Synthesis, Properties and Complexation Studies on 3-Amino-6,6'-dimethyl-2,2'-bipyridine†

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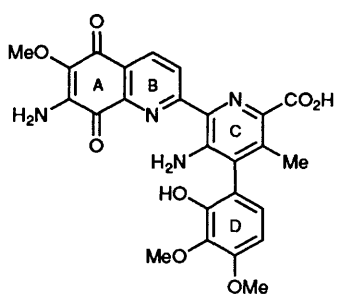
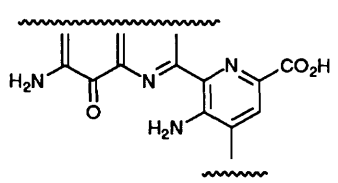
The new unsymmetrical bipyridyl ligand 6,6'-dimethyl-3-nitro-2,2'-bipyridine was prepared *via* coupling of 6-methyl-2-trimethylstanniopyridine and 2-chloro-6-methyl-3-nitropyridine in the presence of $[Pd(PPh_3)_2Cl_2]$. Reduction of the nitro group afforded 3-amino-6,6'-dimethyl-2,2'-bipyridine (L), a model for the central subunit of the antitumour drug streptonigrin. At low temperatures, in $[^2H_6]$acetone, L is planar, held in place by a hydrogen bond from the amino group to the pyridyl nitrogen in the adjacent ring. From ^1H NMR lineshape analysis the barrier to rotation about the amino–bipyridyl bond ($\Delta G_b^{\ddagger}$) was estimated to be ≈ 38 kJ mol^{-1} at 200 K. This value is significantly lower than the barrier to rotation about the biaryl bond connecting the aryl rings. In solution, L co-ordinates to Cd^{II}, Cu^{I} and Zn^{II} as a bipyridyl ligand; in these complexes the chemical shift of the amino group protons shifts upfield to *ca.* δ 5 compared to L where they resonate at δ 6.5. The crystal structure of $[(CdLCl_2)_2]$ was determined by X-ray diffraction methods and refined to a residual of 0.027 for 1895 independent observed reflections. The crystals are monoclinic, space group $P2_1/n$, $a = 9.560(2)$, $b = 16.886(2)$, $c = 9.577(3)$ Å, $\beta = 118.37(2)°$. The complex crystallized as a dimer in which each cadmium binds three chloride ligands and a bipyridyl ligand in a distorted trigonal-bipyramidal arrangement. The relevance of these results to the structure and properties of the antitumour drug streptonigrin is discussed.

Streptonigrin is a highly functionalized 7-aminoquinoline-5,8-dione and is one of the most effective agents for the treatment of human cancers.[1–6] Studies carried out on synthetic analogues of the drug[7–9] have shown that the substructure **I** is the minimum unit required for biological activity.[10] The mechanism of action of streptonigrin is not fully understood, but studies suggest that it causes DNA degradation *via* reduction to the semiquinone in the presence of metal ions in a process involving oxygen and radicals.[9–13] The exact role of the metal ions in this process is currently under investigation in our laboratories.

Analysis of the structure of streptonigrin shows that there are several potential co-ordination sites, and several metal–streptonigrin complexes have been proposed,[10,14,15] although no structural proof has been provided. As a first step toward full characterization of the solution structure(s) of the metal complexes of streptonigrin, this paper reports the synthesis of 3-amino-6,6'-dimethyl-2,2'-bipyridine (L) and a study of its co-ordination chemistry. This compound is a model of the central co-ordination unit of streptonigrin and was designed to allow the role of the amino group of the bipyridyl framework in the determination of the mode of co-ordination to be assessed. Dynamic NMR spectroscopy was used to determine the solution conformation of the ligand, and NMR spectral parameters that allow characterization of the complexes were obtained.



