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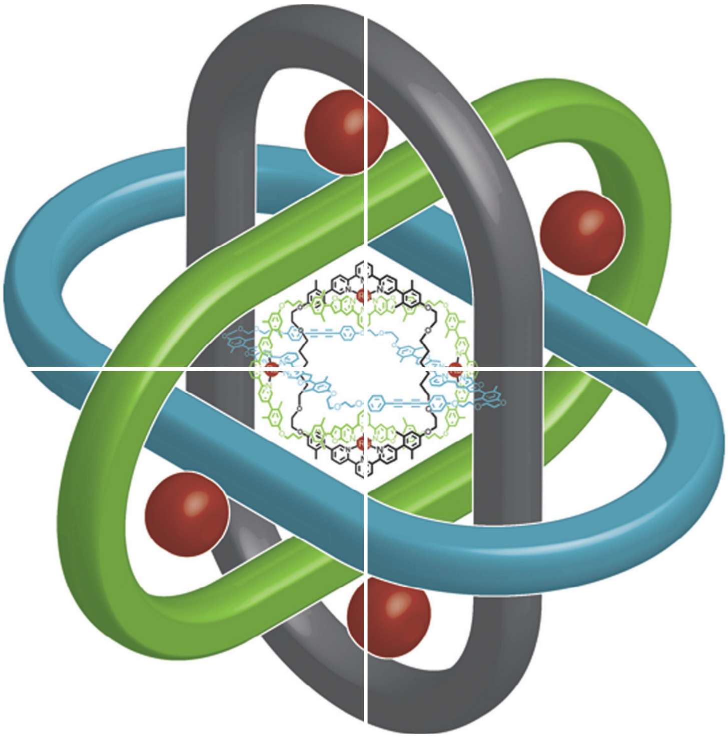

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Conformations of large macrocycles and ring-in-ring complexes†

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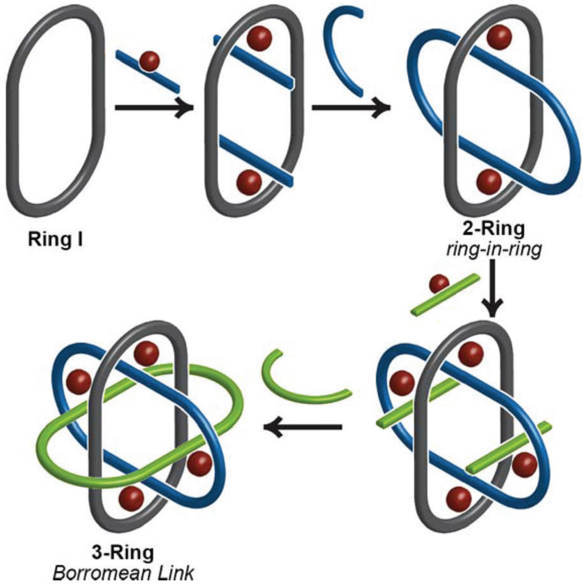
A kinetically directed, stepwise approach towards molecular Borromean links enabled the isolation and structural characterization of synthetic intermediates along the way. Here we report the synthesis and crystal structures of three flexible macrocyclic intermediates and a new ring-in-ring complex, anchored together through ruthenium(II) centers, which contains open terpyridine caps in the inner Ring II. Terpyridines circumvent the conformational *cis*/*trans* limitations of bipyridines and the new ring-in-ring complex forms tetrametallic complexes with Zn(II), Pt(II) and Ru(III) metal ions. Analysis of the four macrocyclic structures provides a good foundation for the conformational flexibility in these complexes and demonstrates the robust applicability of the terpyridine design elements towards the engineered synthesis of ring-in-ring topologies.

