

Copper(I)- or Iron(II)-Templated Synthesis of Molecular Knots Containing Two Tetrahedral or Octahedral Coordination Sites

Gwénaél Rapenne, Christiane Dietrich-Buchecker, and Jean-Pierre Sauvage*

Contribution from the Laboratoire de Chimie Organo-Minérale, UMR 7513, CNRS, Université Louis Pasteur, Institut Le Bel, 4 rue Blaise Pascal, 67070 Strasbourg, France

Received June 26, 1998

Abstract: Molecular trefoil knots have been prepared from metal-assembled precursors using the ring closing metathesis (RCM) cyclization methodology. The templating metal is either copper(I) or iron(II) and the coordinating fragments 1,10-phenanthroline or 2,2':6',2''-terpyridine, respectively. The RCM approach, newly applied to the field of catenanes and knots, represents a spectacular synthetic improvement in terms of yield and experimental conditions (no high dilution required). The dicopper(I) trefoil knot has been synthesized in a 74% yield. A similar approach also led to the first knot constructed around two iron(II) bis(terpyridine) moieties, demonstrating that iron(II) can also be used as a highly efficient template. Moreover, for both Cu(I) and Fe(II) knots, it has been possible to quantitatively reduce the cyclic olefins formed during the macrocyclization by catalytic (Pd/C) hydrogenation. An X-ray structure of the double helix of iron(II) bis-(1,2-bis(5-(5''-methyl-2,2':6',2''-terpyridinyl))ethane) is given which shows that the double-stranded helical precursor is well predisposed for the formation of a molecular knot.

Introduction

Knots as molecular objects have been envisaged since the 60's, either in purely theoretical discussions¹ or as real synthetic targets.² DNA-based knots have been identified more than two decades ago³ and prepared at will more recently.⁴ Knots have also been found in proteins.⁵

The use of transition metals as templates allowed us to prepare a molecular trefoil knot a few years ago,⁶ although the preparative procedure was extremely delicate and far from being really preparative. Very recently, another strategy based on aromatic acceptor–donor complexes has also produced small quantities of a molecular trefoil knot.⁷

In the course of the past few years, our original approach has been continuously improved, by modifying various factors of the precursors. In this way, sufficient amounts of the molecules could be prepared so as to allow various physical studies to be carried out. In particular, some of the compounds revealed fascinating kinetic properties⁸ (inertness toward demetalation) and photochemical or electrochemical behavior.^{9,10} One of the key factors to the dramatic improvement of the synthetic pro-

cedure was to use 1,3-phenylene groups as linkers between the chelates. These spacers favor helical structures^{11–13} and thus allow quantitative formation of double-stranded helical dinuclear complexes, used as precursors to the knots.

The ring-closing metathesis of olefins (RCM), as recently developed by Grubbs and co-workers,¹⁴ represents a real breakthrough in the field of large-ring synthesis.¹⁵ The utilization of this methodology turned out to be surprisingly efficient as far as the preparation of [2]-catenanes is concerned,¹⁶ leading to almost quantitative yields of interlocking rings from open chain diolefinic fragments. Preliminary work demonstrated that trefoil knots could be obtained using the RCM approach.¹⁷

The present report deals with the use of RCM for synthesizing molecular trefoil knots, following two markedly distinct approaches. One uses copper(I) as a template, leading to molecular knots with two tetrahedral (or pseudotetrahedral) coordination sites, in analogy with the previous strategies developed in our

(1) Frisch, H. L.; Wasserman, E. *J. Am. Chem. Soc.* **1961**, *83*, 3789–3795.

(2) Schill, G. In *Catenanes, Rotaxanes and Knots*; Academic Press: New York, 1971. Schill, G.; Keller, U.; Fritz, H. *Chem. Ber.* **1983**, *116*, 3675–3784. Schill, G.; Doerjter, G.; Logemann, E.; Fritz, H. *Chem. Ber.* **1979**, *112*, 3603–3615. Schill, G.; Boeckmann, J. *Tetrahedron* **1974**, *30*, 1945–1957.

(3) Wang, J. C. *J. Mol. Biol.* **1971**, *55*, 523–533.

(4) Seeman, N. C. *Acc. Chem. Res.* **1997**, *30*, 357–363.

(5) Liang, C.; Mislow, K. *J. Am. Chem. Soc.* **1994**, *116*, 11189–11190. Liang, C.; Mislow, K. *J. Am. Chem. Soc.* **1995**, *117*, 4201–4213.

(6) Dietrich-Buchecker, C. O.; Sauvage, J. P. *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 189–192. Dietrich-Buchecker, C. O.; Guilhem, J.; Pascard, C.; Sauvage, J. P. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 1154–1156.

(7) Ashton, P. R.; Matthews, O. A.; Menzer, S.; Raymo, F. M.; Spencer, N.; Stoddart, J. F.; Williams, D. J. *Liebigs Ann. Chem.* **1997**, 2485–2494.

(8) Meyer, M.; Albrecht-Gary, A. M.; Dietrich-Buchecker, C. O.; Sauvage, J. P. *J. Am. Chem. Soc.* **1997**, *119*, 4599–4607.

(9) Dietrich-Buchecker, C. O.; Sauvage, J. P.; De Cian, A.; Fischer, J. *J. Chem. Soc., Chem. Commun.* **1994**, 2231–2232.

(10) Dietrich-Buchecker, C. O.; Sauvage, J. P.; Armaroli, N.; Ceroni, P.; Balzani, V. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1119–1121.

(11) Williams, D. J.; Colquhoun, H. M.; O'Mahoney, C. A. *J. Chem. Soc., Chem. Commun.* **1997**, 2053–2054.

(12) Rüttimann, S.; Piguët, C.; Bernardinelli, G.; Bocquet, B.; Williams, A. F. *J. Am. Chem. Soc.* **1992**, *114*, 4230–4237.

(13) Constable, E. C.; Hannon, M. J.; Tocher, D. A. *J. Chem. Soc., Dalton Trans.* **1993**, 1883–1890.

(14) Fu, G. C.; Grubbs, R. H. *J. Am. Chem. Soc.* **1992**, *114*, 5426–5427. Grubbs, R. H.; Miller, S. J.; Fu, G. C. *Acc. Chem. Res.* **1995**, *28*, 446–452. Schwab, P.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc.* **1996**, *118*, 100–110.

(15) Fürstner, A.; Kindler, N. *Tetrahedron Lett.* **1996**, *37*, 7005–7008. König, B.; Horn, C. *Synlett* **1996**, 1013–1014. Marsella, M. J.; Maynard, H. D.; Grubbs, R. H. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1101–1103. Yang, Z.; He, Y.; Vourloumis, D.; Vallberg, M.; Nicolaou, K. C. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 166–168. Armstrong, S. K. *J. Chem. Soc., Perkin Trans.* **1998**, 371–388. Pariya, C.; Jayaprakash, K. N.; Sarkar, A. *Coord. Chem. Rev.* **1998**, *168*, 1–48. Grubbs, R. H.; Chang, S. *Tetrahedron* **1998**, *54*, 4413–4450.

(16) Mohr, B.; Weck, M.; Sauvage, J. P.; Grubbs, R. H. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1308–1310.

(17) Dietrich-Buchecker, C. O.; Rapenne, G.; Sauvage, J. P. *J. Chem. Soc., Chem. Commun.* **1997**, 2053–2054.

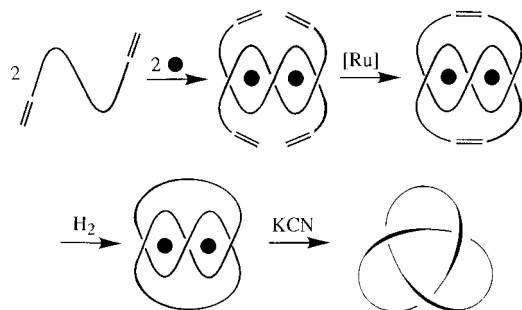


Figure 1. Synthetic strategy. Two coordinating fragments are gathered and interlaced around two metal centers. Each stringlike molecule incorporates two chelating subunits and bears terminal olefins. The metal template (black dot) is either Cu(I) or Fe(II). After RCM with a ruthenium catalyst, the desired knot is obtained which contains two tetrahedral or two octahedral coordination sites, respectively.

group. The second approach is based on iron(II) and 2,2':6',2''-terpyridine (terpy) derived ligands, $\text{Fe}(\text{terpy})_2^{2+}$ being known for several decades to be a very stable complex.¹⁸ The knots obtained by following this second strategy contain two pseudooctahedral coordination sites of (terpy)₂ type. It should be stressed that copper(I) has been used extensively in our group and others¹⁹ as a template to make various interlocking and threaded structures, but very few other metals have been used.^{20,21} A few years ago, the synthesis of a [2]-catenane based on a Ru(terpy)₂²⁺ core was reported,²² but the preparative procedure was far from satisfactory, in part due to the kinetic inertness of the ruthenium complex once incorporated in the catenane structure, thus preventing generation of the free ligand.

Results and Discussion

1. Strategy. The synthesis principle is indicated in Figure 1. It uses the template effect of metal ions to form a double helix which, after double cyclization, leads to the trefoil knot.