Streptonigrin



I

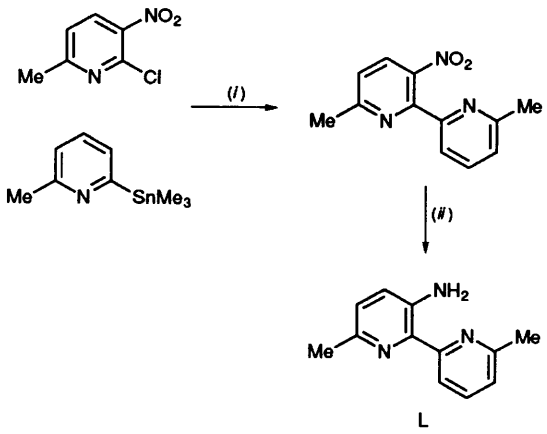
Results and Discussion

Synthesis of 3-Amino-6,6'-dimethyl-2,2'-bipyridine.—This compound was prepared from 6,6'-dimethyl-3-nitro-2,2'-bipyridine *via* a coupling reaction using $[Pd(PPh_3)_2Cl_2]$ as a catalyst (Scheme 1). Thus, treatment of 2-chloro-3-nitro-6-methylpyridine[16] with 6-methyl-2-trimethylstanniopyridine in the presence of $[Pd(PPh_3)_2Cl_2]$, according to the method of Ghadiri *et al.*[17] afforded 6,6'-dimethyl-3-nitro-2,2'-bipyridine in good yield. The nitro group was converted into the amine L by catalytic reduction in ethanol, or by reduction with tin(II) chloride–hydrochloric acid.

Coupling reactions in the presence of transition metals have been widely used in the preparation of unsymmetrical biaryls,[18] but there are very few examples of this approach applied to the direct synthesis of unsymmetrical bipyridines.[17] The synthesis of the related compound 3-amino-2,2'-bipyridine from 3,3'-diamino-2,2'-bipyridine has been reported.[19] However, the reaction sequence required three steps and the product was a

† *Supplementary data available:* see Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1993, Issue 1, pp. xxiii–xxviii.

Non-SI unit employed: mmHg $\approx$ 133 Pa.



Scheme 1 (*i*) $[Pd(PPh_3)_2Cl_2]$, tetrahydrofuran; (*ii*) H_2, Pd/C

minor component of the reaction mixture (10%). The route used in this work provides a much more efficient and high-yielding route to unsymmetrical bipyridines and should be generally applicable to the synthesis of other bipyridine systems.

NMR Studies on 3-*Amino*-6,6'-*dimethyl*-2,2'-*bipyridine* (L).—Variable-temperature ^1H NMR experiments were carried out in order to provide information about the solution conformation of the ligand L. Spectra were acquired at temperatures in the range 298–171 K (Fig. 1). The most dramatic change occurs for the amino protons which appear as a broad singlet at 298 K, but split and appear as two singlets separated by almost 3 ppm at low temperatures. The large difference in chemical shifts of the two protons was attributed to the presence of a hydrogen bond between one of the amino protons and the nitrogen in the adjacent ring. The most downfield singlet (δ 8.9) was assigned to H_a, the proton involved in the hydrogen bond, and the second singlet (δ 6.0) was assigned to H_b (Fig. 1).

At temperatures below 220 K the spectra are amenable to lineshape analysis.[20] Two rotational barriers in compound L (a and b, Fig. 1) need to be considered as both may contribute to the lineshape of the amino protons. The energy barrier for b ($\Delta G^{\ddagger}_b$) was predicted to be significantly lower than the energy barrier for process a ($\Delta G^{\ddagger}_a$), on consideration of the steric interactions associated with each process.[21] At $T < 220$ K, it was assumed that the lineshape of the amino protons was determined by b and the contribution of a was negligible. Spectra were simulated using one rate constant and the parameters $\Delta G_b^{\ddagger}$ (kJ mol^{-1}) and k (s^{-1}) were calculated (Table 1). A plot of $\Delta G_b^{\ddagger}$ (kJ mol^{-1}) against the temperature T(K) was linear, indicating that the assumption that a does not contribute significantly to the lineshape at $T < 220$ K is basically justified.