Introduction

Thanks to a variety of chemical template methodologies,[1] ring-in-ring threaded molecules (catenanes) are now routine design elements and products of chemical synthesis;[2] however, directed inclusion of one macrocycle within another to form non-intertwined ring-in-ring complexes remains an interesting and challenging molecular target. In one strategy for the synthesis of such complexes, a rigid open-host ring, such as a cyclodextrin,[3] curcurbituril,[4] calixarene,[5] pyridinium[6] or metal–organic[7] macrocycle houses a guest macrocycle. In another strategy, metal–ligand complexes serve as anchoring points between the two macrocycles or curved ligands.[8] Phenomenal examples of ring-in-ring elements within higher order structures include: the thermodynamic assembly of a Borromean link (B-link),[9] in which three rings form a topological link without concatenation, Borromean networks,[10] and the assembly of curved-aromatic carbon materials in onion-like ring and shell hierarchies.[11]

Focusing on B-links as topologically special targets of molecular synthesis,[12] a stabilized single ring-in-ring element could serve as a key intermediate in a general design strategy for a kinetic, stepwise synthesis of B-links (Scheme 1).[13] One embodiment of this intermediate comprises an outer macrocycle with two inward pointing (*endo*) terpyridine (terpy) elements and an inner macrocycle with two outward (*exo*) pointing terpy



Scheme 1 A conceptual stepwise kinetic strategy for an interlocked Borromean link that begins with a single macrocycle (Ring I) which templates formation of the second ring (Ring II) as the key ring-in-ring intermediate (2-Ring).

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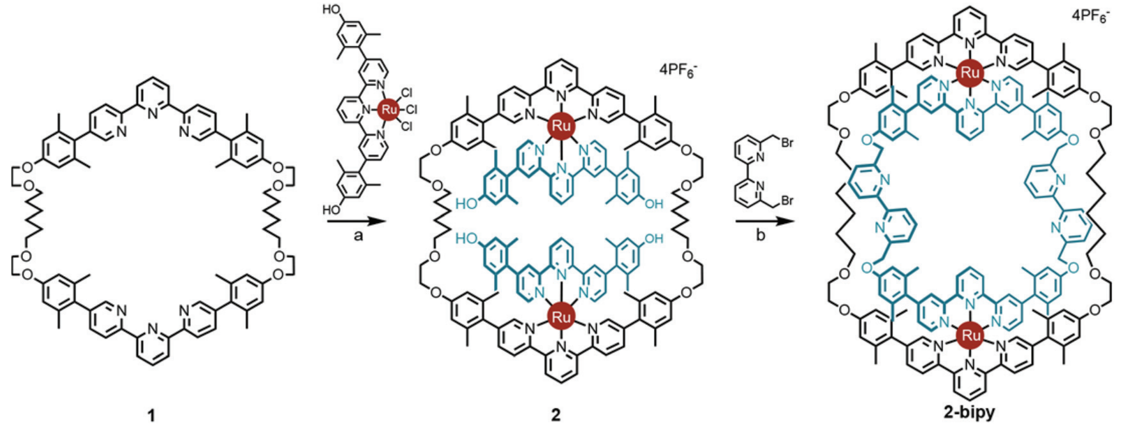


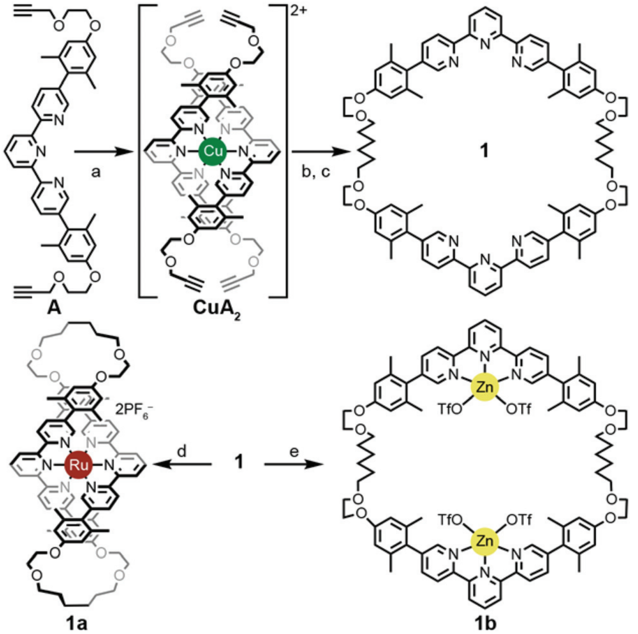
Scheme 2 Synthesis of ring-in-ring structure **2-bipy** *via* the doubly threaded Ring I intermediate **2**. Reaction conditions: (a) 2 : 1 : 1 CH_2Cl_2 : EtOH : ethylene glycol, reflux, 12 h, 65%; (b) Cs_2CO_3, acetonitrile, reflux, 72 h, 49%.[13]