The cyclization step has the synthetic advantage of dividing by two the number of reaction centers involved during the ring closure procedure as compared to the classical method.^{6,9} In the latter, four phenolic functions of the double helix are reacting with four electrophilic carbons of the polyoxyethylenic diiodide chain, thus involving eight reaction centers.

2. Copper(I) as Template. Synthesis of the Precursor. By reaction of the bis(phenanthroline) thread **1** with 2-(2-chloroethoxy)ethanol in DMF at 80 °C in the presence of cesium carbonate, ligand **2** was obtained in 97% yield (Figure 2). Bis(phenanthroline) **2** was then quantitatively converted into its olefinic derivative **3**, first by generating the dialcoholate with NaH and then reacting the latter with a large excess of allyl bromide in refluxing THF.

The helical precursor **4**²⁺ was obtained quantitatively in the classical way⁹ by adding Cu(MeCN)₄PF₆ onto a solution of the bischelating thread **3** under argon.

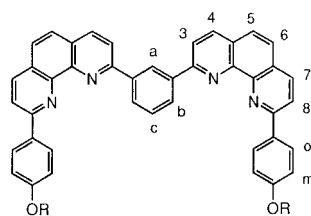
(18) IUPAC Chemical Data Series No. 17; McBryde, W. A. E., Ed.; Pergamon: Oxford, U.K., 1978. A critical review of equilibrium data for proton and metal complexes of 1,10-phenanthroline, 2,2'-bipyridyl, and related compounds. Constable, E. C. *Adv. Inorg. Chem. Radiochem.* **1986**, *30*, 69–121.

(19) Momenteau, M.; Looock, B.; Le Bras, F. *Tetrahedron Lett.* **1994**, *35*, 3289–3292. Gruter, G. J. M.; De Kanter, F. J. J.; Markies, P. R.; Nomoto, T.; Akkerman, O. S.; Bickelhaupt, F. *J. Am. Chem. Soc.* **1993**, *115*, 12179–12180.

(20) Fujita, M.; Ibukuro, F.; Seki, H.; Kamo, O.; Imanari, M.; Ogura, K. *J. Am. Chem. Soc.* **1996**, *118*, 899–900. Wu, C.; Lecavalier, P. R.; Shen, Y. Y.; Gibson, H. W. *Chem. Mater.* **1991**, *3*, 569–572.

(21) Mingos, D. M. P.; Yau, J.; Menzer, S.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.* **1997**, *34*, 1894–1895.

(22) Sauvage, J. P.; Ward, M. *Inorg. Chem.* **1991**, *30*, 3869–3874.



- 1:** R = H
2: R = CH₂CH₂OCH₂CH₂OH
3: R = (CH₂CH₂O)₂CH₂CH=CH₂

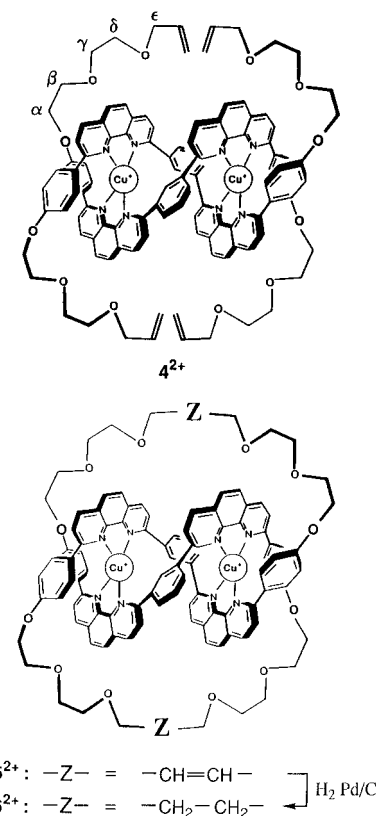


Figure 2. Chemical structure of the organic precursors and of the knots in the phenanthroline-based series.

The ¹H NMR spectrum of complex **4**²⁺ is typical of a double helical structure.^{6,9} In particular we can see the magnetic influence of the phenanthroline cores on the anisyl groups, leading to significant shielding of H_m (−1.3 ppm) and H_o (−1.4 ppm) protons of these groups (Figure 3a) as compared to the free ligand.

Cyclization. The metathesis reaction was performed in dichloromethane at room temperature, with a copper complex **4**²⁺ concentration of 0.01 M. The catalyst was ruthenium(II) dichloride phenylmethylene bis(tricyclohexylphosphine) [RuCl₂(PCy₃)₂(=CHPh)].

After 16 h of reaction, purification by chromatography yielded 74% of the knotted complex **5**²⁺. ¹H NMR spectroscopy (Figure 3b) showed total disappearance of the starting material. The signals of the terminal olefins (5.31 and 5.20 ppm) had vanished, whereas those of cyclic olefins had appeared at lower field (6.38 and 6.24 ppm).

Mass spectroscopy also confirmed the absence of any starting material, the only peak observed (*m/z*: 1965.3, [M − PF₆]⁺) corresponding to the expected knotted complex (Figure 4).

Finally, a two-dimensional ROESY ¹H NMR study showed a spatial proximity between the protons 5 and 6 of the phenan-

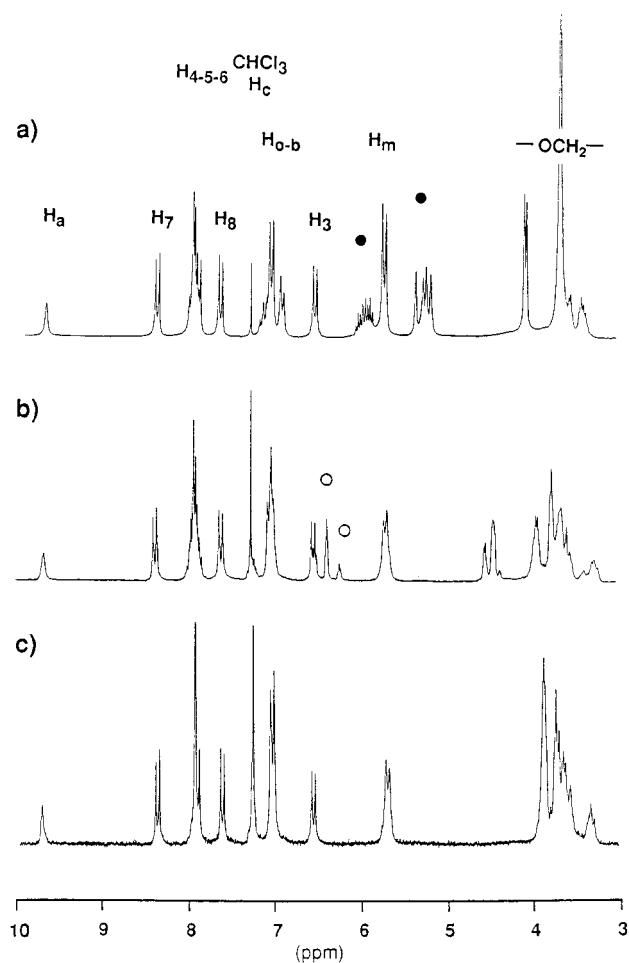


Figure 3. ^1H NMR (200 MHz, CDCl_3) spectra of (a) the helical precursor 4^{2+} with the signals corresponding to the four terminal olefins (●), (b) the trefoil knot 5^{2+} with the signals corresponding to the two olefins incorporated in the molecule (○), and (c) the trefoil knot 6^{2+} after catalytic reduction of the olefins.

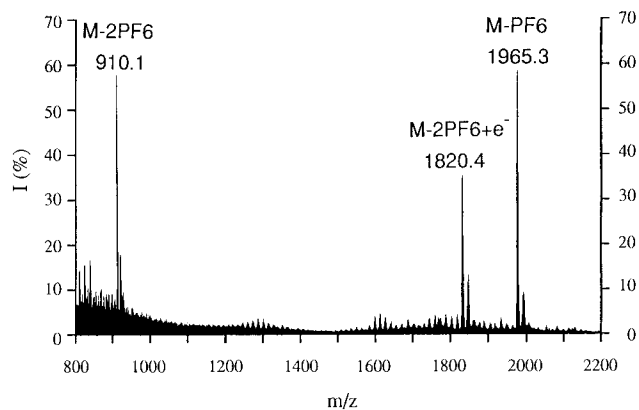


Figure 4. Positive FAB-MS spectrum of the knot 5^{2+} in a *p*-nitrobenzyl alcohol matrix (display from $m/z = 800$ – 2200). The signals at m/z 1836.4 and 1981.3 correspond to the reduction of the product by the matrix.

throlene fragments and the olefinic protons, which constitutes unambiguous evidence of the expected knotted structure.²³

Catalytic Reduction of the Cyclic Olefins. The copper(I) knot 5^{2+} is initially obtained as a mixture of three isomers. Since each double bond formed by the metathesis reaction can be *cis*

or *trans*, the *cis*–*cis*, *cis*–*trans*, or *trans*–*trans* isomers can be formed. Therefore the ^1H NMR signals of the phenanthroline are broad (or split into two), due to the different cycle strain in each isomer.