Streptonigrin crystallizes from a solution of ethyl acetate with the amino group of ring C hydrogen bonded to the pyridyl nitrogen in ring B[22] but the solution structure of the drug has not been reported. The results obtained with ligand L suggest that it is highly likely that the major solution conformation of streptonigrin parallels the structure observed in the solid state[22] and that a hydrogen bond stabilizes a planar arrangement between rings A, B and C. The chemical shifts of the amino protons on ring C in streptonigrin at low temperature show a similar pattern to that observed in the variable-temperature experiments on L.[23] The energy barriers measured in this work for L give estimates of the corresponding energy barriers in streptonigrin and provide useful data for the assignment of its solution conformation.

π-*Bond Order*.—Research on a large number of chemical frameworks has shown conclusively that there is a correlation between the allylic spin–spin coupling constant ($^4J_{MeH}$) and the

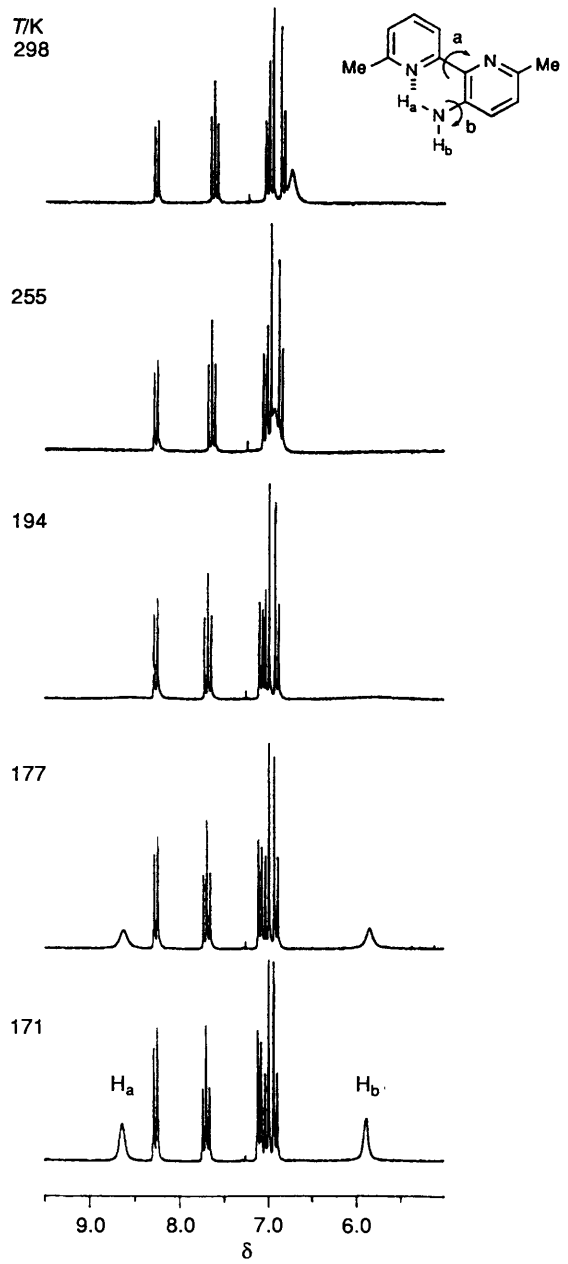


Fig. 1 Variable-temperature ^1H NMR ([$^2H_6$]acetone, 200 MHz) spectra of L

Table 1 Activation parameters obtained by lineshape analysis of the amino protons in L

T/K	k_b/s^{-1}	$\Delta G_b^{\ddagger}$/kJ mol^{-1}
177	47.5 ± 2.5	36.90 ± 0.08
188	147.5 ± 2.5	37.52 ± 0.03
194	300 ± 10	37.62 ± 0.05
197	395 ± 5	37.78 ± 0.02
199	465 ± 15	37.91 ± 0.05