elements, plus two bipyridine (bipy) elements (**2-bipy**) (Scheme 2). Failed attempts to extend this entity into a B-link motivate structural studies to better understand these intermediates. This work details such studies and reports the synthesis of **2-terpy** with two open terpyridine moieties.

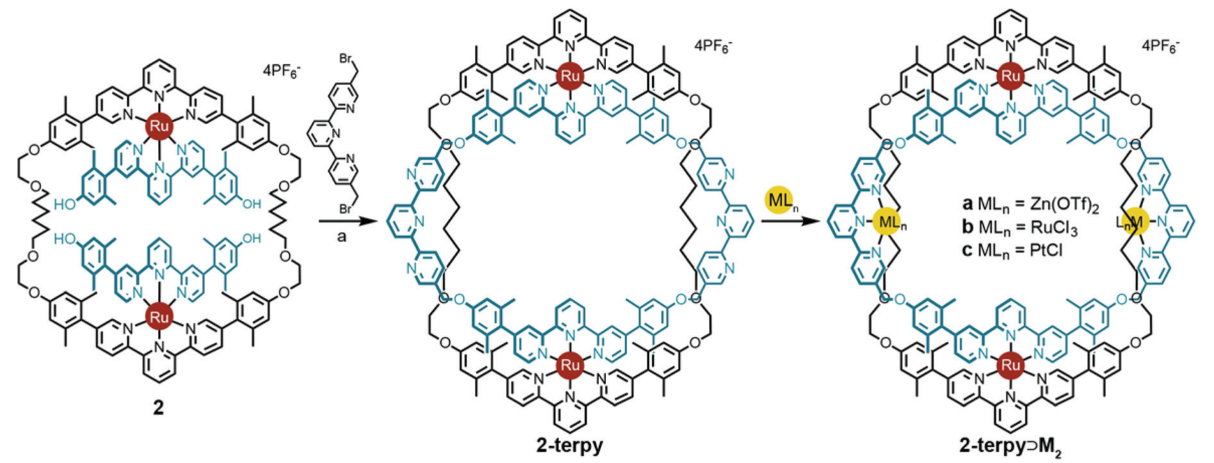
Results

A thermodynamically controlled approach to ring-in-ring structures employs the spontaneous assembly of two macrocycles, stabilized by the strength of non-covalent bonding between them. A kinetically controlled approach[13] to ring-in-ring structures differs by employing the stepwise construction of each ring and requires a virtually irreversible anchoring point (*e.g.* a $[Ru(terpy)_2]^{2+}$ complex) to hold the pieces together. One reduction to practice of this latter strategy starts by forming a macrocycle **1** with *endo* terpy segments (Ring I). Treatment of **1** with two equivalents of monoleptic $[Ru(terpy)Cl_3]$ reagent, generates threaded structure **2** with two heteroleptic terpy/terpy′ Ru complexes in which the two terpy′ units are threaded within Ring I and lie proximal to each other (Scheme 2). In the final step, the two terpy′ units are connected to form an inner macrocycle (Ring II) and afford the representative ring-in-ring complex. Specifically, 2,2′-bipyridine units were used to link the terpy′ units and form Ring II, in the hope of iterating the process to form a B-link.[13]

