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A molecular gate: control of free intramolecular rotation by application of an external signal†

Rita Annunziata, Maurizio Benaglia, Mauro Cinquini, Laura Raimondi and Franco Cozzi*

CNR-ISTM and Dipartimento di Chimica Organica e Industriale, Università di Milano, via Golgi 19, 20133 Milan, Italy

ABSTRACT: Control of internal movement in a conformationally free pentiptycene derivative is achieved by complexation of two phenanthroline units by copper(I) cation. Copyright © 2004 John Wiley & Sons, Ltd.

KEYWORDS: molecular device; pentiptycene; phenanthroline; copper(I) complex; restricted rotation

Over the last three decades, control of molecular movement has been a coveted goal for chemists interested in the development of molecular devices (for reviews, see Ref. 1). In this context, command of internal rotation has been sought by two different approaches. One approach, pioneered and mastered by Mislow, entailed the synthesis of a sterically congested molecule that displays discrete motion as the consequence of temperature variation (for reviews and recent examples, see Ref. 2). In other endeavours, conformationally free molecules were forced to undergo discrete movements by application of an external signal, the removal of which restored the original situation[3] (for recent reports describing the control of other molecular movements, see Ref. 4).

Here, we report preliminary results on the development of a molecular gate to control internal rotation in a conformationally unrestricted molecule. The molecular design (Fig. 1) is based on the connection of two phenanthroline units to a pentiptycene skeleton representing the free-rotating rotor A (gate open), the movement of which should be controlled by application of the external signal (phenanthroline complexation) as in B or C (gate closed). [In a previous study by Kelly *et al.*,[3a] a similar approach was employed to block the internal rotation of a triptycenyl bipyridine derivative. In that case however, it was shown that, in the absence of an external signal, internal rotation could also be slowed (although not completely prevented) by decreasing the temperature, the molecule under investigation being considerably less conformationally mobile than those reported in this work. We believe that the term 'gate' (a device that allows/prevents passage) descibes more precisely than 'brake' (an apparatus for checking motion) the sort of movement restriction reported here and in previous work.[3a] In other words, the notion of 'molecular brake' implies a much more refined movement control than that of 'molecular gate'.]

**Correspondence to:* F. Cozzi, Dipartimento di Chimica Organica e Industriale, Università di Milano, via Golgi 19, 20133 Milan, Italy.
E-mail: franco.cozzi@unimi.it
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†Dedicated to Kurt Mislow on the occasion of his 80th birthday.

In a first attempt to prepare a molecule suitable for this study, hydroquinone **1**[5] (for the use of **1** in the development of chemosensors, see Refs 5b and c) (Scheme 1) was alkylated with mesylate **3**, obtained from 2-(4-hydroxyphenyl)-1,10-phenanthroline **2**[6] by *O*-alkylation with 6-bromohexanol (Cs_2CO_3, acetonitrile, 60 °C, 72 h, 90% yield), followed by mesylation (MsCl, triethylamine, dichloromethane, 23 °C, 12 h, 96% yield) (all new compounds had spectral data in agreement with the proposed structures). ^{1}H NMR analysis of **4**, obtained in 21% unoptimized yield (Cs_2CO_3, acetonitrile, 80 °C, 72 h), showed one set of signals for the eight aromatic hydrogens shown as H_a in Scheme 1 and another set of signals for those indicated as H_b. Thus, a clear demonstration of the equivalence of the four phenyl rings and, hence, of the unhidered rotation of the pentiptycene moiety around the C—O bond in this compound was obtained.

Treatment of **4** with 1 mol equiv. of CuOTf in 1:1 chloroform–acetonitrile (23 °C, 24 h) led to the formation of a dark-red complex that was purified by short-path chromatography to afford **4**·Cu (>90% yield). The complex **4**·Cu was characterized as a single monomeric species by mass spectrometry {fast atom bombardment (FAB); *m/z* 1234/1236 $[M - OTf]^+$}. Also ^{1}H and ^{13}C NMR spectra (CD_3OD) were consistent with the formation of a single complex; the resonances of the H atoms *meta* to nitrogen in the phenanthroline moieties underwent upfield shifts of ~0.5 ppm and those of the C atoms in the same position were shifted downfield by ~4 ppm with respect to those of **4**. The phenantroline protons gave sharp ^{1}H NMR signals, whereas those of the phenyl groups of the pentiptycene skeleton were found to be broad and unresolved in the temperature range from −60 to +60 °C. Thus, even if complexation of **4** had indeed occurred, this structural modification was not sufficient to prevent the free rotation of the pentiptycene rotor. Decomplexation with cyanide ions restored the original ligand **4**.