π-bond order.[24] In general, the higher the coupling constant the higher is the bond order and more localized the π electrons (Fig. 2). In heterocyclic systems, for example 2-methylpyridine, $^4J_{MeH}$ is considerably lower than the value in toluene due to the electronic effects of the nitrogen in the aromatic ring, which has the ability to accept an electron into its p_z orbital. Similarly, in 2-amino-6-methylpyridine, the increase in coupling constant compared with 2-methylpyridine is due to the donation of the

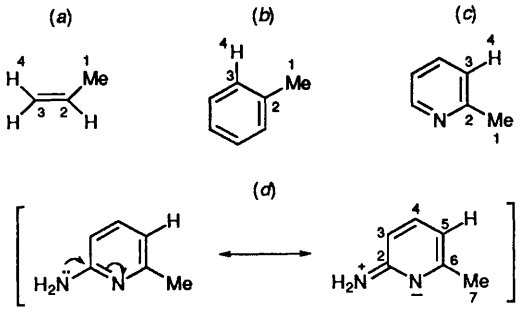
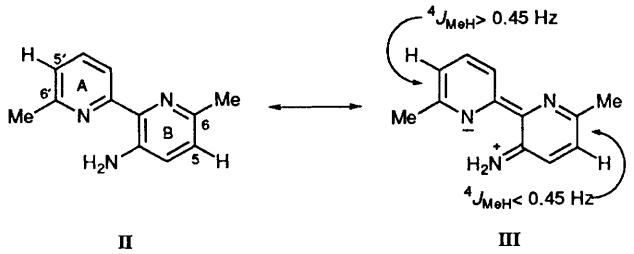
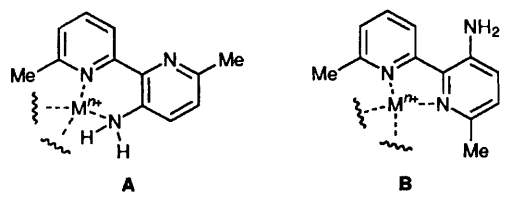


Fig. 2 Values of the allylic spin–spin coupling constant ($^4J_{MeH}$ in Hz) in aromatic systems: 1.6 (*a*), 0.8 (*b*), 0.45 ± 0.03 (*c*) and 0.58 ± 0.03 (*d*)



II **III**

Fig. 3 Resonance contributors for L showing expected range of values for $^4J_{MeH}$ (Hz): (measured values) ring A, 0.51 ± 0.03; ring B, 0.34 ± 0.03



A **B**

Fig. 4 The two possible modes of co-ordination of ligand L

amino lone pair of electrons into the aromatic ring, thus causing partial localization of the electrons between C^5 and C^6 (Fig. 2).

Fig. 3 shows the two main resonance contributors for compound L, and the measured values for the two allylic coupling constants. The values indicate that the π-bond order between $C^{5'}$ and $C^{6'}$ in ring A is higher than that between C^5 and C^6 in ring B, which may be rationalized by the contribution of the resonance structure **III** to the overall structure of L. Thus the electronic distribution in the two aryl rings in this compound is substantially altered by the presence of the amino group.

Complexation Studies.—There are two potential types of complexes that may be formed between metal ions and 3-amino-6,6′-dimethyl-2,2′-bipyridine, **A** and **B**, shown schematically in Fig. 4. The co-ordination chemistry and properties of bipyridine ligands are well documented.[25] There are several reports of crystal structures of metal complexes which contain amino-N and pyridyl-N chelating ligands[26] co-ordinated to Cu^{II}. It has been suggested that Cu^{II} co-ordinates in a similar manner with streptonigrin to form a complex of type **A** and not a bipyridyl-type complex **B**.[10,14] When competing bipyridyl and amino-N/pyridyl-N binding sites are available, the strong chelating properties of the bipyridyl unit would be expected to dominate. In the present study, however, formation of the bipyridyl complex **B** in which the two aryl rings are planar may not be preferred over **A** due to steric interactions between the amino group and the hydrogen on the adjacent ring, and complexes of type **A** have been suggested to form with streptonigrin,[8,10,14] in which the aryl ring D may also influence the type of complex formed.