Macrocycle **1** was first presented as the key intermediate in a stepwise synthetic approach to a B-link topology. Although macrocycle **1** is a quite flexible and large ring – formally 66-membered – its immediate tetraalkyne precursor forms in high overall yield by Eglington macrocyclization of two halves (**A**) assisted by metal coordination.[13] The assumption has been that the intermediate is a figure-eight shaped metal complex **CuA**$_2$, which then springs open to release the metal after ring formation; subsequent hydrogenation yields **1**. A kinetically inert cognate of the putative figure-eight intermediate (**1a**) forms during the reaction of **1** with one equivalent of Ru(II)-$Cl_2(DMSO)_4$ (Scheme 3). Structural elucidation of **1a** shows the expected overall structure and a linear *crankshaft* conformation of the hexamethylene unit, where the linear methylenediyne-methylene unit would have been in the intermediate, thus providing little evidence of any specific strain that could be the "loaded spring". Nonetheless, the formation of a preorganized complex that reduces the degrees of freedom and favours cyclization seems reasonable.



Scheme 3 Synthesis of bis-terpyridine macrocycle **1** and metal complexes **1a** and **1b**. Reaction conditions: (a) $Cu(OAc)_2 \cdot H_2O$ (0.5 equiv.), ethanol, RT, 1 h; (b) $Cu(OAc)_2 \cdot H_2O$ (10 equiv.), ethanol, reflux, 72 h, 91%; (c) H_2, 80 psi, Pd/C (10%), 1 : 1 ethanol : CH_2Cl_2, 6 h, 91%; (d) Ru $(DMSO)_4Cl_2$, 10 : 4 : 1 ethylene glycol : dichloroethane : ethanol, reflux, 16 h, 96%; (e) $Zn(OTf)_2$, 1 : 1 ethanol : CH_2Cl_2, RT, 6 h, 97%.



Scheme 4 Synthesis of new ring-in-ring structure **2-terpy** and the subsequent coordination of metal ions to give tetrametallic two-ring structures **2-terpy** ⊃ **Ma–c**. Reaction conditions: (a) Cs_2CO_3, dimethylformamide, reflux, 4 h, 56%; (b) $Zn(OTf)_2$, acetonitrile, RT, 3 h, 94%; (c) $RuCl_3 \cdot 3H_2O$, 1 : 1 ethanol : 1,2-dichloroethane, 80 °C, 16 h, 99%; (d) $PtCl_2(COD)$, $AgBF_4$, acetonitrile, RT, 30 min, 70%.

In contrast, treating macrocycle **1** with one equivalent of Zn(II)OTf_2, a more kinetically-labile metal, gave a complex mix of spectroscopic signatures, while increasing the amount of metal to greater than a two-fold excess of the Zn(II)OTf_2 reagent transformed **1** cleanly into **1b** (Scheme 3). The ease of formation of complexes **1a**/**b** and their crystal structure geometries support the notion of a conformationally flexible macrocycle **1**.

