A phen–terpy conjugate whose chelate coordination axes are orthogonal to one another and its zinc complex†

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A new highly rigid ditopic ligand has been prepared which consists of a terpy fragment connected through its 4′ position to the 3 position of a phen nucleus *via* a 1,4-phenylene linker. The chemical structure of the presently reported two-chelate ligand is such that the coordination axes of the two chelates are orthogonal to one another. The reaction of this phen–terpy conjugate with Zn^{2+} affords in good yield a dimeric structure, as shown by ES-MS and ^1H NMR spectroscopies.

Multisite ligands containing two or several aromatic polyimines and their complexes have been extensively used in relation to electron and energy transfer processes, most of the time with ruthenium(II) centres and other d^6 transition metals.[1] They have also been utilised extensively to construct elegant multinuclear architectures such as grids,[2a] helical complexes,[2b,c] racks,[2d,e] *etc.* or new topologies such as knots[3] or rotaxane dimers.[4] As far as we know, two-site ligands whose chelate coordination axes are orthogonal to one another are not common. Such compounds should favour the formation of multinuclear complexes with well defined geometries and nuclearities.[5] Once incorporated in macrocyclic systems, they should also allow the synthesis of multi-rotaxanes. The coordination principle is given in Fig. 1.

The present report deals with the synthesis and the properties of such a two-site ligand, containing a 2,2′:6′,2″-terpyridine unit (terpy = tridentate chelate) attached to a 1,10-phenanthroline nucleus (phen = bidentate chelate). The rigid linker used (1,4-phenylene) connects the two chelates *via* appropriate positions (4′ position of terpy and 3 position of phen) so that the coordination axes are perpendicular to one another. The phen–terpy ligand **1** is represented in Scheme 1 as well as the synthetic route leading to it. It should be noticed that both chelating units are very distinct from one another (A of Fig. 1 is the phen unit, and B the terpy fragment). If the complexed metal M has a strong preference for 5-coordinate situations, M(A)(B) complexes should be strongly favoured *versus* symmetrical complexes of the $M(A)_2$ or $M(B)_2$ type.

Compound **2** had previously been made by reacting Grignard reagents with the nitrile derivative.[6] We developed a new efficient route inspired by the procedure described by Holm,[7] which upon lithiation of the brominated precursor and addition of *N*,*N*-dimethylacetamide afforded **2** in 52% yield. Two parallel reactions were then carried out. On one hand, azachalcone **3** was obtained by classical aldol condensation of **2** and 4-bromobenzaldehyde, and subsequent dehydration of the intermediate[8,9] (86%). On the other hand, reaction of **2** with iodine in pyridine[10] yielded the pyridinium iodide **4** (74%). Precursors **3** and **4** were then allowed to react according to the classical Kröhnke synthesis[8,11,12] and terpyridine **5** was obtained in 60% yield. The functionality at the back of the terpyridine was then modified by changing the bromine atom for a boronic ester function in the presence of bis(neopentyl glycolato)diboron according to the well described procedure.[13] Compound **6** was thus obtained in quantitative yield from **5**. The precursor used for the phenanthroline fragment was 3,8-dibromo-1,10-phenanthroline which was synthesized following the usual procedure.[14,15] It was then dissymetrized by a statistical Suzuki coupling reaction[15,16] on *p*-anisylboronic acid, and the mono-coupled product **7** was isolated in 46% yield. A last Suzuki coupling reaction[13,15,16] between **6** and **7** under classical conditions yielded the phen–terpy conjugate **1** (24%), containing seven conjugated 6-membered aromatic rings.

