

Synthesis of tripodal [2]rotaxanes: high concentration principle†

Kirill Nikitin, Brenda Long and Donald Fitzmaurice*

Department of Chemistry, University College Dublin, Belfield, Dublin 4, Ireland.

E-mail: donald.fitzmaurice@ucd.ie; Fax: +353 1 7162127; Tel: +353 1 7162107

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Symmetrical and non-symmetrical tripodal [2]rotaxanes (**1**) incorporating 1,1'-disubstituted-4,4'-bipyridinium cations (**2**) and 34-crown-10 (**3**) have been prepared directly from 4,4'-bipyridine or from monocationic intermediates in high yields at room temperature and atmospheric pressure under conditions that permit the use of high reagent concentrations (0.1–0.2 M, 150–200 g l⁻¹).

The bottom-up assembly of functional nanoscale architectures in solution is a goal shared by researchers in many fields.¹ Expected benefits include greater control over material properties and technologies that address unmet needs.²

One approach envisaged is the self-assembly of nanoscale architectures, consisting of molecular and condensed phase components, in solution.³

In considering what molecular and condensed phase components might be suitable,^{4–6} one is immediately attracted to high-information content molecules,⁷ and nanoparticles whose properties can be tuned by controlling their size and surface composition.⁸

There exists a growing number of examples where high-information content molecules and nanoparticles have been self-assembled in solution to yield novel nanoscale architectures, some with significant technological potential.^{9–11}

It is in this context that we report the synthesis of novel tripodal [2]rotaxanes (**1a–c**) (Fig. 1) consisting of tripodal axial units (**2a–c**) threaded into bis(*p*-phenylene-34-crown-10) (**3**) which is prevented from dethreading by a full stopper (**ST**) group (**A**) or partial stopper groups (**B**, **C**). The tripodal group (**TP**) binds (after hydrolysis) to the surface of a metal oxide nanoparticle and orients the axial unit **2** of the rotaxane normal to the surface.¹²

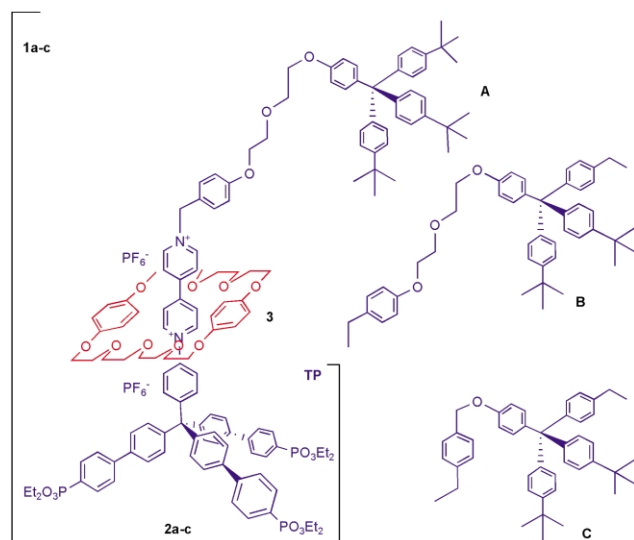


Fig. 1 Tripodal [2]rotaxanes **1a–c** and their components.

In principle, **1a–c** may be synthesised by adopting one of two approaches. A slippage approach,¹³ in which the axial group is terminated with a partial stopper **B** or **C** that the crown can 'slip-over' at elevated temperatures. A threading approach,¹⁴ in which the axial group threads the crown to form a pseudorotaxane and a full stopper group is subsequently attached to the axial group.

Assembling **1a** using the slippage approach was not expected to yield the desired product since the full stopper group **A**, based on the tris(4-*tert*-butylphenyl)methyl moiety, is too bulky.¹³ An option was to prepare **2b** or **2c** using a partial stopper (**B** or **C**) and thread the crown **3** at elevated temperatures. The partial stoppers **B** and **C** are sufficiently bulky to prevent dethreading at room temperature.¹³

Accordingly, partially stopped axial molecules of the general formula **2** were reacted with the crown **3** (Fig. 2). The conditions and yields of **1** are given in Table 1.