After molecular mechanics calculations suggested that a more rigid tether between the pentiptycene and phenanthroline groups could provide a better candidate to

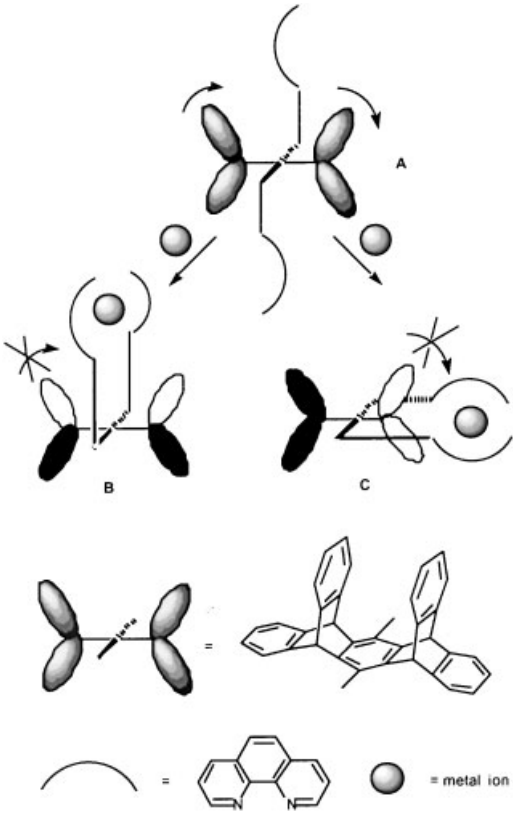
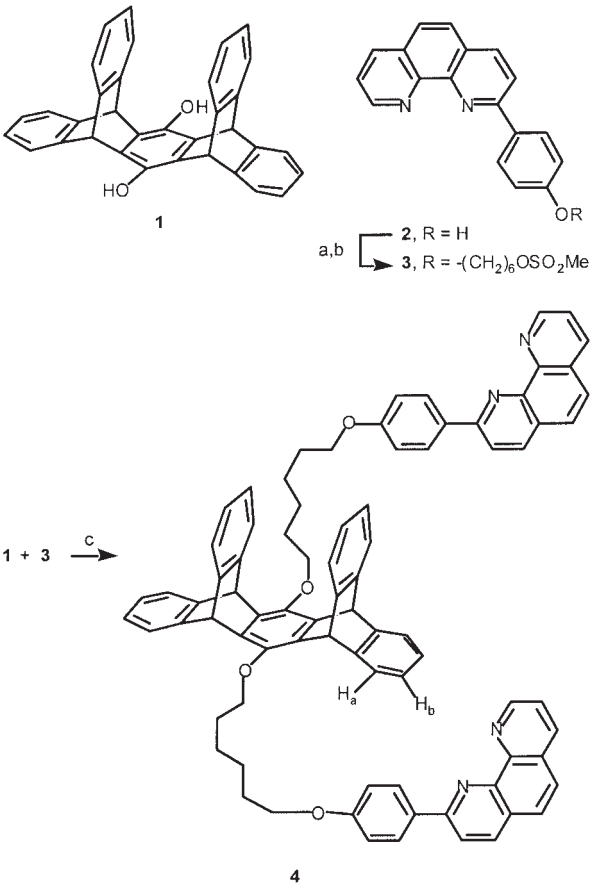


Figure 1. Schematic represenatation of (A) free and (B, C) blocked rotors. Lobes of the same shade indicate symmetry-equivalent rings in pentiptycene

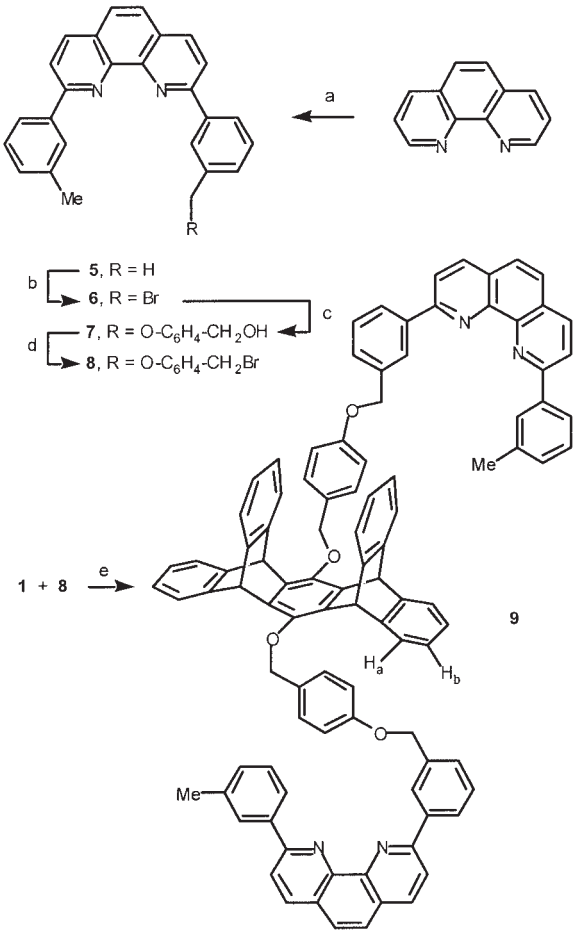


Scheme 1. Synthesis of ligand **4**. Reagents and conditions: a, 6-bromohexanol, Cs_2CO_3, CH_3CN, 60 °C, 72 h; b, MsCl, Et_3N, CH_2Cl_2, 23 °C, 12 h; c, **3**, Cs_2CO_3, CH_3CN, 80 °C, 72 h