Zn^{2+} forms stable 5-coordinate complexes and it is most of the time sufficiently labile to allow formation of coordination compounds under thermodynamic control. This metal was thus selected for complexation studies with ligand **1**. It should be noticed that non-distorted trigonal bipyramid geometries, with their two A and B chelates orthogonal to one another, are expected to favour formation of 4-metal centre assemblies similar to that represented in Fig. 1. By contrast, other

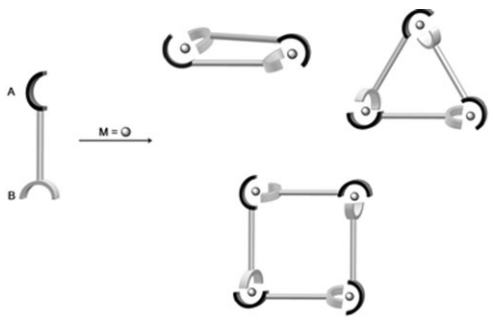

Fig. 1 Formation of M(A)(B) complexes should lead to oriented cyclic structures. Depending on the coordination sphere geometry of the transition metal used, various rings and nuclearities could be obtained.

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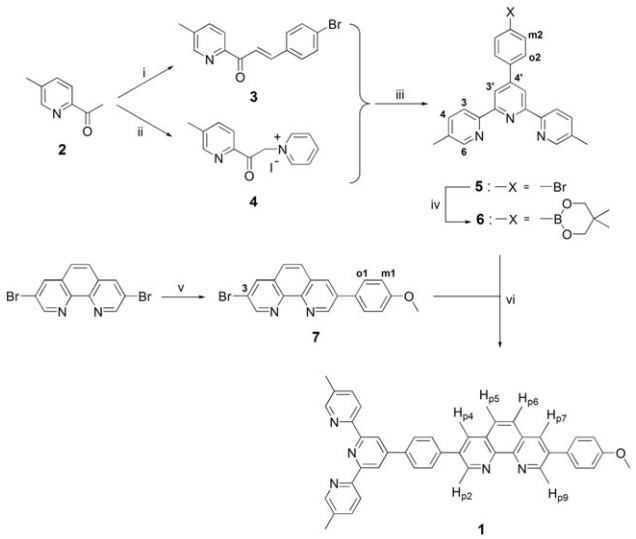

Scheme 1 *Reagents and conditions*: (i) 4-bromobenzaldehyde, MeOH –$NaOH_{(aq)}$, 30 min; (ii) I_2, pyridine, reflux 1 h, rt 14 h; (iii) NH_4OAc, AcOH, reflux 7 h, rt 14 h; (iv) $Pd(dppf)Cl_2$, KOAc, B_2neo_2, dioxane, 80 °C, 18 h; (v) $Pd(PPh_3)_4$, Na_2CO_3, *p*-anisylboronic acid, toluene–H_2O, reflux, 14 h; (vi) $Pd(PPh_3)_4$, Na_2CO_3, reflux, 30 h.

5-coordinate geometries such as, for example, square pyramid or distorted trigonal pyramid, should afford smaller rings such as 3-metal assemblies or even dinuclear species. For entropic reasons, the reaction between Zn^{2+} and **1** is expected to lead to the smallest possible complex, the size of the species obtained having nevertheless to be compatible with the coordination constraints imposed by the metal and the ligand. If distortion of Zn^{2+} coordination sphere and/or of the ligand backbone costs less than the entropic price needed to build the large ideal 4-metal species, lower nuclearities will be formed. This is the case in the present system. To our surprise, the dimer was the sole complex formed, without formation of tetramer nor even trimer complexes. The reaction is represented in Fig. 2 along with a molecular model (Chem 3D software) of the complex.

The coordination reaction of Zn^{2+} to **1** was carried out by mixing equimolar amounts of respectively **1** in CH_2Cl_2 and $Zn(OTf)_2$ in MeOH. The resulting orange solution was allowed to stir for 28 hours, the solvent was then evaporated, the crude mixture was taken up in methanol, filtered, and the filtrate evaporated to dryness. The dimer complex $[Zn_2 \cdot (\mathbf{1})_2]^{4+} \cdot 4OTf^-$ was obtained in good yield (78%) as a yellow solid. It is only sparingly soluble in common organic solvents. At this stage, it is difficult to know if, in solution, the Zn^{2+} centres are really 5-coordinate or if the counterion ($CF_3SO_3^- = OTf^-$) participates in the Zn^{2+} complexation. The X-ray structure of a recently published hexanuclear complex with Borromean rings as organic backbone[17] showed that 6-coordinate Zn^{2+} complexes with $Zn(N)_5(OTf^-)$ coordination spheres are stable. The dimer complex with two 6-coordinate Zn^{2+} centres is moreover certainly less strained in terms of organic ligand distortion than the putative analogous complex in which the Zn^{2+} centres would be 5-coordinate. The chemical structure of $[Zn_2 \cdot (\mathbf{1})_2]^{4+}$ (*M*) was proven by electrospray ionization mass spectroscopy (ES-MS) and ^1H NMR spectroscopies. ES-MS analysis of the yellow solid revealed three major peaks at mass-to-charge (*m*/*z*) ratios of 342.6, 506.4, and 834.6, corresponding to $[M]^{4+}$, $[M + OTf]^{3+}$, and $[M + 2OTf]^{2+}$, respectively, a situation that is consistent with the proposed dimer compound $[Zn_2 \cdot (\mathbf{1})_2] \cdot 4OTf$.