The broadness of the signal enables the attribution, since we know that a *trans* coupling (3J) between two olefinic protons is about 16–18 Hz, whereas it is only 7–8 Hz in the case of a *cis* coupling. Consequently, integration of the NMR signals leads to the percentage of *cis* and *trans* double bonds, which was found to be 80 and 20%, respectively.

To obtain a single species, we decided to reduce the olefins. Hydrogenation catalyzed by palladium (5% molar in Pd) was quantitative by saturating a 1/1 (v/v) ethanol/dichloromethane solution of the knot with hydrogen during 16 h, at room temperature.

The ^1H NMR spectrum of knot 6^{2+} does not show any olefinic signals and the phenanthroline signals are narrow (see Figure 3c), indicating the presence of a single species. This observation corroborates our tentative explanation of the broad signals before reduction, due to the coexistence of three olefinic isomers.

3. Iron(II) as Template. Design of the Ligand. The bridge between the two terpyridines plays a crucial role. It must be flexible enough to enable the entanglement of the ligand around the metal–metal axis but also short enough to prevent the two coordinating sites from folding up around a single metal and to avoid the formation of a face-to-face dinuclear complex.²³ Finally, a short connector should maintain the fragments in close proximity thus stabilizing the double helix by stacking of the aromatic π -systems. Relying on preceding experiments,^{24,28} we opted for a $(\text{CH}_2)_2$ bridge.

To avoid high-spin Fe(II) complexes obtained previously²⁴ with anisyl groups in the 6 positions, our target ligand was a bis(terpyridine) bridged in the 5" positions by a $(\text{CH}_2)_2$ bridge and substituted in the 5 positions by a poly(oxyethylene) chain bearing a terminal olefin.

Preparation of a Model Iron(II) Double Helix. To test the feasibility of the strategy and the stability of these kinds of complexes, the bis(terpyridine) **9** was prepared to synthesize its iron(II) complex.

Following a literature method,²⁸ the dimethylterpyridine **8** was reacted with 1 equiv of lithium diisopropylamide (LDA) in THF at -78 °C. The benzylic anion formed was subsequently oxidized with 1,2-dibromoethane and the bis(terpyridine) **9** (see Figure 5) isolated after chromatography on alumina with 28% yield.

The metalation with iron(II) was achieved according to literature procedures.²⁹ Ligand **9** was dissolved in hot acetone, and an aqueous iron(II) sulfate solution was added in excess under argon and under stirring. Addition of an excess of saturated aqueous potassium hexafluorophosphate and evaporation of the acetone caused a purple solid to precipitate, yielding 10^{4+} with 94% yield.

This model could be fully characterized by mass spectrometry and NMR and its structure determined by X-ray diffraction. The

(24) Crane, J. D.; Sauvage, J. P. *New J. Chem.* **1992**, *16*, 649–650.

(25) Cárdenas, D. J.; Sauvage, J. P. *Synlett* **1996**, 916–918.

(26) Martin, A. E.; Bulkowski, J. E.; *J. Org. Chem.* **1982**, *47*, 415–418.

(27) Johnstone, R. A. W.; Rose, M. E. *Tetrahedron* **1979**, *35*, 2169–2173.

(28) Elliott, C. M.; Freitag, R. A.; Blaney, D. D. *J. Am. Chem. Soc.* **1985**, *107*, 4647–4655. Schmehl, R. H.; Auerbach, R. A.; Wacholtz, W. F.; Elliott, C. M.; Freitag, R. A. *Inorg. Chem.* **1986**, *25*, 2440–2445. Lehn, J. M.; Ziessel, R. *Helv. Chim. Acta* **1988**, *71*, 1511–1516. Youinou, M. T.; Ziessel, R.; Lehn, J. M. *Inorg. Chem.* **1991**, *30*, 2144–2148.

(29) Serr, B. R.; Andersen, K. A.; Elliott, C. M.; Anderson, O. P. *Inorg. Chem.* **1988**, *27*, 4499–4504.

(23) Dietrich-Buchecker, C. O.; Sauvage, J. P.; Kintzinger, J. P.; Maltèse, P.; Pascard, C.; Guilhem, J. *New J. Chem.* **1992**, *16*, 931–942.

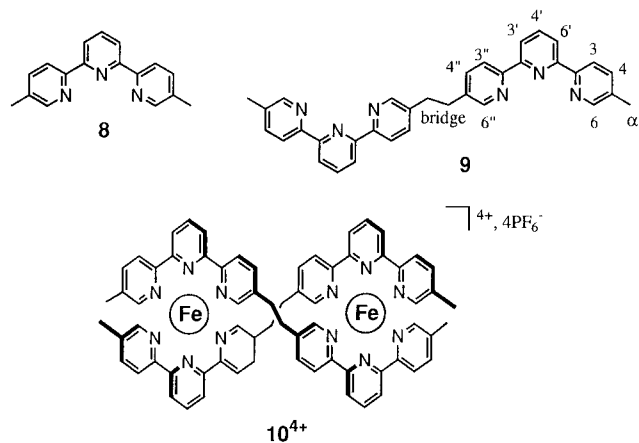


Figure 5. Terpyridine precursors leading to the double helix 10^{4+} .

Table 1. X-ray Experimental Data for the Double Helix 10^{4+}

formula	$C_{74}H_{64}N_{12}OF_{24}P_4Fe_2$ $C_{68}H_{56}N_{12}Fe_2 \cdot 4PF_6 \cdot C_6H_6 \cdot H_2O$
M_r	1828.97
cryst system	monoclinic
space group	$P121/c1$
a (Å)	21.306(1)
b (Å)	11.751(1)
c (Å)	35.564(1)
β (deg)	99.86(1)
V (Å ³)	8772(1)
Z	4
color	dark red
cryst dimens (mm)	0.15 × 0.12 × 0.10
D_{calc} (g cm ⁻³)	1.38
F_{000}	3712
μ (mm ⁻¹)	0.497
temp (K)	294
wavelength (Å)	0.710 73
radiation	Mo K α graphite monochromated
diffractometer	KappaCCD
scan mode	φ scans
hkl limits	0,20/0,11/-35,35
θ limits (deg)	2.5/20.82
no. of data with $I > 3\sigma(I)$	3741
weighting scheme	$4F_o^2/(\sigma^2(F_o^2) + 0.0016F_o^4) + 3.0$
no. of variables	1054
R	0.096
R_w	0.126
GOF	1.269
largest peak in final diff (e Å ⁻³)	1.098

FAB-MS spectrum showed that complex 10^{4+} was indeed of the type two metals and two ligands, whereas its ¹H NMR spectrum corresponded to a highly symmetrical compound, typical of a double helix.

The helical structure of 10^{4+} has been confirmed by X-ray crystallographic studies (Table 1). This structure is shown in Figure 6. Each terpyridine is gripped around the metallic centers, as illustrated by the average angle of 103° between the two ortho positions of the central pyridine.

The four terpyridine fragments are planar. The coordination polyhedra around each iron(II) are distorted octahedra, the angles varying between 77 and 101°.

The four terpyridines and the two bridges are chemically equivalent, 10^{4+} having three perpendicular C_2 axes.

Significant shielding of protons 6 and 6'' can be noticed in double helix 10^{4+} (from 8.5 ppm in ligand **9** to 7.2 for H₆ and 6.4 for H_{6''}), which can be explained by their location in the shielding cones of the neighboring terpyridines. The situation of the α protons is very similar; they are shielded by 0.5 ppm (from 2.4 to 1.9 ppm).

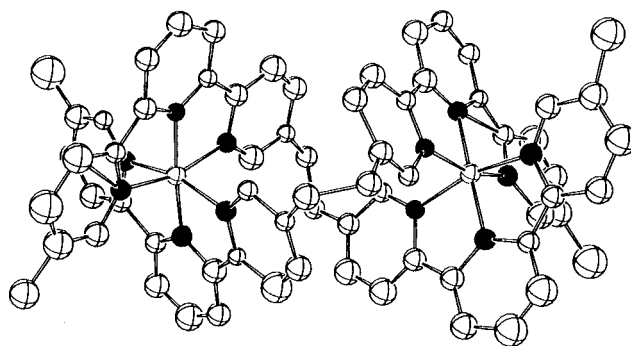


Figure 6. ORTEP representation of the X-ray structure of the diiron(II) double helix 10^{4+} . The solvent molecules, PF₆ anions, and hydrogen atoms have been omitted for clarity.

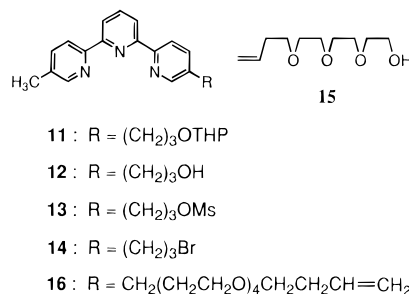


Figure 7. Terpyridinic precursors.

Synthesis of the Terpyridinic Precursors. The unexpected ease of formation as well as the stability of model double helix 10^{4+} encouraged us to undertake the synthesis of an analogous tetraolefinic double helix, the necessary precursor in a trefoil knot synthesis based on RCM as depicted in Figure 1.