Compound L was treated with the metal ions Zn^{II}, Cu^{II}, Cd^{II}, Pd^{II} and Cu^{I}, *i.e.* those reported to interact with streptonigrin

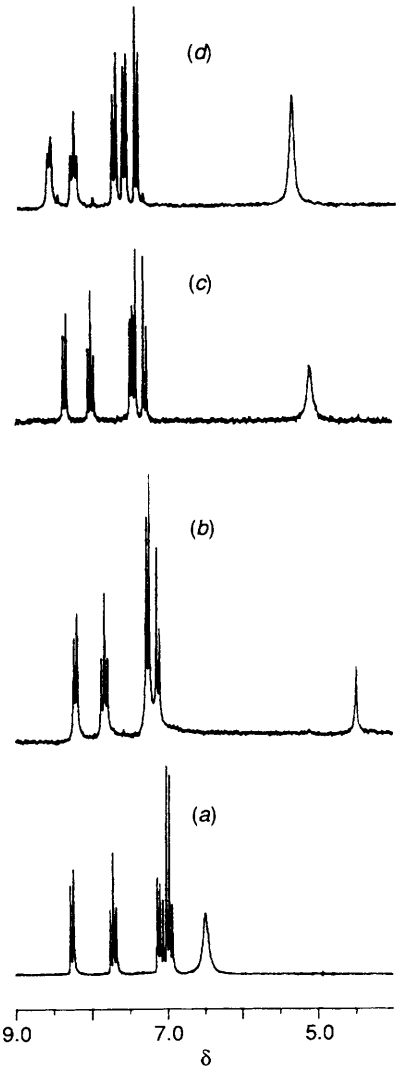


Fig. 5 The ^{1}H NMR (CD_3CN, 200 MHz) spectra at 298 K of (*a*) L, (*b*) L + 1 equivalent $[Cu(MeCN)_4]PF_6$ (**3**), (*c*) L + 1 equivalent $CdCl_2$ (**1**) and (*d*) L + 1 equivalent $Zn(CF_3SO_3)_2$ (**2**)

and to enhance biological activity.[13] With the exception of Cu^{II}, these metal ions form diamagnetic complexes with bipyridyl ligands which can be characterized by NMR spectroscopy. The complexes were prepared from mole equivalents of L and the metal ions, *i.e.* the stoichiometry that has been reported for the metal complexes of streptonigrin. Counter ions were chosen to give complexes soluble in organic solvents which would allow the amino protons to be observed by ^{1}H NMR spectroscopy.

The ^{1}H NMR spectra of the complexes of Cd^{II}, Zn^{II} and Cu^{I} with L, **1**–**3** respectively are shown in Fig. 5. Of particular importance is the upfield shift of the amino proton resonance in the complexes (≈δ 5) compared to free L (δ 6.5). The change in chemical shift occurring on complexation is consistent with formation of a bipyridyl complex **B**. Compared to free L, the amino protons in **1**–**3**, which are no longer hydrogen bonded, move upfield and resonate in the region typical for aminoaryl compounds. If complex **A** were formed, the chemical shift of the amino protons would be expected to move downfield due to the close proximity of the protons to the positive charge. Addition of 1.0 equivalent of palladium(II) acetate to L afforded a product having an NMR spectrum consistent with the formation of multiple products which were not characterized. These complexes arise presumably due to the fact that palladium(II) favours formation of square-planar complexes with bipyridyl ligands. This co-ordination cannot be readily achieved with L due to the substituents on the bipyridine rings.