DOSY (diffusion-ordered spectroscopy) experiments[18] carried out on a solution of the yellow solid in MeOD (Fig. 3) revealed unambiguously the presence of a single species, characterized by its diffusion coefficient ($D = 470$ μm^2 s^{-1}; monomer **1** in CD_2Cl_2: $D = 1000$ μm^2 s^{-1}) and its hydrodynamic radius ($r_H = 8.5$ Å; monomer **1**: $r_H = 5.3$ Å).

Computational simulation of the hydrodynamic radius of an ellipsoid object which matches with the experimental value of the radius enabled us to predict the size of the product in solution: $a = 14$ Å and $b = c = 6$ Å. The object is thus a prolate ellipsoid, which is consistent with the proposed dimer compound $[Zn_2 \cdot (\mathbf{1})_2] \cdot 4OTf$. The ratio a/b being approximately around 2, it would nevertheless be impossible to exclude the possibility of having an oblate ellipsoid ($a = b = 14$ Å and $c = 6$ Å) which would be more consistent with the geometry of the tetramer species. But considering the results of both ES-MS and DOSY experiments, we can tell that the sole product formed during the complexation process is the dimer species $[Zn_2 \cdot (\mathbf{1})_2] \cdot 4OTf$. Moreover, ^1H NMR clearly shows what was expected for a dimer species: the geometry around the zinc centre is so distorted that the p_2 proton of the phen part of one monomer points right into the shielding cone of the central ring of the terpy fragment of the other monomer, and consequently the p_2 proton signal is strongly shifted upfield ($\Delta\delta = 2.82$ ppm).

In conclusion, a new phen–terpy conjugate **1** has been synthesized which contains two chelates whose coordination axes are perpendicular to one another. Whereas the expected structure for the Zn^{2+} complex formed with ligand **1** was that of a tetramer ($[Zn_4 \cdot (\mathbf{1})_4]^{8+}$), a dimer was the sole product observed. The present example tends to indicate that entropy is a prevailing factor in the complexation process: the reaction leads to the smallest possible complex in spite of probable distortion of the Zn^{2+} coordination sphere and constraints within the organic ligand **1**. Obviously, the use of other transition metal centres than Zn^{2+} with more demanding

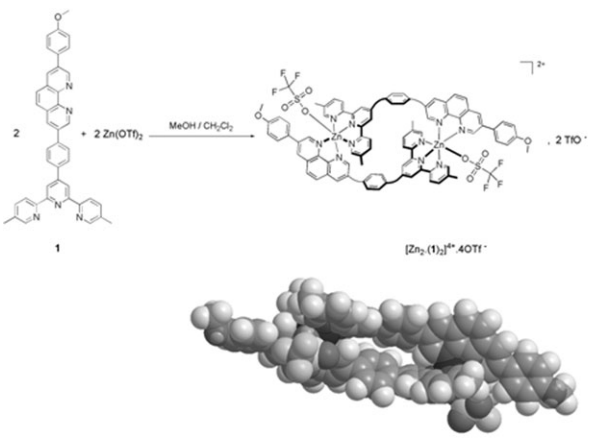

Fig. 2 Reaction between **1** and Zn^{2+} leading to the dimer complex, and its molecular model (Chem 3D software).

