A self-complexing and self-assembling pillar[5]arene†

Nathan L. Strutt,ab Huacheng Zhang,a Marc A. Giesener,a Juying Leoa and J. Fraser Stoddartab

Received 28th September 2011, Accepted 29th November 2011
DOI: 10.1039/c2cc16030g

A monofunctionalised pillar[5]arene derivative carrying a viologen side chain which exhibits self-complexation in dilute dichloromethane solutions forms supramolecular daisy chain polymers and eventually organogels as its concentration is increased three-fold over the range from 0.1 to 100 mM.

The host–guest chemistry of macrocycles such as cyclodextrins, crown ethers, calixarenes, cucurbiturils and cyclophanes has been well researched. Add to this list, pillar[5]arene, a synthetic macrocycle composed of five hydroquinone rings linked mutually through their para positions by methylene bridges, and we have a highly symmetrical cylindrical structure with a π-electron rich cavity which renders it an ideal host for electron poor guests such as the viologens.

Recently, we have described a monofunctionalised pillar[5]arene 1 which was used to synthesise a pillar[5]arene derivative capable of detecting the binding of alkanediamines. Compound 1 carries a single azide which can react with a suitable alkyne by means of the Huisgen-type copper(i) catalysed azide–alkyne cycloaddition (CuAAC).

Tethering a guest to a host, such as pillar[5]arene, provides a unique insight into the nature of the noncovalent bonding interactions since it transforms the intermolecular association present in a 1 : 1 complex into an intramolecular one within the molecule itself. The strong interactions in the self-complexing superstructure are predicted to be comparable with the interactions in pillar[5]arene pseudorotaxanes involving viologen threads. Here, we describe how we have employed click chemistry in order to tether the viologen 2, carrying an alkyne functionality, to the monoazide 1 of pillar[5]arene to give (Scheme 1) a self-complexing derivative 3 which, it is expected, will undergo self-assembly to form both cyclic and acyclic supramolecular daisy chains (Fig. 1), similar to structures reported for weakly bound copillar[5]arenes by Zhang et al.

The UV/vis absorption spectrum of 3 shows (ESI†) a charge–transfer (CT) band at 450 nm arising from the donor–acceptor interactions between the π-electron rich pillar[5]arene cavity and the π-electron poor viologen unit, giving the compound a brick-red colour. The intensity of the CT band in the absorption spectrum of solutions of 3 was found to be highly dependent on the nature of the solvent. The intensity of this band reaches a maximum for CH₂Cl₂ solutions of 3 as opposed to MeCN or Me₂CO solutions (ESI†) of 3. The intensity is also temperature dependent, increasing significantly (33%) on going from 30 °C down to 0 °C (ESI†). Decreasing the temperature of a CT pair in solution is known to shift complexation equilibria towards the associated forms, increasing the observed intensity as a result.
The λ<sub>max</sub> of the CT band in the absorption spectrum exhibits (ESI<sup>†</sup>) a non-linear correlation with concentration in the range 1.0 × 10<sup>-4</sup> to 2.0 × 10<sup>-2</sup> M, supporting the proposed formation of supramolecular oligomers<sup>10a</sup>. A fluorescence spectroscopic titration (ESI<sup>†</sup>) between a model compound (S4<sup>†</sup>) and 1,4-dimethoxypillar[5]arene<sup>6a</sup> (S5<sup>†</sup>) was used to calculate an association constant (K<sub>a</sub>) of 130 000 M<sup>−1</sup> (100 μM, 24 : 1 CH<sub>2</sub>Cl<sub>2</sub>/MeCN) for the complex.<sup>12</sup>

The influence of the pillar[5]arene cavity on the reduction potential of the bound viologen (V<sup>2+</sup>) unit in 3 was examined (ESI<sup>†</sup>) by cyclic voltammetry<sup>6e</sup> (CV). The half-wave potential (E<sub>1/2</sub>) for the first one-electron reversible reduction of V<sup>2+</sup> to the radical cation (V<sup>+</sup>) is shifted by ~20 mV compared to that for the same redox process in 2. This negative shift in E<sub>1/2</sub> indicates that the pillar[5]arene cavity binds V<sup>2+</sup> more strongly than it does V<sup>+</sup>. The E<sub>1/2</sub> for the second one-electron reversible reduction to the neutral viologen (V) is shifted by ~33 mV, indicating a stronger preference by pillar[5]arene for V<sup>+</sup> than for V.

At low concentrations (≤0.1 mM), 3 exists as a single molecular species with minimal intermolecular interactions. Variable temperature (VT) <sup>1</sup>H NMR spectroscopy was performed (Fig. 2a) on a sample (0.1 mM, CD<sub>2</sub>Cl<sub>2</sub>) of 3 in order to probe its the self-complexing characteristics. 2D-NMR spectroscopy (COSY, NOESY, and HSQC) was employed to assign (ESI<sup>†</sup>) <sup>1</sup>H resonances to protons at this low concentration. At temperatures below 0 °C, the peaks corresponding to the bismethylene protons on C-3 and C-4 between the triazole ring and the pillar[5]arene begin to broaden and separate, each of them, into two new resonances at ca. −30 °C. Below this temperature the rate of self-complexation/decomplexation (k<sub>c</sub>) becomes slow on the 1H NMR timescale with most of the molecules residing in the self-complexed form. It has been reported<sup>6b</sup> that a viologen guest located in the cavity of pillar[5]arene inhibits the rotation of the phenylene units through its cavity, conferring chirality upon the molecule. The concomitant slowing down of the site exchange processes render the protons of the two pairs of constitutionally heterotopic methylene groups in the C-3/C-4 bismethylene linker diastereotopic in each case, leading to the emergence at low temperature of an ABCD system for these protons. The k<sub>c</sub> value was estimated<sup>15</sup> to be 230 s<sup>−1</sup> at the coalescence temperature (T<sub>c</sub>) of −25 °C, corresponding to a free energy barrier (ΔG<sup>‡</sup>) of 11.8 kcal mol<sup>−1</sup> for the site exchange process.