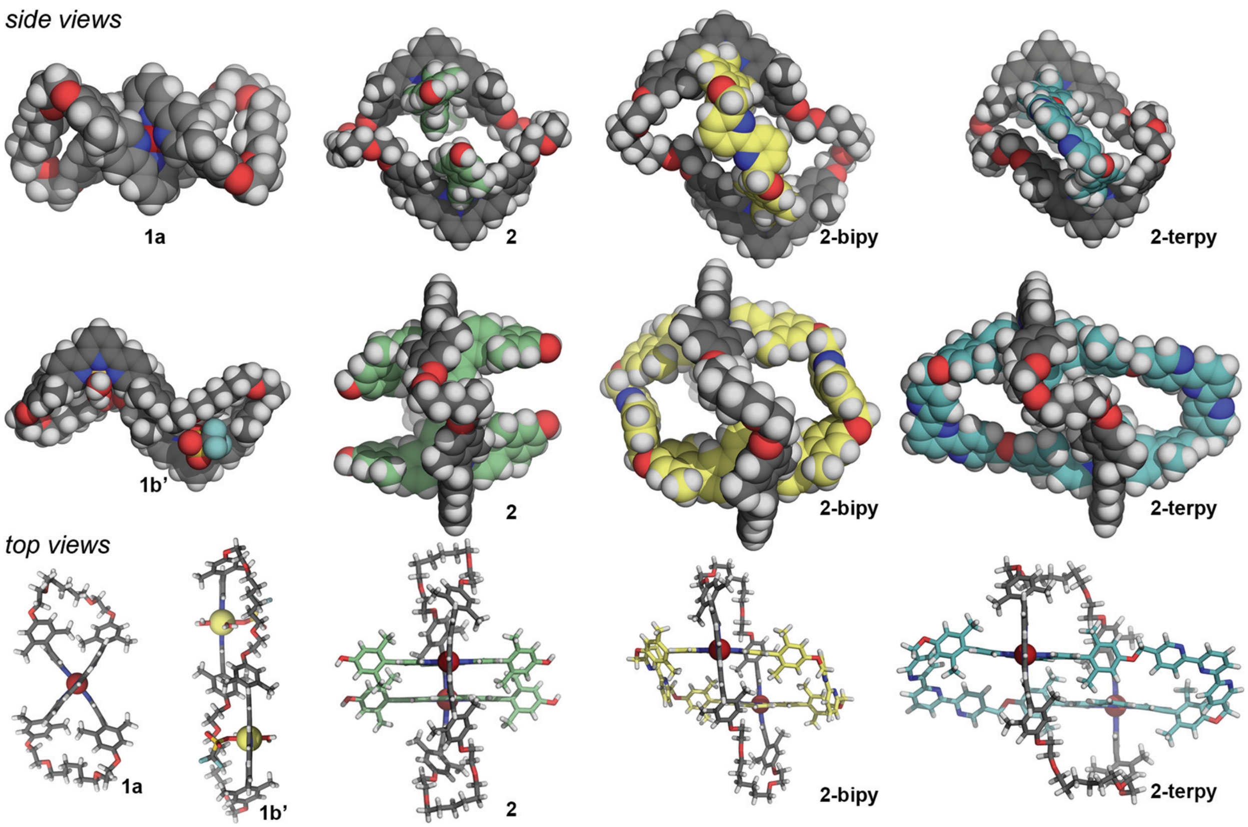


Fig. 1 Side and top views of macrocyclic cation structures from crystal diffraction analyses emphasizing the conformational flexibility of macrocycle **1** (black) in complexes **1a** Ru(II); **1b'** Zn(II); doubly threaded complex **2**; and ring-in-ring structures **2-bipy** and **2-terpy** with Ring II highlighted in yellow and blue, respectively. Disordered atoms, solvent molecules, and anions removed for the sake of clarity.

The terpy elements in macrocycle **1** are 5,5″-diaryl substituted and sometimes denoted as V-terpys in reference to their overall shape. An alternative form is the 4,4″-diaryl substitution, which then becomes a W-terpy by analogy. The reaction of macrocycle **1** with two equivalents of an appropriate W-terpyRuCl$_3$ complex gives the doubly threaded ring-in-ring precursor **2** (Scheme 2). The structure of **2** further exemplifies the conformational manifold accessible to the alkyl chains in these systems. From the crystal structure of **2**, one also sees that the strategy of using V-shaped and W-shaped terpy derivatives to direct the ends of the segments makes ring-selective coupling more feasible. Combined with the insight from the structure **1b**, one gets a feeling for the dynamic range of metrics suitable for a coupling bridge.