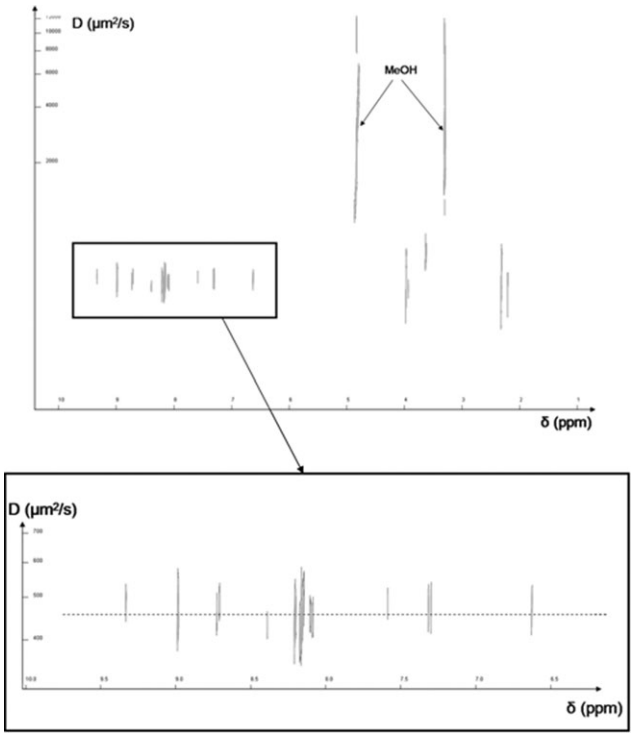

Fig. 3 DOSY experiment on the dimer complex in MeOD, and zoom on the aromatic region of the spectrum. Apart from the MeOH broad signals, a single product is present.

stereoelectronic requirements, making distortion more difficult, should favour formation of trimers or tetramers.

Experimental

General

^{1}H, ^{13}C NMR and DOSY spectra were acquired either on a Bruker AVANCE 300 (300 MHz) or a Bruker AVANCE 500 (500 MHz) spectrometer, using the deuterated solvent as the lock and residual solvent as the internal reference. Mass spectra were obtained by using a Bruker MicroTOF spectrometer (ES-MS). $Pd(PPh_3)_4$ and $Zn(OTf)_2$ were commercial products.