The monofunctionalization of the dimethylterpyridine **8**²⁵ was achieved by reacting 2-(2-bromoethoxy)tetrahydropyran with the benzylic anion of dimethylterpyridine generated with 1 equiv of lithium diisopropylamide (LDA) in THF at -78 °C. The terpyridine **11** shown in Figure 7 was isolated in 51% yield.

The synthesis of the bromo derivative **14** was performed in three steps from **11**. After deprotection of the alcohol function in the presence of a catalytic amount of *p*-toluenesulfonic acid in refluxing ethanol, the alcohol **12** was activated via the formation of its mesyl derivative **13** under classical conditions.²⁶ The bromo derivative **14** was subsequently prepared by adding a large excess of lithium bromide in refluxing acetone. The overall yield of these three steps, each of which required purification on alumina, was 67%.

The chain bearing a terminal olefin was prepared as explained in the experimental part. It was then introduced in the terpyridine subunit by generating the alcoholate of **15** with KOH in DMSO²⁷ and reacting the latter with the bromoterpyridine derivative **14**. The terpyridine **16** was obtained in a 37% yield after purification.

After the homocoupling reaction described in Figure 8, the bis(terpyridine) **17** was obtained in a 13% yield. The metalation with iron(II) was achieved as described before, yielding the diiron(II) double helix **18**⁴⁺ with 91% yield.

Formation of the Diiron(II) Trefoil Knot. The metathesis reaction performed as described Figure 9 afforded, after chromatography on alumina, 6.5 mg of pure knot **19**⁴⁺ from 32 mg of **18**⁴⁺, corresponding to a yield of 20%.

Its ¹H NMR (Figure 10) and mass spectra were both consistent with the expected cyclic molecule. It is noteworthy that the signals of the terminal olefins were replaced by signals at lower field.

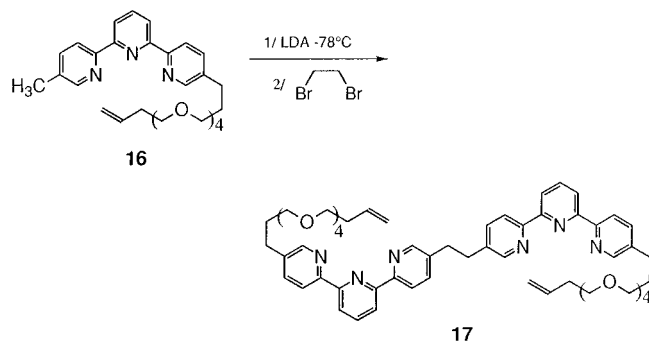


Figure 8. Synthetic pathway affording the bis(terpyridine) **17**, precursor of the diiron(II) double helix

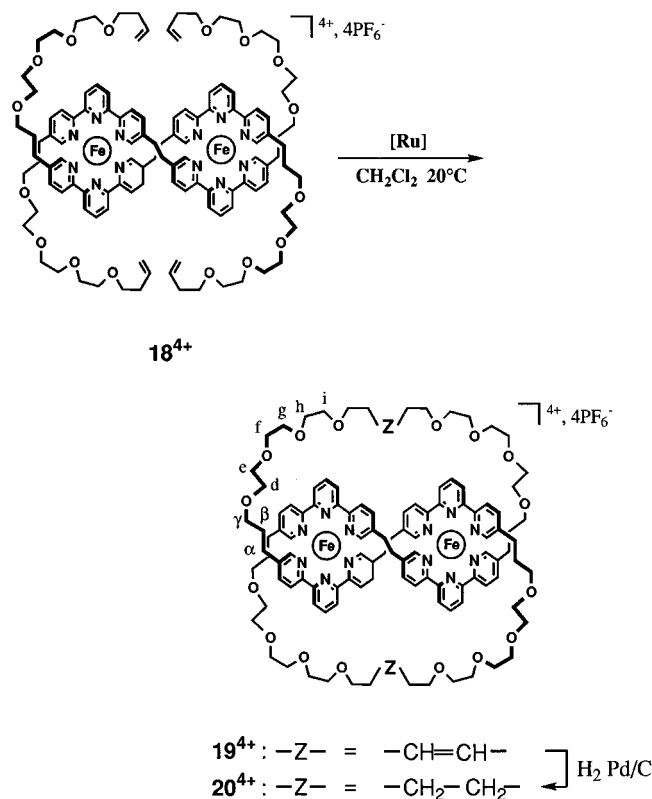


Figure 9. Diiron(II) molecular trefoil knots obtained after the ring-closing metathesis cyclization reaction.

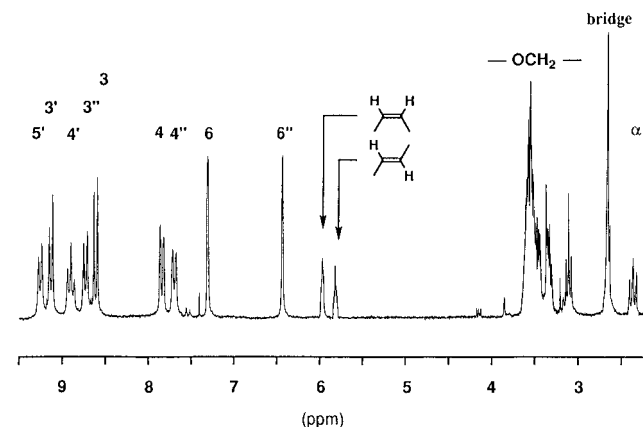


Figure 10. ^1H NMR spectra (200 MHz, acetone- d_6) of the diiron(II) trefoil knot 19^{4+} .

According to the ^1H NMR, the metathesis reaction yielded cis (55%) and trans (45%) olefins. To study in more detail a single species, the reduction of 19^{4+} was performed in the same

conditions as described previously. 20^{4+} was obtained quantitatively.

The knotted structure of 20^{4+} was confirmed by a 2D ROESY ^1H NMR experiment which showed an interaction between the central protons of the terpys (3', 4', and 5') and some protons (d-i) of the chain. Such interaction was only expected in the case of a knot.

These arguments, based on a detailed NMR study, brought us to the conclusion that the only isolated product in the reaction described was a molecular knot.

Conclusion

By combination of the quantitative formation and the great stability of the Cu(I) bis(phenanthroline) helix with *m*-phenylene bridges and the highly efficient intramolecular metathesis reaction developed by Grubbs and his group, the copper(I) complex of the trefoil knot **23** could be obtained in seven steps from commercial 1,10-phenanthroline in a 35% overall yield.

This approach also led to a knot constructed around two iron(II) bis(terpyridine)s for the first time, demonstrating that iron(II) can be used as highly efficient template. The latter result may be considered as the starting point for a new generation of knots. Due to the richness of the coordination chemistry of terpyridines, one can imagine the tuning of their properties by varying the transition metal used. In addition, the olefins at the poles of knots could be used for further functionalization or could take part in catalytic processes.

It is also interesting to note that, thanks to the high efficiency of the metathesis reaction, the cyclization step is no longer the yield-limiting step in the synthesis of topologically nontrivial species.

Experimental Section

General Procedures. The following chemicals were obtained commercially and were used without further purification: Cs_2CO_3 (Aldrich); KCN (Janssen); KPF_6 (Janssen); $\text{RuCl}_2(\text{PCy}_3)_2(=\text{CHPh})$ (Strem). Some materials were prepared according to literature procedures: **1**;⁹ **8**;²⁵ $\text{Cu}(\text{MeCN})_4\text{PF}_6$;³⁰ tetrahydropyranyl 2-bromoethyl ether.³¹ Dry solvents were obtained by distillation from suitable desiccants (Et_2O and THF from Na with benzophenone; MeCN and CH_2Cl_2 from P_2O_5). Thin-layer chromatography (TLC) was performed on aluminum sheets coated with silica gel 60 F₂₅₄ (Merck 5554) or coated with neutral alumina 60 F₂₅₄ (Merck 5550). After elution, the plates were either scrutinized under a UV lamp or exposed to I_2 or, for terpyridine derivatives, put in a solution of $(\text{NH}_4)_2\text{Fe}^{\text{II}}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$ in 50:50 MeOH/ H_2O . Column chromatography was carried out on silica gel 60 (Merck 9385, 230–400 mesh) or neutral alumina 90 (Merck 1076, 0.060–0.200 mm). UV-visible spectra were recorded on a Kontron Instruments UVIKON 860 spectrophotometer. Fast atom bombardment mass spectra (FAB-MS) were recorded in the positive ion mode with either a krypton primary atom beam in conjunction with a 3-nitrobenzyl alcohol matrix and a Kratos MS80RF mass spectrometer coupled to a DS90 system, or a xenon primary atom beam with the same matrix and a ZAB-HF mass spectrometer. The ^1H NMR spectra were recorded on either Bruker WP200 SY (200 MHz) or WP400SY (400 MHz) spectrometers (using the deuterated solvent as the lock and residual solvent as the internal reference).

