conveniently followed by UV–vis spectroscopy, since the diamagnetic dimer shows a stronger UV–vis absorption above 800 nm.[18,23,25] Compound **2** has a max absorption at 850 nm, while the free radical has a max absorption at 760 nm (See Figure 3), which allowed for

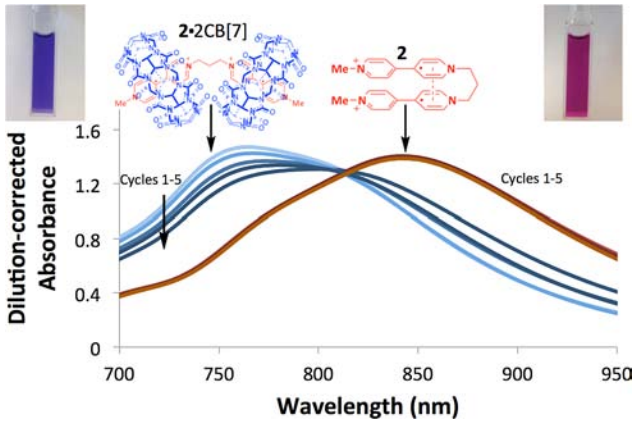

Figure 3. Dilution corrected UV–vis spectrum obtained by alternate additions of 2 equiv of predissolved CB[7] and 2 equiv of predissolved **3** to a 100 μM solution of **2** in buffer. Five sequential cycles within a single cuvette are shown.

identification of the state of the compound during cycling. We cycled this switch five times by alternating addition of 2 equiv of CB[7] with 2 equiv of **3** in a cuvette and inspecting the dilution-corrected absorbances. The 5 cycles show complete return to the diamagnetic dimer. The small reduction in the formation of the complexed paramagnetic form with each switching is attributed to reduced complexation with CB[7] as the sample is diluted during the sequential additions to a single argon-purged cuvette. Note that viologen cation radicals have dissociation constants with CB[7] of ~10^{-5} M, near the

dx.doi.org/10.1021/ja403505z | J. Am. Chem. Soc. 2013, 135, 10594–10597

concentration of the experiment (100 μM). Thus, the small drop in the formation of the ternary complex with each cycle can be attributed to dilution favoring the dissociated rather than complexed forms. However, since the spectrum of **2** is fully restored with each cycle upon addition of **3**, it is clear that no radical decomposition occurs.

While the EPR titration experiments indicate that uncomplexed diradical **2** is a diamagnetic singlet (with a small thermal population of the paramagnetic form), the nature of the radical interaction is not obvious. Prior studies of viologen radicals indicate that these radicals can form both sigma dimers and pi dimers (pimers),[26,28,37,42,43] although related linked viologen dication diradicals are thought to form pi dimers.[44,45] The latter pimer interaction can be thought of as deriving from the overlap of stacked π SOMO orbitals rather than via formation of a traditional σ bond. We evaluated the structures and energies of both **2** and propyl singlet viologen diradical dimers using broken-symmetry density functional theory computations (UM06/6-31G(d,p)) (see Supporting Information for details). We find that the untethered propyl viologen cation radical dimer has minima for both the π dimer structure and a sigma dimer structure (signified by a planar stacked structure and a buckled structure, respectively). These two forms can perhaps be viewed as bond stretch isomers with the pimer structure computed to be lower in energy.[46,47] In contrast, we were only able to find a minimum for the pimer structure for **2**. Inspection of the Kohn–Sham HOMO of **2** indicates the weak bonding interaction that leads to spin pairing between the viologen rings derives from overlap of the stacked SOMO π orbitals on both ring systems (see Figure 4). TD-DFT computations of the

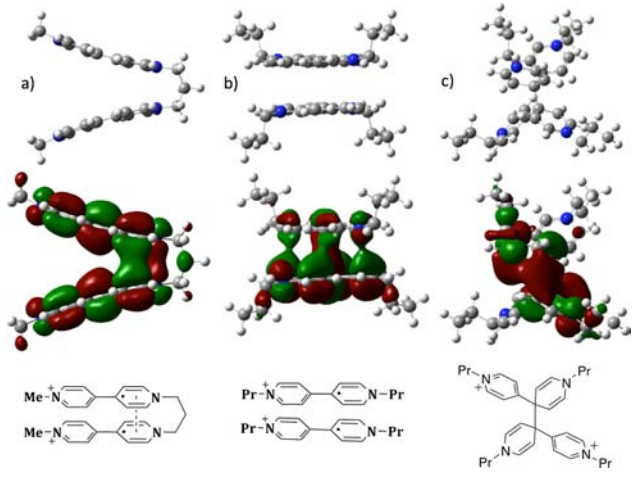

Figure 4. Visualization of the singlet Kohn–Sham HOMO using UM06/6-31G(d,p) (isovalue = 0.02) of (a) **2**, (b) untethered propyl viologen pimer minimum, (c) untethered propyl viologen sigma minimum.

UV–vis absorptions are also more supportive of a pimer than a sigma dimer (see Supporting Information). Thus, the computational evidence suggests that the singlet **2** is likely a pimer rather than a sigma dimer.

In conclusion, we have demonstrated a noncovalently reversible organoparamagnetic switch that can be cycled between diamagnetic and paramagnetic forms without radical decomposition using noncovalent chemistry in room-temperature water. In addition to the applications described in the introduction, we note that there is considerable interest in developing biological EPR probes capable of detecting diamagnetic species such as enzymes for use in EPR-based sensing and animal imaging using EPRI and PEDRI.[48−50] Current EPR spin probes and spin traps are essentially limited to the detection of paramagnetic biological species, which are small in number. However, since this report describes a molecule that has a switch-on of EPR signal by a diamagnetic molecule (CB[7]), the overall strategy of shifting a diamagnetic dimer/paramagnetic diradical equilibrium by a diamagnetic species may represent a promising avenue for achieving switch-on EPR probes for diamagnetic analytes.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Binding details, compound characterizations, and computational coordinates/absolute energies. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We are indebted to Prof. Andrzej Rajca for assistance with the EPR studies (NSF CHE-1012578 and DMR-0216788). We thank the Petroleum Research Fund and the Cottrell Scholar award from the Research Corporation for Science Advancement for financial support.

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