Previously, intermediate **2** was shown to react with 6,6′-bis-bromomethyl-2,2′-bipyridine to give the bipy ring-in-ring complex **2-bipy** (Scheme 2).[13] In the present context, one can see that although the metrics of the *trans* conformation of 6,6′-bis-bromomethyl-2,2′-bipyridine fit the structural model well, the *cis*-conformation is too short; therefore the idea of using the bipy bridge for further coordination complex formation was ill-fated, as was the use of this bridge in a strategic synthesis of the B-link.

The V-terpy bridged ring-in-ring structure **2-terpy** removes the shape ambiguity associated with s-*cis*/s-*trans* bipy conformations. s-*cis*/s-*trans* conformations of the V-terpy leave the linking vectors essentially unchanged in their position and direction. The 5-to-5″ distance in 5,5″-dimethylterpy fits the structural model and was added as a new design element. The new ring-in-ring structure was thus prepared from precursor **2** and 5,5″-bis(bromomethyl)-terpyridine under Williamson ether synthesis conditions in dimethylformamide (Scheme 4). Addition of aqueous potassium hexafluorophosphate resulted in a red precipitate, which was purified by column chromatography to provide pure **2-terpy** in 56% yield. Characteristic benzylic signals corresponding to the terpyridine units appeared in the complex but highly symmetrical (D_{2h}) ^{1}H and ^{13}C NMR spectra (Fig. S6 and S7, ESI†). The robust ring-in-ring complex was stable under ESI-MS conditions and the sequential loss of PF_6^- counter-ions was observed. Final structural confirmation was supplied by single crystal X-ray analysis using synchrotron radiation (Fig. 1).

Circumventing the previous conformational issues arising from s-*cis*/s-*trans* isomerisation of 2,2′-bipyridine in **2-bipy**, enabled ring-in-ring structure **2-terpy** to coordinate additional metal ions. To demonstrate this, treatment of ring-in-ring complex **2-terpy** with two equivalents of Zn(II), Ru(II), or Pt(II) gave high yields of the mixed tetra-metal complexes **2-terpy** ⊃ **Ma–c**, respectively (Scheme 4).

Structural studies

X-ray diffraction quality crystals of **1a**, **1b′**, **2**, and **2-terpy** were grown using solvent diffusion techniques.¶[14] The crystal structure of macrocyclic complex **1a** confirmed the figure-eight helical structure wound upon a central Ru(II) ion (centrosymmetric space group $P2_1/n$) (Fig. 1). The kinetically inert character of the Ru(II) complex should impose configurational stability in the molecule. As such, it should be possible to resolve these complexes into the pure, time-averaged D_2 symmetric enantiomers, analogous to Prelog's vesperines.[15]

Macrocycle complex **1b** crystallizes as **1b′** in space group $P\bar{1}$, with each macrocyclic cation resting across a crystallographic centre of inversion. Each terpyridine subunit binds a single Zn(II) cation with the remaining coordination sites occupied by one triflate anion and two water molecules that displaced the weakly bound, second triflate anion of **1b**. The macrocycle adopts a collapsed conformation with the two Zn(II) cations offset; the Zn⋯Zn distance is *ca.* 13 Å (Fig. 1). This slipped structure is further characterized by intramolecular and anti-parallel offset aromatic–aromatic contacts between the manisyl groups of opposing V-terpy elements.[16] Whereas the Ru(II) in **1a** holds the opposing V-terpy planes of Ring I roughly orthogonal, the planes of the V-terpy units in **1b′** are parallel but offset (Fig. 1). Complex **1b′** is achiral by virtue of a centre of inversion in the crystal; in solution, the dynamic symmetry consistent with the NMR data is time-averaged D_{2h}.

The crystal structure of threaded two-ring precursor **2** adopts space group $P\bar{1}$ with the macrocycle again sitting across a crystallographic centre of inversion. The two W-terpyRu(II) elements clearly thread Ring I, forming a double pseudo-rotaxane (Fig. 1). Outer Ring I adopts an expanded conformation with *ca.* 25 Å between the apical 4′-terpyridine H's. The planes of the two terpyridine units in Ring I are parallel but slightly offset avoiding steric congestion of the two 4′-hydrogen atoms.