Preparation of 2. A suspension of Cs_2CO_3 (1.3 g, 4 mmol) in DMF (200 mL) was added dropwise and under argon to a degassed solution of *m*-bis(2-(*p*-hydroxyphenyl)-1,10-phenanthrolyl)benzene (**1**) (458 mg, 0.74 mmol) in DMF (30 mL). The mixture, which immediately turned bright orange and later red, was heated to 80 °C under vigorous stirring. After 1 h at 80 °C, some 2-(2-chloroethoxy)ethanol (0.25 mL, 2.37 mmol) was added via a syringe. The mixture progressively turned

(30) Kubas, G. J.; Monzyk, B.; Crumbliss, A. M. *Inorg. Synth.* **1990**, 28, 68–70.

(31) Wälchi, P. C.; Engster, R. *Helv. Chim. Acta* **1978**, 61, 885–898.

orange. The reaction was monitored by TLC (SiO₂; eluent, CH₂Cl₂/3% MeOH), which showed that the (chloroethoxy)ethanol had disappeared. This was balanced by a further addition of this reactant (0.25 mL, 2.37 mmol) after 16 h of reaction. The reaction mixture was maintained at 80 °C under argon for a further 6 h. DMF was then evaporated (0.1 mmHg, 50 °C), and the residue (yellow brick color) was dissolved in a 1:1 H₂O/CH₂Cl₂ mixture. The organic phase was decanted, and the aqueous phase was extracted 3 times with 200 mL portions of CH₂Cl₂. The organic phases were combined, dried over MgSO₄, and filtered. The solvent was evaporated, and the yellow brick solid was chromatographed (SiO₂; eluent, hexane/0–80% CH₂Cl₂) to give **2** in a 97% yield (570 mg, 0.72 mmol), beige solid (mp: 172 °C). ¹H NMR (CDCl₃, 200 MHz): 9.52 (s, 1H, H_a); 8.43 (dd, 2H, H_b, ³J = 7.7 Hz, ⁴J = 1.7 Hz); 8.22 (d, 4H, H_o, ³J = 8.9 Hz); 8.19 (broad s, 4H, H_{3–4}); 8.06 (d, 2H, H₇, ³J = 8.5 Hz); 7.85 (d, 2H, H₈, ³J = 8.5 Hz); 7.58 (s, 4H, H_{5–6}); 7.56 (t, 1H, H_c, ³J = 7.7 Hz); 6.76 (d, 4H, H_m, ³J = 8.9 Hz); 3.94 (t, 4H, H_α, ³J = 4.3 Hz); 3.66 (t, 4H, H_β, ³J = 4.3 Hz); 3.3–3.6 (m, 8H, H_{γ–δ}); 2.89 (t, 2H, OH, ³J = 5.5 Hz). Anal. Calcd for C₅₀H₄₂N₄O₆: C, 75.55; H, 5.32; N, 7.05. Found: C, 75.22; H, 5.37; N, 6.98.

Preparation of 3. A degassed solution of **2** (565 mg, 0.72 mmol) in THF (100 mL) was added dropwise at 0 °C and under argon to a suspension of NaH (3.6 mmol) in THF (200 mL). The mixture turned yellow. Its temperature was allowed to rise up to room temperature before allyl bromide (25 mL, 72 mmol) was added via a syringe. The mixture was then heated to reflux. The reaction was monitored by TLC (SiO₂; eluent, CH₂Cl₂/5% MeOH). More allyl bromide (25 mL, 72 mmol) was added after 40 h of reaction. The reaction mixture was kept under reflux and under argon for 70 h. The temperature was then brought down to 0 °C, and excess NaH was neutralized by adding small portions (5 mL) of absolute ethanol, until there was no more gas formed. The solvent was then evaporated, and the residue taken up in a 1:1 H₂O/CH₂Cl₂ mixture. The organic phase was decanted, and the aqueous phase was extracted 3 times with 200 mL portions of CH₂Cl₂. The organic phases were combined, dried over MgSO₄, filtered, and evaporated to dryness. The yellow brick solid was chromatographed (SiO₂; eluent, hexane/0–100% CH₂Cl₂) to give **3** in a 100% yield (627 mg, 0.72 mmol), beige-orange solid (mp: 135 °C). ¹H NMR (CDCl₃, 200 MHz): 9.65 (s, 1H, H_a); 8.66 (dd, 2H, H_b, ³J = 7.7 Hz, ⁴J = 1.5 Hz); 8.42 (d, 4H, H_o, ³J = 8.8 Hz); 8.34 (d, 2H, H₃, ³J = 8.5 Hz); 8.26 (d, 2H, H₄, ³J = 8.5 Hz); 8.15 (d, 2H, H₇, ³J = 8.5 Hz); 7.98 (d, 2H, H₈, ³J = 8.5 Hz); 7.80 (t, 1H, H_c, ³J = 7.8 Hz); 7.67 (s, 4H, H_{5–6}); 7.02 (d, 4H, H_m, ³J = 8.8 Hz); 5.93 (ddt, 2H, H_{olefin}, ³J_{trans} = 17.2 Hz, ³J_{cis} = 10.3 Hz, ³J = 5.6 Hz); 5.27 (m, 2H, H_{olefin-trans}, ³J = 17.2 Hz, ⁴J = 1.3 Hz, ³J_{gem} ~ 1 Hz); 5.17 (m, 2H, H_{olefin-cis}, ³J = 10.3 Hz, ⁴J = 1.3 Hz, ³J_{gem} ~ 1 Hz); 4.17 (t, 4H, H_α, ³J = 5.2 Hz); 4.02 (td, 4H, H_β, ³J = 5.6 Hz, ⁴J = 1.3 Hz); 3.88 (t, 4H, H_β, ³J = 5.2 Hz); 3.74 (m, 4H, H_γ); 3.61 (m, 4H, H_δ). Anal. Calcd for C₅₆H₅₀N₄O₆: C, 76.87; H, 5.76; N, 6.40. Found: C, 76.62; H, 6.10; N, 6.36.

Preparation of 4²⁺. A degassed solution of copper(I) hexafluorophosphate (280 mg, 0.69 mmol) in acetonitrile (70 mL) was added at room temperature and under argon to a solution of ligand **3** (607 mg, 0.69 mmol) in dichloromethane. The resulting dark red mixture was stirred for 1 h. The solvents were then evaporated and the residue washed with water and dried under vacuum. The pure double helix **4²⁺** was obtained in a quantitative yield as a dark red solid (751 mg, 0.69 mmol). ¹H NMR (CDCl₃, 200 MHz): 9.64 (s, 2H, H_a); 8.35 (d, 4H, H₇, ³J = 8.4 Hz); 7.94 (AB, 8H, H_{5–6}, ³J = 8.8 Hz); 7.87 (d, 4H, H₄, ³J = 8.4 Hz); 7.62 (d, 4H, H₈, ³J = 8.4 Hz); 7.12 (t, 2H, H_c, ³J = 7.8 Hz); 7.03 (d, 8H, H_o, ³J = 8.6 Hz); 6.90 (dd, 4H, H_b, ³J = 7.8 Hz, ⁴J = 1.2 Hz); 6.52 (d, 4H, H₃, ³J = 8.4 Hz); 5.99 (ddd, 4H, H_{olefin}, ³J_{trans} = 17.2 Hz, ³J_{cis} = 10.3 Hz, ³J = 5.6 Hz); 5.72 (d, 8H, H_m, ³J = 8.6 Hz); 5.31 (m, 2H, H_{olefin-trans}, ³J = 17.2 Hz, ⁴J = 1.3 Hz, ³J_{gem} ~ 1 Hz); 5.20 (m, 2H, H_{olefin-cis}, ³J = 10.3 Hz, ⁴J = 1.3 Hz, ³J_{gem} ~ 1 Hz); 4.07 (dt, 8H, H_α, ³J = 5.6 Hz, ⁴J = 1.3 Hz); 3.10–3.70 (m, 32H, H_{α–β–γ–δ}).

Preparation of the Dicopper(I) Trefoil Knot 5²⁺. Double helix **4²⁺** (150 mg, 69 mmol) was dissolved in freshly distilled and degassed dichloromethane (5 mL) at room temperature to obtain a 0.01 M solution. The catalyst (Grubbs ruthenium(II) carbene,¹⁴ 6 mg, 5% mol) dissolved in dichloromethane (2 mL) was then added using Schlenk

techniques. The reaction could be monitored by ¹H NMR, the chemical shifts of the cyclic olefins being sharply different from that of the terminal olefins. After 16 h, the solvent was evaporated and the crude product was chromatographed (SiO₂; CH₂Cl₂/0–1% MeOH) to give pure **5²⁺** in a 74% yield (108 mg, 51 mmol), dark red solid (mp: >280 °C). MS (FAB⁺): *m/z* 1965.3 ([M – PF₆]⁺, calcd 1965.5; 60%), 1820.4 ([M – 2PF₆[–] + e]⁺, calcd 1820.5; 36%), 910.1 ([M – 2PF₆[–]]²⁺, calcd 910.3; 58%). UV–vis (CH₂Cl₂), [λ_{max} (nm) ε (mol^{–1}·L·cm^{–1})]: 236 (107 300); 250 sh (104 200); 279 sh (77 700); 325 (62 400); 520 (2880). ¹H NMR (CDCl₃, 200 MHz): 9.67 (s, 2H, H_a); 8.35 (d, 4H, H₇, ³J = 8.4 Hz); 7.87 (m, 12H, H_{4–5–6}); 7.62 (d, 4H, H₈, ³J = 8.4 Hz); 7.12 (t, 2H, H_c, ³J = 7.8 Hz); 7.03 (m, 12H, H_{o–b}); 6.52 (d, 4H, H₃, ³J = 8.4 Hz); 6.38 (m, 2.8H, H_{cis-olefin}); 6.24 (m, 1.2H, H_{trans-olefin}); 5.73 (m, 8H, H_m); 3.20–4.50 (m, 40H, H_{α–β–γ–δ–ε}). The latter assignment was confirmed by 2D-NMR spectroscopy (ROESY). Anal. Calcd for C₁₀₈H₉₂Cu₂F₁₂N₈O₁₂P₂: C, 61.45; H, 4.39; N, 5.31. Found: C, 60.96; H, 4.04; N, 4.88.