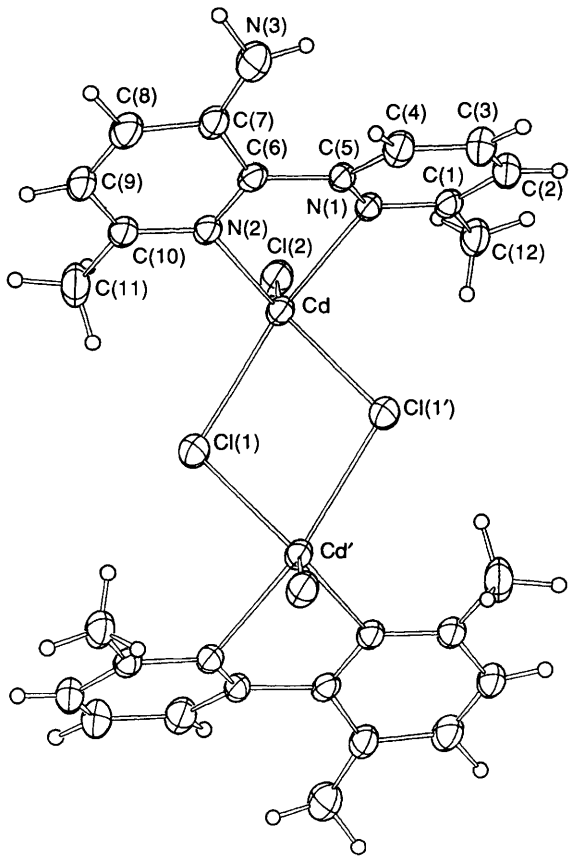


Fig. 6 View of the molecular structure of $[(CdLCl_2)_2]$ **1**

An electrospray (ES) mass spectrum of complex **3** showed a strong peak for $[CuL]^+$. A weak peak due to $[CuL_2]^+$ was also detected indicating that despite a metal : ligand ratio of 1 : 1 some of the 1 : 2 complex is also formed. These two complexes would have indistinguishable NMR spectra. Both FAB and ES spectra of the zinc chelate **2** failed to detect the expected molecular ion for the complex and were dominated by the $[L]^+$ peak. This result suggests that, compared to the copper(I) chelate **3**, the zinc chelate **2** is much weaker which leads to rapid fragmentation.

The crystal structure of the cadmium complex **1** (Fig. 6), crystallized from acetone–water (4 : 1) solution, supports the conclusions reached by analysis of the ^{1}H NMR spectrum of **1**. The structure consists of neutral dichloro-bridged $[(CdLCl_2)_2]$ dimers with a Cd ··· Cd distance of 3.952 Å. The bidentate ligands are co-ordinated to the Cd atoms through two pyridyl-N atoms; the amine-N atom is rotated away from the Cd atom and exists in the neutral NH_2 form. The geometry about the Cd atom is intermediate between trigonal bipyramidal, in which N(1)–Cd–Cl(1) defines the apical direction, and square pyramidal, in which N(1), N(2), Cl(1) and Cl(1') define the basal plane and Cl(2) the apex. There are hydrogen bonds between each of the H(amine) atoms and the non-bridging chloro ligand. Least-squares planes through the two six-membered rings of the bidentate ligand reveal that these rings are significantly distorted from planarity. The largest deviation in ring A is 0.12 Å and in ring B it is 0.16 Å. The pendant amine group of ring B is 0.14 Å out of the least-squares plane. The distortions are almost certainly caused by interactions between the amine of ring B with ring A and it is notable that the amine group and its H atoms are bent away from the nearby atoms of ring A. The torsion angles about the C(5)–C(6) bond are 21.3 for N(1)–C(5)–C(6)–N(2) and 25.1° for C(4)–C(5)–C(6)–C(7). Taken with the interplanar angle of 17.9°, this shows that the twisting is not a pure rotation about C(5)–C(6) and that the N(3)–C(4) interaction results in an overtwisting of C(4)–C(5)–C(6)–C(7).

The usefulness of infrared spectroscopy in establishing the type of complex formed, by analysis of the NH_2 frequencies, was also investigated. One would expect that formation of complex type **A** in which the amino group is fixed in the plane of co-ordination may give rise to two N–H stretches at different frequencies from the N–H stretch in a complex of type **B**. Of the metals studied, Cu^{II} is the strongest candidate that may form a complex **A**. However, the IR spectrum of its complex was not significantly different from those of **1**–**3** which had been characterized by ^{1}H NMR spectroscopy. In the absence of further data, the structure of this complex cannot be defined and will require X-ray crystallography for characterization. Attempts to obtain crystals for this analysis have not been successful at the present time.