Slipping of **3** onto **2c**, bearing the partial stopper **C**, did not proceed in acetonitrile under usual conditions at 60 °C (Table 1, run 1).¹³ The same reaction was repeated using higher reagent concentrations in benzonitrile (runs 2 and 3). Although benzonitrile dissolves the reagents at concentrations as high as 0.1 M at the reaction temperature, the highest yield achieved did not exceed 5% (run 3). The yield can not be improved using **2b**, bearing stopper group **B** (run 4). The symmetrical axial compound **2d**, incorporating a stopper group **C** at each end (run 5), also did not react with crown even under high concentration conditions. It is concluded that the tripodal [2]rotaxanes **1** can not be synthesised using the slippage approach.

Having been unsuccessful in preparing the tripodal [2]rotaxanes **1b–d** using the slippage approach, we considered the threading approach. The threading approach would generally¹⁴ be justified on the basis of the assumption that the 4,4'-

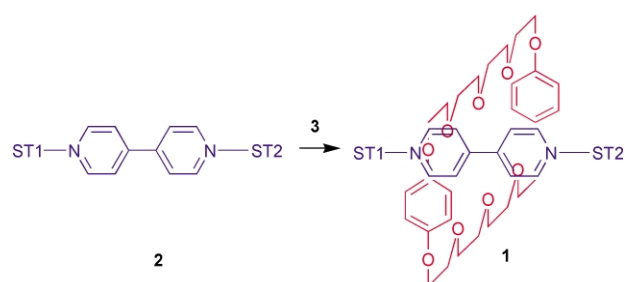


Fig. 2 Slippage of **3** to form [2]rotaxanes **1**.

Table 1 Attempted slippage synthesis of [2]rotaxanes **1b–d**^a

Run	1	2 :ST1/ST2	Solvent	[2]/M	T/°C	Time	Yield (%)
1	1c	2c :TP/C	MeCN	0.01	60	12 h	0
2	1c	2c :TP/C	PhCN	0.05	60	2 d	0
3	1c	2c :TP/C	PhCN	0.1	60	5 d	5
4	1b	2b :TP/B	PhCN	0.1	50	2 d	0
5	1d	2d :C/C	PhCN	0.1	75	2 d	0

^a All reactions were run at 2:1 ratio of crown **3** to the axial unit **2**.

† Electronic supplementary information (ESI) available: experimental details. See <http://www.rsc.org/suppdata/cc/b2/b209836a/>

bipyridinium dication of the axial group would form a pseudorotaxane with the crown **3** followed by stoppering of the pseudorotaxane with a suitable stopper. However, for the synthesis of **1** that approach would require complexation of **3** to the 4,4'-bipyridinium monocation before alkylation to form the dication. It should be noted that rotaxane formation based on the complexation of the monocation under ultra high pressure (30 °C, 12 kbar, 2 days, 26% yield) has been reported.¹⁵ On this basis more facile conditions were sought.

Reactions of 4,4'-bipyridyl with a full stopper alkylating reagent **A-Br** (Fig. 3) were studied. Concurrent formation of **1e** and **2e** under a range of conditions (Table 2) was observed. As has previously been reported, the self-assembly of rotaxane **1e** practically did not proceed in acetonitrile (run 1).¹⁵ Traces of **1e** were found when the reaction was run in DMF (run 2). In benzonitrile the solubility of all components is high and both products are formed at relatively good yields (run 3). It is assumed that the mechanism of rotaxane formation involves the crown **3** being threaded by the monocation intermediate **4** to form a weak complex **5** and subsequent alkylation of **5** at the remaining pyridine nitrogen (Fig. 4).

In short, under mild conditions (room temperature and atmospheric pressure) and in the presence of a high concentration of crown **3** in benzonitrile, conditions that favour formation of a complex **5** between the crown **3** and the interim monocation **4**, a good yield of **1e** is obtained (36%).