Preparation of 6²⁺. The dicopper(I) trefoil knot **5²⁺** (95 mg, 45 mmol) was dissolved in a 1:1 mixture of CH₂Cl₂/EtOH (100 mL). The catalyst (Pd/C, 5% mol in Pd) was then added. At room temperature and under vigorous stirring, the solution was maintained under a hydrogen atmosphere for 16 h. The reaction could also be monitored by ¹H NMR, since the signal of the olefin progressively disappeared. After filtration on alumina and evaporation of the solvent, the pure reduced knot **6²⁺** was obtained in a quantitative yield (95 mg, 45 mmol) as a dark red solid (mp: >280 °C). UV–vis (CH₂Cl₂) [λ_{max} (nm) ε (mol^{–1}·L·cm^{–1})]: 235 (109 800); 251 sh (104 200); 280 sh (75 700); 325 (63 200); 513 (3100). ¹H NMR (CDCl₃, 200 MHz): 9.71 (s, 2H, H_a); 8.37 (d, 4H, H₇, ³J = 8.4 Hz); 7.93 (AB, 8H, H_{5–6}, ³J = 8.8 Hz); 7.90 (d, 4H, H₄, ³J = 8.4 Hz); 7.62 (d, 4H, H₈, ³J = 8.4 Hz); 7.24 (t, 2H, H_c, ³J = 7.8 Hz); 7.04 (m, 12H, H_{o–b}); 6.58 (d, 4H, H₃, ³J = 8.4 Hz); 5.72 (d, 8H, H_m, ³J = 8.6 Hz); 3.30–4.00 (m, 40H, H_{α–β–γ–δ–ε}).

Preparation of Free Ligand 7. To a solution of **6²⁺** (50 mg, 23 mmol) in refluxing wet acetonitrile (100 mL) was added potassium cyanide (0.5 g, large excess). The mixture was stirred at 80 °C for 4 h, during which the dark red color of the copper(I) complex progressively disappeared. The solvent was evaporated, and the residue was dissolved in dichloromethane. The crude mixture was washed 3 times with 0.1 M ammonia in water, dried over MgSO₄, and filtered to give **7** in a quantitative yield (39 mg, 23 mmol). Its ¹H NMR spectrum is very complex and shows a mixture of conformers in reptation.

Remetalation was achieved by adding a degassed solution of Cu-(MeCN)₄PF₆ (5 mg, 24 mmol) in acetonitrile (20 mL) to a solution of ligand **7** (39 mg, 23 mmol) in dichloromethane (20 mL), at room temperature and under argon. The dark red solution was stirred for 1 h. The solvent was then evaporated, and the residue was washed with water and dried under vacuum to give knot **6²⁺** in a quantitative yield (50 mg, 23 mmol).

Preparation of 9. A degassed solution of **8** (2 g, 7.66 mmol) in anhydrous THF (250 mL) was cooled to –78 °C. While this temperature was maintained, a freshly prepared LDA solution (7.7 mmol in 30 mL THF) was added. The reaction mixture progressively turned from deep red to purple. It was stirred for a further 2 h at –80 °C, after which the temperature was allowed to rise to 0 °C and brought down to –78 °C again. Dibromoethane (6.44 g, 34.3 mmol), previously filtered over basic alumina, was then added via syringe. Once the addition was finished, the mixture was left at –78 °C for 4 h, after which it was allowed to heat up to room temperature. After 4 h of stirring at room temperature, the emerald green solution was hydrolyzed by 200 mL of water and turned orange. After evaporation of the THF and extraction with CH₂Cl₂, the organic layer was dried over MgSO₄, and the solvent was evaporated. The crude mixture was chromatographed (Al₂O₃; eluent, hexane/CH₂Cl₂ 10–70%) to give pure **9** in a 28% yield (573 mg, 1.1 mmol), beige solid (mp: 187 °C). ¹H NMR (CDCl₃, 200 MHz): 8.51 (m, 8H, H_{6–6′–3′–5′}); 8.39 (d, 4H, H_{3–3′}, ³J = 7.8 Hz); 7.92 (t, 2H, H₄, ³J = 7.9 Hz); 7.61 (AB, 4H, H_{4–4′}, ³J = 7.8 Hz, ⁴J = 2.1 Hz); 3.07 (s, 4H, CH₂); 2.40 (s, 6H, CH₃). Anal. Calcd for C₃₄H₂₈N₆: C, 78.43; H, 5.42; N, 16.14. Found: C, 79.05; H, 4.91; N, 15.70.

Preparation of 10⁴⁺. A solution of dimethylbis(terpyridine) **9** (31 mg, 60 mmol) dissolved in hot acetone (25 mL) was added under argon,

via cannula, at room temperature and under stirring to an aqueous solution of FeSO₄ (2 mmol dissolved in 5 mL). The purple mixture was brought to 50 °C for 1 h, whereafter the acetone was evaporated. The iron complex was subsequently precipitated by the addition of a saturated aqueous solution of KPF₆ (50 mL). The suspension was left for 2 h in the refrigerator, and the solid was filtered off, washed with water, and dried under vacuum to give pure **10**⁴⁺ in a 94% yield (48 mg, 28 mmol), fuschia red solid (mp: >280 °C). MS (FAB⁺): *m/z* 1587.2 ([M - PF₆]⁺, calcd 1587.2; 5%), 1442.4 ([M - 2PF₆ + e⁻]⁺, calcd 1442.3; 3%), 1297.5 ([M - 3PF₆ + 2e⁻]⁺, calcd 1297.3; 2%), 1152.5 ([M - 4PF₆ + 3e⁻]⁺, calcd 1152.4; 2%), 721.4 ([M - 2PF₆]²⁺, calcd 721.2; 18%). UV-vis (CH₂Cl₂), [λ_{\max} (nm) ϵ (mol⁻¹ L·cm⁻¹)]: 228 (85 700); 256 (68 600); 279 (85 100); 288 (76 400); 328 (100 300); 375 sh (7600); 480 sh (9800); 552 (18 700); 618 sh (4100). ¹H NMR (acetone-*d*₆, 200 MHz): 9.19 (d, 4H, H₅, ³J = 8.0 Hz); 9.07 (d, 4H, H₃, ³J = 8.0 Hz); 8.83 (t, 4H, H₄, ³J = 8.0 Hz); 8.67 (d, 4H, H_{3'}, ³J = 7.9 Hz); 8.55 (d, 4H, H₃, ³J = 8.1 Hz); 7.78 (d, 4H, H₄, ³J = 8.1 Hz); 7.64 (d, 4H, H_{4'}, ³J = 7.9 Hz); 7.25 (s, 4H, H₆); 6.39 (s, 4H, H_{6'}); 2.73 (s, 8H, CH₂); 1.91 (s, 12H, CH₃). The latter assignment was confirmed by 2D-NMR spectroscopy (ROESY). Anal. Calcd for C₆₈H₅₆F₂₄Fe₂N₁₂P₄: C, 78.44; H, 5.42; N, 16.14. Found: C, 78.12; H, 5.27; N, 15.98.