As a means of probing supramolecular oligomer/polymer formation, <sup>1</sup>H NMR spectra (Fig. 2b) were recorded over a range of concentrations from 0.1 up to 125 mM. The spectra start to broaden above 5 mM with significant movements in the chemical shifts for the bipyridinium protons H<sub>a</sub>, H<sub>b</sub> and H<sub>b</sub>′, as well as for the aromatic protons of the pillar[5]arene macrocycle, suggesting<sup>10e</sup> a change in the nature of the binding associated with 3 when it forsakes intra- for intermolecular complexation involving dimeric, oligomeric and polymeric supramolecular entities which could be cyclic or acyclic.

The ability of 3 to form supramolecular assemblies was also probed by 2D diffusion-ordered NMR spectroscopy<sup>6f,14</sup> (DOSY). Measurements of diffusion coefficients (D) were performed on samples of 3 from 0.1 up to 125 mM in CD<sub>2</sub>Cl<sub>2</sub>. A plot of D values against concentration (Fig. 3) revealed a sharp decrease in D between 0.1 and 10 mM with comparatively little further change in D between 10 and 125 mM. This large decrease in D over a small change in concentration supports the formation of aggregates, i.e., monomers of 3 held together by intermolecular interactions. In the low concentration region, D appears to decrease in steps (Fig. 3 inset), suggesting the

![Fig. 2](https://example.com/fig2.png)

**Fig. 2** (a) VT <sup>1</sup>H NMR spectra (600 MHz, 0.1 mM, CD<sub>2</sub>Cl<sub>2</sub>) of 3. (b) <sup>1</sup>H NMR spectra (500 MHz, rt, CD<sub>2</sub>Cl<sub>2</sub>) of 3 at multiple concentrations.

![Fig. 3](https://example.com/fig3.png)

**Fig. 3** Two-dimensional DOSY of solutions of 3 (600 MHz, CD<sub>2</sub>Cl<sub>2</sub>, multiple concentrations). Inset: D decreases in steps in the concentration range of 0.5 to 2.5 mM.
formation of low molecular weight supermolecules, such as dimers or trimers, in the concentration range of 0.5 to 2.5 mM. Viscometry (ESI†) was performed in CH₂Cl₂ solutions of 3 at dilute concentrations (0.5 to 30 mM) below the gelation point. A double logarithmic plot of specific viscosity against concentration shows a drastic change in slope at 15 mM indicating a progression from the presence of small oligomers in solution to longer supramolecular polymers.

Dynamic light scattering (DLS) measurements can be used to estimate the size of supramolecular oligomers in solution. Freshly prepared solutions of 3 in CH₂Cl₂ extending across a range of concentrations reveal (ESI†) an increase in hydrodynamic radius (R₉) as the concentration is increased. Solutions of 3 at 1 mM did not have R₉ values of reproducible size by DLS while solutions at concentrations from 5 to 50 mM have average R₉ values of 4 to 6 nm: at 75 mM, the average R₉ is 8 nm. Molecular modelling (ESI†) of linear supramolecular assemblies of 3 composed of three and four monomers have lengths of approximately 5.5 and 7.3 nm, which may contribute to the average R₉ values found by DLS.

Sealed solutions of 3 in CH₂Cl₂ at concentrations above 25 mM form gels (Fig. 4) after standing for 12 h. Optical microscopy and scanning electron microscopy (SEM) indicate that the gels are fibrous in nature. Powder X-ray diffraction (XRD) data (ESI†) also indicates that the gel is composed of thread-like polymers. Unfunctionalised pillarene and pillarene derivatives have previously been reported to form gels composed of tubular fibres. The gelation process is expected to occur as longer daisy-chain type polymers of 3 form and intertwine to create thin fibres which bundle together and entangle, trapping solvent and forming a gel structure.

Supramolecular daisy chain oligomers and polymers are formed by self-assembly in CH₂Cl₂ solutions in the intermediate concentration range (5 to 100 mM) of a pillarene carrying a viologen side-chain which exhibits self-complexation in dilute solution (0.1 mM). The compound forms an organogel when allowed to stand at high concentration (>25 mM). Investigations on the switching behaviour of this gel are now underway.

We acknowledge support from the World Class University (WCU) Program (R-31-2008-000-10055-0) in Korea and a joint National Science Foundation (NSF)/Engineering and Physical Sciences Research Council (EPSRC) grant (CHE-0924620). H. Z. thanks the Chinese Scholarship Council for providing financial support during his stay at Northwestern University. N. L. S. acknowledges the NSF for a Graduate Research Fellowship.

Notes and references
12 A Job Plot (ESI†) indicates a 1:1 stoichiometry for the complex. The Kₛ value for the complex was also determined using a UV-Vis spectroscopic titration (ESI†).

Fig. 4 (a) Gel formed by 3. (b) Optical microscopy image (500x) of aggregates of 3. This gel formation is predicted to result from intertwining of supramolecular polymers of 3. (c) Optical microscopy image (100x) of gel. (d,e) SEM image of gel in CH₂Cl₂.