Syntheses

Phen–terpy conjugate 1. To a degassed solution of 3-bromo-8-(4-methoxyphenyl)-1,10-phenanthroline (**7**, 49 mg; 0.134 mmol) and $Pd(PPh_3)_4$ (7.8 mg; 0.007 mmol) in 10 mL of toluene were added, under argon, 1 mL of a degassed solution of 2 M aqueous Na_2CO_3 and a solution of 4′-(4-(neopentyl glycolatoboron)phenyl)-5,5″-dimethyl-2,2′:6′,2″-terpyridine (**6**, 62 mg; 0.138 mmol) in 5 mL of toluene. It is very important to respect the following sequence in the additions: (a) dibromophenanthroline in toluene, (b) 3 vacuum–argon cycles, (c) addition of the catalyst, (d) 3 vacuum–argon cycles, (e) addition of the degassed solution of Na_2CO_3, (f) 3 vacuum–argon cycles, (g) addition of the degassed solution of the boronic ester. The reaction was monitored by TLC, and after 30 h reflux, the reaction mixture was allowed to cool to room temperature. The solvent was removed by rotary evaporation and the crude mixture was taken up in CH_2Cl_2 and washed with water. The combined organic layers were dried over Na_2SO_4 and the solvent evaporated. Chromatography (aluminium oxide, CH_2Cl_2 to CH_2Cl_2–MeOH (99 : 1)) gave 20 mg (0.032 mmol; 24%) of pure product **1** as a white solid. ^{1}H NMR (for atom numbering see ESI†) (300 MHz, $CDCl_3$) δ (ppm): 2.44 (s, 6H, H_{CH3}), 3.90 (s, 3H, OCH_3), 7.08–7.11 (dm, 2H, 8.8 Hz, H_{o1}), 7.67–7.71 (dm, 2H, 8.1 Hz, 2.0 Hz, 0.5 Hz, H_4–$H_{4''}$), 7.72–7.75 (dm, 2H, 8.8 Hz, H_{m1}), 7.88 (d, 2H, 1.5 Hz, H_{p5}–H_{p6}), 7.91–8.11 (dd, 4H, 8.3 Hz, H_{o2}–H_{m2}), 8.34 (d, 1H, 2.3 Hz, H_{p7}), 8.46 (d, 1H, 2.3 Hz, H_{p4}), 8.57 (m, 2H, H_6–$H_{6''}$), 8.56–8.58 (d, 2H, 7.4 Hz, H_3–$H_{3''}$), 8.75 (s, 2H, $H_{3'}$–$H_{5'}$), 9.42 (d, 1H, 2.25 Hz, H_{p9}), 9.50 (d, 1H, 2.25 Hz, H_{p2}). ^{13}C NMR (300 MHz, $CDCl_3$) δ (ppm): 160.07 (*i*); 156.19 (*2′*); 153.80 (*2*); 149.62 (*6*); 149.43 (*4′*); 149.36 (*p9*); 149.30 (*p2*); 146.02 (*p12*); 145.40 (*p3*); 144.72 (*p11*); 138.68 (*y*); 137.44 (*4*); 135.46 (*p8*); 134.92 (*x*); 133.57 (*5*); 133.41 (*p4*); 132.59 (*p7*); 130.00 (*p*); 128.69 (*m1*); 128.67 (*p14*); 128.37 (*p13*); 128.21 (*o2*); 127.97 (*m2*); 127.24 (*p6*); 127.06 (*p5*); 120.96 (*3*); 118.16 (*3′*); 114.78 (*o1*); 55.47 (OCH_3); 18.48 (CH_3). EI-MS, *m*/*z* exp.: 622.254 (**1**, calc. for [M + H]: 622.260). DOSY (CD_2Cl_2, 500 MHz): $D = 1000$ μm^2/s; $r_H = 5.3$ Å.

Dimer $[Zn_2 \cdot (1)_2] \cdot 4OTf$. Phen–terpy conjugate **1** was suspended in 0.25 mL of CH_2Cl_2. A solution of $Zn(OTf)_2$ in CH_3OH (23.8 mg in 1 mL) was prepared, and 0.25 mL were added to the ligand suspension, which became clear and orange. The reaction mixture was allowed to stir for 28 h, the solvent was then evaporated and the crude mixture taken up in methanol, filtered, and the filtrate evaporated to dryness yielding $[Zn_2 \cdot (\mathbf{1})_2] \cdot 4OTf$ as a yellow solid (10.5 mg; 78%). ^{1}H NMR (500 MHz, CD_3OD) δ (ppm): 2.37 (s, 6H, H_{CH3}), 4.02 (s, 3H, OCH_3), 6.68 (s, 1H, H_{p2}), 7.35–7.37 (d, 2H, 8.85 Hz, H_{o1}), 7.64–7.66 (dm, 2H, 8.0 Hz, H_{m2}), 8.12 (m, 2H, H_4), 8.14–8.16 (dm, 2H, 8.0 Hz, H_{o2}), 8.20 (m, 4H, H_{p5}–H_{p6}–H_{m1}), 8.25 (m, 2H, H_6–$H_{6'}$), 8.44–8.46 (d, 1H, H_{p9}), 8.76–8.78 (d, 2H, 8.1 Hz, H_3–$H_{3'}$), 8.94 (m, 1H, H_{p4}), 9.04 (s, 2H, $H_{3'}$–$H_{5'}$), 9.39 (s, 1H, H_{p7}). EI-MS, *m*/*z* exp.: 342.592 (calc. for $[Zn_2(\mathbf{1})_2]^{4+}$: 342.590); 506.439 (calc. for $[Zn_2(\mathbf{1})_2, OTf]^{3+}$: 506.438); 834.681 (calc. for $[Zn_2(\mathbf{1})_2, 2OTf]^{2+}$: 834.637). DOSY ($CD_3OD$, 500 MHz): $D = 470$ μm^2 s^{-1}; $r_H = 8.5$ Å.

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