Preparation of 11. A degassed solution of dimethylterpyridine **8** (1.8 g, 6.89 mmol) in anhydrous THF (100 mL) was cooled to -78 °C. While this temperature was maintained, a freshly prepared LDA solution (6.9 mmol in 20 mL of THF) was added. The reaction mixture progressively turned from deep red to purple. It was stirred for a further 2 h at -80 °C, after which the temperature was allowed to rise to 0 °C and brought down to -78 °C again. Meanwhile, a solution of tetrahydropyranyl 2-bromoethyl ether (1.435 g, 6.89 mmol) in anhydrous THF (100 mL) was cooled to 0 °C and degassed. This solution was then transferred under argon onto the anion of **8** at -78 °C, the mixture turning deep purple. Once the addition was finished, the mixture was allowed to heat up to room temperature. After 20 h of stirring, the deep blue solution was hydrolyzed by 200 mL of water and turned from blue to green and finally orange. After evaporation of the THF and extraction with CH₂Cl₂, the organic phases were dried over MgSO₄ and the solvent evaporated. The crude mixture was chromatographed (Al₂O₃; eluent, hexane/10–100% Et₂O). We obtained 32% of starting material (0.581 g, 2.22 mmol), 51% of the desired monosubstituted product (1.367 g, 3.52 mmol), and 11% of disubstituted product (0.382 g, 0.75 mmol), colorless solid. ¹H NMR (CDCl₃, 200 MHz): 8.58 (s, 1H, H₆); 8.55 (s, 1H, H_{6'}); 8.53 (d, 2H, H_{3-3'}, ³J = 7.7 Hz); 8.44 (d, 2H, H_{3-3'}, ³J = 7.9 Hz); 7.95 (t, 1H, H₄, ³J = 7.9 Hz); 7.68 (t, 2H, H₄, ³J = 7.7 Hz); 7.66 (t, 2H, H_{4'}, ³J = 7.7 Hz); 4.62 (t, 1H, ³J = 3.5 Hz); 3.3–3.9 (m, 4H); 2.83 (t, 2H, H_α, ³J = 8.4 Hz); 0.8–2 (m, 8H).

Preparation of 12. Terpyridine **11** (3.34 g, 8.6 mmol) was dissolved in ethanol (30 mL) and heated to reflux in the presence of a catalytic amount of *p*-toluenesulfonic acid (50 mg). The reaction was followed by TLC, and the reflux was maintained during 4 h. After evaporation of the ethanol and extraction with a CH₂Cl₂/H₂O mixture, the organic phases were combined and dried over MgSO₄, and the solvent was evaporated. The crude mixture was chromatographed (Al₂O₃; eluent, CH₂Cl₂/0–2% MeOH) to give **12** in an 86% yield (2.24 g, 7.4 mmol), colorless solid. ¹H NMR (CDCl₃, 200 MHz): 8.40 (m, 4H, H_{3-3'-6-6'}); 8.27 (d, 2H, H₃, ³J = 7.8 Hz); 8.26 (d, 2H, H₅, ³J = 7.8 Hz); 7.82 (t, 1H, H₄, ³J = 7.8 Hz); 7.54 (t, 1H, H₄, ³J = 7.0 Hz); 7.53 (t, 1H, H_{4'}, ³J = 7.0 Hz); 3.82 (s, 1H, OH); 3.58 (t, 2H, 2H_β, ³J = 6.3 Hz); 2.66 (t, 2H, H_α, ³J = 7.3 Hz); 2.26 (s, 3H, CH₃); 1.80 (tt, 2H, H_β, ³J = 7.3 Hz, ³J = 6.3 Hz).

Preparation of 13. A suspension of **12** (2.24 g, 7.36 mmol) in anhydrous CH₂Cl₂ (100 mL) was placed at -5 °C and under argon in the presence of freshly distilled NEt₃ (10 mL, 70 mmol). A solution of mesyl chloride (1.42 mL, 18.4 mmol) in anhydrous CH₂Cl₂ (30 mL) was slowly added to this suspension, which progressively dissolved (-5 < T < -2 °C) to give a clear yellow solution. After 2 h of stirring, TLC showed complete disappearance of the starting materials. The reaction mixture was washed with water, the organic phases were combined and dried over MgSO₄, and the solvent was evaporated. The beige powder thus obtained was chromatographed (Al₂O₃; eluent,

hexane/50–100% CH₂Cl₂) to give **13** as a colorless powder in a 67% yield (1.88 g, 4.91 mmol). ¹H NMR (CDCl₃, 200 MHz): 8.40 (m, 4H, H_{3-3'-6-6'}); 8.36 (d, 2H, H₃, ³J = 7.7 Hz); 8.35 (d, 2H, H₅, ³J = 8.0 Hz); 7.89 (t, 1H, H₄, ³J = 7.8 Hz); 7.64 (t, 1H, H₄, ³J = 7.4 Hz); 7.62 (t, 1H, H_{4'}, ³J = 7.3 Hz); 4.24 (t, 2H, 2H_β, ³J = 6.2 Hz); 2.98 (s, 3H, CH₃SO₂); 2.80 (t, 2H, H_α, ³J = 7.2 Hz); 1.95 (s, 3H, CH₃); 2.08 (tt, 2H, H_β, ³J = 7.2 Hz, ³J = 6.2 Hz).

Preparation of 14. Terpyridine **13** (1.88 g, 4.91 mmol) was dissolved in acetone (100 mL, analytical grade) and reacted under argon with anhydrous LiBr (4.26 g, 49.1 mmol). The reaction mixture was heated to reflux for 6 h and the reaction monitored by TLC. After evaporation of acetone, the crude mixture was dissolved in a CH₂Cl₂/H₂O mixture. The organic phases were combined and dried over MgSO₄, and the solvent was evaporated to give terpyridine **14** in a 97% yield (1.75 g, 4.76 mmol). ¹H NMR spectrometry showed the conversion to be quantitative. Compound **14** was therefore used without further purification, colorless solid. ¹H NMR (CDCl₃, 200 MHz): 8.45 (m, 4H, H_{3-3'-6-6'}); 8.38 (d, 2H, H_{3-3'}, ³J = 8.0 Hz); 7.92 (t, 1H, H₄, ³J = 7.9 Hz); 7.66 (t, 1H, H₄, ³J = 7.3 Hz); 7.64 (t, 1H, H_{4'}, ³J = 7.2 Hz); 3.40 (t, 2H, 2H_β, ³J = 6.5 Hz); 2.84 (t, 2H, H_α, ³J = 7.1 Hz); 2.38 (s, 3H, CH₃); 2.19 (tt, 2H, H_β, ³J = 7.1 Hz, ³J = 6.5 Hz).

Preparation of 15. The preparation of the mono(tetrahydropyranyl) monobromide derivative of triethylene glycol has been prepared after mesylation²⁶ followed by bromination of the mono(tetrahydropyranyl) derivative according to the literature procedure. Finely crushed potassium hydroxide (1.44 g, 26 mmol) was suspended in DMSO (4 mL), and but-3-enol (0.52 mL, 432 mg, 6.4 mmol) was added. The reaction mixture was heated to 50 °C for 1 h. The bromide derivative (1.68 g, 5 mmol), dissolved in DMSO, was then added, and the mixture was stirred under argon for 4 h. The crude mixture was diluted with CH₂Cl₂ (50 mL) and washed with water (5 × 120 mL). The organic phases were dried over MgSO₄ and the solvent evaporated. The yellow oil obtained was chromatographed over alumina (eluent, hexane/50% CH₂Cl₂). The elimination product was very difficult to separate off, because its polarity was very similar to that of the desired product. After three chromatographies the protected **15** was isolated in a 29% yield (530 mg, 1.84 mmol). **15** has been obtained as a pale yellow oil after a classical deprotection reaction using catalytic *p*-toluenesulfonic acid in refluxing ethanol. ¹H NMR (CDCl₃, 200 MHz): 5.81 (m, 1H, H_b); 5.06 (m, 2H, H_a); 3.3–3.8 (m, 16H, CH₂); 2.62 (s, 1H, OH).

Preparation of 16. In a 250 mL three-necked flask were dissolved finely ground potassium hydroxide (259 mg, 4.6 mmol) and **15** (235 mg, 1.15 mmol) in DMSO (3 mL). After 3 h at 50 °C and under argon, terpyridine **14** dissolved in DMSO (3 mL) was added to the alkoxide solution, and the mixture was heated to 80 °C. The mixture progressively turned from yellow to orange and then to dark brown. After 16 h at 80 °C, some CH₂Cl₂ (100 mL) was added and the mixture was thoroughly washed with water (400 mL first and 5 × 200 mL). The crude mixture was hereafter separated from DMSO and therefore could be chromatographed (Al₂O₃; eluent, Et₂O/0–1% MeOH) to give **16** as a colorless powder in a 36% yield (204 mg, 0.415 mmol). ¹H NMR (CDCl₃, 200 MHz): 8.47 (m, 4H, H_{3-3'-6-6'}); 8.44 (d, 2H, H_{3-3'}, ³J = 7.9 Hz); 7.95 (t, 1H, H₄, ³J = 7.9 Hz); 7.68 (t, 1H, H₄, ³J = 7.7 Hz); 7.66 (t, 1H, H_{4'}, ³J = 7.7 Hz); 5.79 (m, 1H, H_{olefin}); 5.05 (m, 2H, H_{olefin}); 3.3–3.7 (m, 18H, CH₂ polyoxo chain); 2.75 (t, 2H, H_α, ³J = 7.2 Hz); 2.37 (s, 3H, CH₃); 1.95 (tt, 2H, H_β, ³J = 7.2 Hz, ³J = 6.4 Hz).