¶Crystal data for **1a**: $C_{82}H_{90}F_{12}N_6O_8P_2Ru\cdot 5CH_3CN$, M_r = 1883.87, red prism: 0.07 × 0.20 × 0.32 mm, monoclinic, $P2_1/n$, a = 20.3614(3), b = 15.5902(3), c = 30.5936(5) Å, β = 94.4504(9)°, V = 9682.3(3) Å^3, Z = 4, ρ = 1.292 g cm^{-3}, Mo Kα radiation, $F(000)$ = 3920, μ = 0.276 mm^{-1}, T = 160 K, $2\theta_{max}$ = 50°, 141 740 measured reflections, 17 083 unique reflections used, 9660 with $I_o > 2\sigma(I_o)$, R_{int} = 0.120, 1455 parameters, 4603 restraints, GoF = 1.032, $R(F)$ = 0.1001 [$I_o > 2\sigma(I_o)$ reflections], w$R(F^2)$ = 0.3174 (all reflections), $2.05 > \Delta\rho > -0.70$ e Å^{-3}. Crystal data for **1b′**: $C_{86}H_{98}F_{12}N_6O_{24}S_4Zn_2\cdot 4CH_3CN\cdot 2C_4H_{10}O$, M_r = 2399.14, colourless plate: 0.13 × 0.30 × 0.30 mm, triclinic, $P\bar{1}$, a = 11.0301(2), b = 12.3939(4), c = 21.8715(7) Å, α = 76.878(1), β = 78.788(2), γ = 87.305(2)°, V = 2856.3(1) Å^3, Z = 1, ρ = 1.395 g cm^{-3}, Mo Kα radiation, $F(000)$ = 1252, μ = 0.587 mm^{-1}, T = 160 K, $2\theta_{max}$ = 50°, 43 549 measured reflections, 10 053 unique reflections used, 7931 with $I_o > 2\sigma(I_o)$, R_{int} = 0.060, 783 parameters, 153 restraints, GoF = 1.035, $R(F)$ = 0.0495 [$I_o > 2\sigma(I_o)$ reflections], w$R(F^2)$ = 0.1256 (all reflections), $0.70 > \Delta\rho > -0.59$ e Å^{-3}. Crystal data for **2**: $C_{144}H_{144}F_{24}N_{12}O_{12}P_4Ru_2\cdot 11CH_2Cl_2$, M_r = 3950.91, red plate: 0.05 × 0.32 × 0.35 mm, triclinic, $P\bar{1}$, a = 15.0040(5), b = 15.1525(4), c = 21.5611(7) Å, α = 98.402(2), β = 98.012(1), γ = 108.321(2)°, V = 4513.0(2) Å^3, Z = 1, ρ = 1.454 g cm^{-3}, Mo Kα radiation, $F(000)$ = 2014, μ = 0.611 mm^{-1}, T = 160 K, $2\theta_{max}$ = 50°, 77 052 measured reflections, 15 898 unique reflections used, 11 033 with $I_o > 2\sigma(I_o)$, R_{int} = 0.103, 930 parameters, 271 restraints, GoF = 1.033, $R(F)$ = 0.0627 [$I_o > 2\sigma(I_o)$ reflections], w$R(F^2)$ = 0.1674 (all reflections), $0.59 > \Delta\rho > -0.45$ e Å^{-3}. Crystal data for **2-terpy**: $C_{178}H_{166}F_{24}N_{18}O_{12}P_4Ru_2\cdot 12C_6H_6$, M_r = 4468.59, red plate, orthorhombic, $Pnnn$, a = 22.824(1), 22.583(1), 47.813(1) Å, V = 24 645(2) Å^3, Z = 4, ρ = 1.204 g cm^{-3}, λ = 0.8000 Å, $F(000)$ = 9296, μ = 0.309 mm^{-1}, T = 100 K, $2\theta_{max}$ = 55°, 93 055 measured reflections, 13 465 unique reflections used, 9226 with $I_o > 2\sigma(I_o)$, R_{int} = 0.048, 1087 parameters, 852 restraints, GoF = 2.178, $R(F)$ = 0.1536 [$I_o > 2\sigma(I_o)$ reflections], w$R(F^2)$ = 0.4940 (all reflections), $1.19 > \Delta\rho > -0.65$ e Å^{-3}.