To fully exploit these high concentration conditions, pre-formed compounds **4** were reacted with the full stopper **A** or partial stopper **B** in the presence of crown **3** (Table 3). These results show a dramatic increase in the yields obtained.

The yields are higher for the less symmetrical and thus more soluble reagents **4** and **6** incorporating partial stoppers **B** and **C** (Table 3, runs 2 and 4). This effect cannot be accounted for by crown concentration as the same concentration of **3** was used in all cases.

The greater solubility of unsymmetrical reagents **4** and **6** permits total concentrations of ca. 40% by weight. Under these

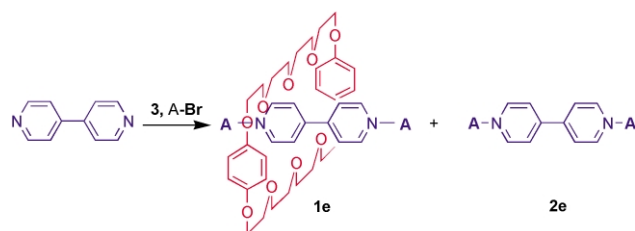


Fig. 3 Direct formation of [2]rotaxane from 4,4'-bipyridyl.

Table 2 Synthesis of **1e** at room temperature^a

Run	Solvent	Solubility	Yield 1e (%)	Yield 2e (%)
1	MeCN	Sparing	2.5	17
2	DMF	Good	9	68
3	PhCN	Complete	36	35

^a Reactions were run at 0.2 M nominal starting concentration of **3** and 0.1 M of 4,4'-bipyridyl.

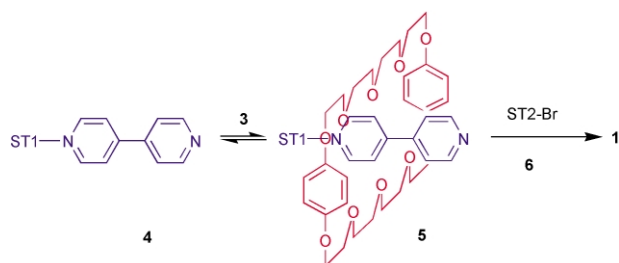


Fig. 4 Possible mechanism for high concentration threading to form **1**.

Table 3 High concentration synthesis of **1^a** (Fig. 4)

Run	Rotaxane	ST1	ST2	Time/days	Yield 1 (%)
1	1e	A	A	10	40
2	1f	C	B	5	84
3	1a	TP	A	5	48
4	1g	B	B	5	90

^a Reactions were run at room temperature in PhCN at 0.2 M starting concentration of **3** and 0.1 M of **4**

Table 4 Synthesis of the tripodal rotaxane **1b** (stopper **B**)^a

T/°C	Time	Yield 1 (%)	Yield 2b (%)
50	20 h	40	37
40	2 d	52	40
30	2 d	62	30
20	5 d	75	24

^a Reactions were run in PhCN at 0.2 M starting concentration of **3** and 0.1 M of **4**

circumstances there may not be enough solvent molecules to completely solvate reagent molecules. Accordingly, the reagents simply solvate *each other* forming intermolecular complexes. In other words, under high concentration conditions the extent of pseudorotaxane **5** formation may be higher than expected on the basis of equilibrium constant as evidenced by the higher yields.

The approach was also applied for the synthesis of tripodal [2]rotaxane **1b**. For this reaction the temperature dependence of the rotaxane yield has been studied (Table 4). Rotaxane formation is favoured at lower temperatures, a finding correspondent with the formation of the interim pseudorotaxane.

To summarise, this work describes a novel and elegant approach to the synthesis of [2]rotaxanes of the common formula **1** showing tripodal structures, at room temperature and atmospheric pressure in high yields. A similar approach may be useful for the synthesis of known and new rotaxanes, catenanes and other supramolecular systems.

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