Preparation of 17. A degassed solution of dimethylterpyridine **16** (204 mg, 0.415 mmol) in anhydrous THF (100 mL) was cooled to -78 °C. While this temperature was maintained, a freshly prepared solution of LDA (7.7 mmol) in THF (30 mL) was added. The reaction mixture progressively turned from deep red to purple. After 2 h of further stirring at -78 °C, the temperature was allowed to rise to 0 °C and brought down to -78 °C again. Dibromoethane (previously filtered on basic alumina) (0.18 mL, 2.08 mmol) was then added via a syringe. After the addition was complete, the mixture was left for 4 h at -78 °C, after which the emerald green solution was allowed to heat up to room temperature and turned yellow. After evaporation of THF and extraction with CH₂Cl₂, the organic phases were combined and dried over MgSO₄ and the solvent was evaporated. The crude mixture was chromatographed (Al₂O₃; eluent, CH₂Cl₂/0–2% MeOH) to give **17** in a 13% yield (26 mg, 26.5 mmol), pale brown solid. ¹H NMR (CDCl₃,

200 MHz): 8.47 (m, 8H, H_{3-3''-6-6''}); 8.34 (d, 4H, H_{3-5'}, ³J = 7.9 Hz); 7.95 (t, 2H, H_{4'}, ³J = 7.9 Hz); 7.68 (t, 2H, H₄, ³J = 7.7 Hz); 7.66 (t, 2H, H_{4''}, ³J = 7.7 Hz); 5.75 (m, 2H, H_{olefin}); 5.04 (m, 4H, H_{olefin}); 3.3–3.7 (m, 36H, CH₂ polyoxo chain); 3.03 (s, 4H, CH₂); 2.73 (t, 4H, H_α, ³J = 7.2 Hz); 1.95 (tt, 4H, H_β, ³J = 7.2 Hz, ³J = 6.4 Hz).

Preparation of 18⁴⁺. A solution of bis(terpyridine) **17** (26 mg, 26.5 μmol) dissolved in hot acetone (10 mL) was added via cannula, under argon, at room temperature and under stirring to an aqueous solution of FeSO₄ (0.1 mmol). The purple mixture was left at 50 °C for 1 h, and the acetone was evaporated. The iron complex was then precipitated by the addition of a saturated aqueous solution of KPF₆ (20 mL). The suspension was left for 2 h in the refrigerator, and the solid was filtered off, washed with water, and dissolved in CH₂Cl₂. The organic phase was washed three times with water and the solvent evaporated. The solid was dried under vacuum for 24 h to give pure **18⁴⁺** in a 91% yield (32 mg, 12 μmol), fuschia red solid. ¹H NMR (acetone-*d*₆, 200 MHz): 9.21 (d, 4H, H_{5'}, ³J = 8.0 Hz); 9.09 (d, 4H, H_{3'}, ³J = 8.0 Hz); 8.85 (t, 4H, H_{4'}, ³J = 8.0 Hz); 8.68 (d, 4H, H_{3''}, ³J = 7.9 Hz); 8.56 (d, 4H, H₃, ³J = 8.1 Hz); 7.80 (d, 4H, H₄, ³J = 8.1 Hz); 7.65 (d, 4H, H_{4''}, ³J = 7.9 Hz); 7.27 (s, 4H, H₆); 6.40 (s, 4H, H_{6''}); 5.78 (m, 4H, H_{olefin}); 5.00 (m, 8H, H_{olefin}); 3.3–3.7 (m, 80H, CH₂ polyoxo chain); 2.73 (s, 8H, bridging CH₂); 2.48 (t, 8H, H_α, ³J = 7.1 Hz).

Preparation of 19⁴⁺. Double helix **18⁴⁺** (32 mg, 12 μmol) and the catalyst (Grubbs ruthenium(II) carbene,¹⁴ 5 mg, 25% mol) were dissolved at room temperature in freshly distilled and degassed dichloromethane, so as to obtain a 0.01 M solution. After 100 h, the solvent was evaporated and the crude mixture was chromatographed (Al₂O₃; eluent, CH₂Cl₂/0–5% MeOH) to give **19⁴⁺** in a 20% yield (6.4 mg, 2.4 μmol) as a mixture of *cis* (55%) and *trans* (45%) olefins, fuschia red solid. MS (FAB⁺): *m/z* 2451.6 ([M – PF₆⁻]⁺, calcd 2451.8; 1.5%), 2306.6 ([M – 2PF₆⁻ + e⁻]⁺, calcd 2306.8; 1.9%), 2161.5 ([M – 3PF₆⁻ + 2e⁻]⁺, calcd 2161.9; 1.6%), 1153.3 ([M – 2PF₆⁻]²⁺, calcd 1153.4; 4.2%), 720.7 ([M – 3PF₆⁻]³⁺, calcd 720.6; 92%). ¹H NMR (acetone-*d*₆, 200 MHz): 9.23 (d, 4H, H_{5'}, ³J = 8.0 Hz); 9.12 (d, 4H, H_{3'}, ³J = 8.0 Hz); 8.87 (t, 4H, H_{4'}, ³J = 8.0 Hz); 8.71 (d, 4H, H_{3''}, ³J = 7.9 Hz); 8.58 (d, 4H, H₃, ³J = 8.1 Hz); 7.82 (d, 4H, H₄, ³J = 8.1 Hz); 7.68 (d, 4H, H_{4''}, ³J = 7.9 Hz); 7.29 (s, 4H, H₆); 6.43 (s, 4H, H_{6''}); 5.97 (m, 2.2H, H_{cis-olefin}); 5.82 (m, 1.8H, H_{trans-olefin}); 3.3–3.7 (m, 72H, CH₂ polyoxo chain); 3.40 (m, 8H, H_β); 3.17 (t, 8H, H_γ, ³J = 6.2 Hz); 2.73 (s, 8H, bridging CH₂); 2.40 (t, 8H, H_α, ³J = 7.4 Hz).

Preparation of 20⁴⁺. The diiron(II) trefoil knot **19⁴⁺** (6.4 mg, 2.4 μmol) was dissolved in a 1:1 mixture of CH₂Cl₂/EtOH (30 mL). The catalyst (Pd/C, 5% mol in Pd) was then added. At room temperature and under vigorous stirring, the solution was maintained under a hydrogen atmosphere for 16 h. The reaction could also be monitored by ¹H NMR, since the signal of the olefin progressively disappeared. After filtration on alumina and evaporation of the solvent, the pure reduced knot **20⁴⁺** was obtained in a quantitative yield (6.4 mg, 2.4 μmol), fuschia red solid. UV–vis (CH₂Cl₂), [λ_{max} (nm) ε (mol⁻¹·L·cm⁻¹): 231 (137 100); 259 (97 800); 278 (118 200); 283 sh (94 700); 327 (115 700); 486 sh (11 400); 551 (19 300); 620 sh (3100)]. ¹H NMR (acetone-*d*₆, 200 MHz): 9.23 (d, 4H, H_{5'}, ³J = 8.0 Hz); 9.12 (d, 4H, H_{3'}, ³J = 8.0 Hz); 8.87 (t, 4H, H_{4'}, ³J = 8.0 Hz); 8.71 (d, 4H, H_{3''}, ³J = 7.9 Hz); 8.59 (d, 4H, H₃, ³J = 8.1 Hz); 7.82 (d, 4H, H₄, ³J = 8.1 Hz); 7.67 (d, 4H, H_{4''}, ³J = 7.9 Hz); 7.29 (s, 4H, H₆); 6.43 (s, 4H, H_{6''}); 3.5–3.7 (m, 64H, CH₂ polyoxo chain); 3.40 (m, 8H, H_β); 3.17 (t, 8H, H_γ, ³J = 6.2 Hz); 2.72 (s, 8H, bridging CH₂); 2.40 (t, 8H, H_α, ³J = 7.4 Hz). ¹H NMR (CD₂Cl₂, 400 MHz): 8.81 (AB, 8H, H_{3-5'}, ³J = 8.0 Hz); 8.68 (t, 4H, H_{4'}, ³J = 8.0 Hz); 8.36 (d, 4H, H₃, ³J = 8.3 Hz); 8.32 (d, 4H, H_{3''}, ³J = 8.3 Hz); 7.73 (d, 4H, H₄, ³J = 7.0 Hz); 7.65 (d, 4H, H_{4''}, ³J = 8.0 Hz); 6.70 (d, 4H, H₆, ⁴J = 3.2 Hz); 6.49 (d, 4H, H_{6''}, ⁴J = 3.2 Hz); 3.3–3.7 (m, 64H, CH₂ polyoxo chain); 3.38 (m, 8H, H_β); 3.15 (t, 8H, H_γ, ³J = 5.9 Hz); 2.38 (t, 8H, H_α, ³J = 7.5 Hz); 2.11 (s, 8H, bridging CH₂). The latter assignment was confirmed by 2D-NMR spectroscopy (ROESY).

Acknowledgment. We thank the CNRS and the EU for financial support and the French Ministry of National Education for a fellowship to G.R. We are also grateful to Dr. J.-P. Collin for fruitful discussions and to J.-D. Sauer for recording the ¹H NMR spectra. Special thanks are due to Nathalie Kyritsakas, André De Cian, and Jean Fischer for the X-ray structure of **10⁴⁺**.

Supporting Information Available: Tables of X-ray data for **10⁴⁺** and figures showing ROESY measurements on **20⁴⁺** and **5²⁺** (25 pages, print/PDF). See any current masthead page for ordering information and Web access instructions.

JA982239+