observe the desired phenomenon, **9** was synthesized as described in Scheme 2. Thus, **5**, prepared in 75% yield from 1,10-phenanthroline and 3-bromotoluene (*t*BuLi, THF, −78 to 23 °C, 40 h, then MnO_2, dichloromethane, 23 °C, 24 h), was sequentially converted into monobromide **6** (NBS, refluxing carbontetrachloride, 2 h, 33% yield at 50% conversion), alcohol **7** (4-hydroxymethylphenol, Cs_2CO_3, acetonitrile, 60 °C, 72 h, 96% yield), and bromide **8** (PBr_3, dichloromethane, 0–23 °C, 12 h, 75%). Alkylation of **1** with **8** (Cs_2CO_3, acetonitrile, 80 °C, 72 h) afforded ligand **9** in 45% unoptimized yield. Also for this compound, ^{1}H NMR analysis showed one set of signals for the eight aromatic protons indicated as H_a and another signal for those indicated as H_b in **9**, confirming the free rotation of the pentiptycene residue that persisted even at −70 °C.

The formation of the corresponding Cu complex was performed as described above for **4** · Cu to afford a >90% isolated yield of **9** · Cu. Mass spectrometry indicated that only monomeric species were formed (FAB; *m*/*z* 1453/1455 $[M - OTf]^+$). ^{1}H and ^{13}C NMR analysis at 25 °C (CD_3CN) showed the presence of two species in a roughly equimolar ratio. For both, the sharp shape and the observed chemical shifts of the H and C signals of the phenanthroline residues clearly indicated that these groups are firmly involved in Cu(I) complexation. The pattern of the hydrogens of the pentiptycene phenyl groups was more complicated. Indeed, for one adduct the 2D NMR [H,H] COSY experiment carried out at 25 °C revealed two distinct, well-resolved pairs of correlated protons, with four of the eight H_a protons resonating at 6.83 ppm and four at 6.91 ppm, and four of the eight H_b protons resonating at 7.12 ppm and four at 7.25 ppm, respectively. [It must be noted that when pentiptycene rotation is frozen, the **9** · Cu complex has C_2 symmetry. Hence the four protons of each pentiptycene phenyl ring should give rise to four resonances (H_a, H_b, $H_{b'}$, $H_{a'}$). *De facto*, accidental isochrony occurs between H_a/$H_{a'}$, and H_b/ $H_{b'}$ which will be considered equivalent in the following discussion. We thank professor Siegel for calling our attention to this problem.] In addition, a third set of poorly resolved signals was observed for the same protons, with H_a resonating at 7.26 ppm and H_b at 7.65 ppm. On cooling to −45 °C, the signals of the first two sets remained almost unchanged (shifting to 6.81, 6.87, 7.07, and 7.29 ppm, respectively), whereas those of the third set became sharper and shifted to 6.95 and 7.35 ppm, respectively. Decomplexation with cyanide ions quantitatively restored the original ligand **9**.

These results can be interpreted as follows. The appearance of distinct sets of signals for H_a and H_b in proximal and distal phenyl rings in **9** · Cu strongly



Scheme 2. Synthesis of ligand **9**. Reagents and conditions: a, *m*-methylphenyllithium, THF, −78 to 23 °C, 40 h, then MnO_2, CH_2Cl_2, 23 °C, 24 h; b, NBS, CCl_4, 80 °C, 2 h; c, $HOC_6H_4CH_2OH$, Cs_2CO_3, CH_3CN, 60 °C, 72 h; d, PBr_3, CH_2Cl_2, 0–23 °C, 12 h; e, **8**, Cs_2CO_3, CH_3CN, 80 °C, 72 h

suggests that the free rotation of the pentiptycene rotor in **9** has been blocked by complexation. Therefore, this event acts as a gate at the molecular level. The restricted rotation results in the non-equivalence of the phenyl groups of the pentiptycene residues, consistent with the NMR evidence (see Fig. 1). The observation of more than two sets of signals shows that more than one complex is formed, possibly two structures similar to B and C (Fig. 1). Accidental isochrony can be invoked to explain why, in one case, only one and not two sets of signals are observed. Although it is not possible at present to assign unequivocally the B or C structure to the observed species, it seems possible that these diastereoisomeric complexes display different hindrances to rotation. The signals whose chemical shift does not change with temperature can tentatively be assigned to the complex in which rotation is more effectively blocked.

In conclusion, the free intramolecular rotation in a pentiptycene derivative suitably modified by insertion of two phenanthroline residues was blocked by complexation of the latter by Cu(I) cation. Removal of the metal restored free rotation. As a whole, the system described here represents an equivalent of a molecular gate. Work is in progress to develop other molecules in which internal rotation can be controlled at will.

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