As a result, the two Ru(II) centres are *ca*. 13 Å apart and, as expected, the phenol oxygen atoms of the threaded terpyridines are preorganized suggesting a favoured macrocyclization O⋯O distance of around 8 Å.

The crystal structure of the bipyridine-containing two-ring complex **2-bipy** has been reported previously, but is discussed here for comparison (space group $P\bar{1}$).[13] Macrocyclization with 6,6′-substituted 2,2′-bipyridines resulted in an expanded Ring I as the bridging bipyridines adopt the extended *trans*-conformation (Fig. 1). Rings I and II adopt a chair-like conformation where the planes defined by the two V-terpy (in Ring I) and two W-terpy (in Ring II) elements are parallel relative to each other, but offset roughly by 5 Å. As a result, the expanse of Ring I is on the order of 26 Å and the two Ru(II) centres are 16 Å apart.

The crystal structure of **2-terpy** adopts space group *Pnnn* and confirmed the new ring-in-ring topology. The limited quality of the diffraction data precludes a detailed analysis of the geometry,[17] but an overview of the cation topology, which is not unlike that of **2-bipy**, is depicted in Fig. 1. The new tetraterpyridine Ring II (blue) assumes a rhomboidal shape tilted relative to the *z*-axis of Ring I. The two coordinated exotopic terpyridine subunits are offset, but the octahedral geometries of the Ru(II) centres ensure a parallel orientation relative to the long *z*-axis of Ring I. Concomitantly, Ring I distorts into a pronounced S or Z-shape where coordinated V-terpy subunits are parallel but displaced. The newly installed V-terpy elements of Ring II span the distance between the W-terpy elements well, consistent with the structural design model.

Overall, the expanse of the new ring-in-ring structure **2-terpy** along the arbitrary *z*-axis of Ring I is on the order of 25 Å, and is comparable to the two-ring structure **2-bipy**. V-terpy-bridged Ring II in **2-terpy** is a 64-atom macrocycle, 10 atoms larger than Ring II in **2-bipy** (Fig. S1, ESI†), and although distorted, the semi-rigid structure of Ring II appears to generate two large pockets suggestive of binding sites for the coordination of subsequent metal ions; unlike in the bipy elements of **2-bipy** the flanking pyridines of the V-terpy elements in **2-terpy** can simply rotate into the requisite s-*cis*-binding conformation with minimal structural rearrangement (Scheme 4).

Discussion and conclusions

The general ring-in-ring strategy for a kinetically directed synthesis of the B-link is enhanced by the ability to isolate and structurally characterize synthetic intermediates along the way. The analysis of four macrocyclic structures has provided a good foundation for the dimensional scope in these complexes and the V-terpy/W-terpy design elements are now robust in terms of their chemical synthesis and their applicability as design elements toward an engineered synthesis of ring-in-ring topologies. Remarkably, even with the apparent space available within the open V-terpy loops of **2-terpy** and the ability to bind additional simple ligated metals, additional bipy or terpy metal complexes have not been successful threading partners for advancing to the final phase of the B-link synthesis. New strategies are needed, among them building the loops with the threading elements already in place.[18] This strategy may be facilitated by the design of newer laterally extended terpy analogues.[19]

Overall, the future for directed synthesis of higher-order topological molecular structures is positive. Soon chemists will have the ability to design in local active sites in these topological molecules. The prospect of catalysis with biological activity and specificity in this class of supramolecules seems well within reach of our design capabilities.

Acknowledgements

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