Experimental

Melting points were determined on a Reichert heating stage and are uncorrected. Ultraviolet spectra were recorded on a Hitachi 150-20 spectrophotometer, NMR spectra on a Bruker AC200 spectrometer. The allylic coupling constants for L were determined on a Bruker AMX400 NMR spectrometer. The temperature of the spectrometer probe was calibrated by the shift difference of methanol resonances in the ^{1}H NMR spectrum.[27] The ^{1}H and ^{13}C NMR spectra of L were fully assigned using decoupling experiments, C–H correlation and correlation spectroscopy *via* long range couplings experiments.[28] Spectra were recorded in the solvent indicated, locked on solvent deuterium and referenced to residual solvent protons. Lineshape analysis was carried out on a Vax computer using the program DNMR3.[29] Activation parameters were obtained from weighted least-squares fits of the rate constants to the Arrhenius and Eyring equations. Mass spectra were recorded on an AEI MS-902 spectrometer at 70 eV, and electrospray (ES) mass spectra were recorded at the University of Wollongong on a Fisons/VG Quattro mass spectrometer. Samples were introduced in MeCN–water at 3–5 μl min^{-1}. Flash column chromatography was carried out on Merck silica gel (type 9385, 230–400 mesh). 2-Chloro-3-nitro-6-methylpyridine was prepared *via* 2-hydroxy-3-nitro-6-methylpyridine according to the literature procedure.[17,30]

Syntheses.—*6-Methyl-2-trimethylstanniopyridine.*[31] 2-Bromo-6-methylpyridine (1.97 g, 11.5 mmol) was dissolved in tetrahydrofuran (thf) (12 cm^3), added dropwise to a solution of butyllithium (2.5 mol dm^{-3}, 4.65 cm^3) in thf (5.8 cm^3) at −78 °C, and the solution stirred for 1 h. Trimethyltin chloride (2.77 g, 12.8 mmol) in thf (2.5 cm^3) was added at −78 °C and the reaction mixture was allowed to warm to room temperature. The solvent was removed under reduced pressure and methylcyclohexane was added to precipitate by-products. The resultant solid was filtered off, the solvent removed and the residue distilled twice (50 °C, 0.5 mmHg) to afford 6-methyl-2-trimethylstanniopyridine as a clear colourless oil (1.69 g, 58%); δ_H($CDCl_3$,200 MHz) 0.33 (9 H, s, $SnMe_3$), 2.57 (3 H, s, Me), 7.00 (1 H, d, *J* 7.6, H^5), 7.24 (1 H, d, *J* 7.2, H^3) and 7.43 (dd, *J* 7.6, 7.2 Hz, H^4); *m/z* 257 ($M^{\cdot+}$, 9.7), 246 (17.8), 242 (100), 241 (34), 240 (82), 239 (30), 238 (47), 212 (43), 165 (13), 135 (50), 120 (16) and 28 (34%).

6,6'-Dimethyl-3-nitro-2,2'-bipyridine. A solution of 2-chloro-6-methyl-3-nitropyridine (2.00 g, 11.6 mmol), 6-methyl-2-trimethylstanniopyridine (3.30 g, 12.9 mmol) and bis(triphenylphosphine)palladium(II) chloride (0.43 g, 0.61 mmol) in dry thf (17 cm^3) was heated at reflux for 28 h. The orange-brown reaction mixture was cooled, the solvent removed and the resultant thick red-brown residue was extracted with light petroleum (b.p. 60–70 °C) (Soxhlet). After 3 h, the light

petroleum was removed *in vacuo* leaving a red-brown liquid which was distilled (130 °C, 0.07 mmHg) to give the crude product. Recrystallization from light petroleum (b.p. 60–70 °C) afforded 6,6′-dimethyl-3-nitro-2,2′-bipyridine as white crystals (1.53 g, 58%), m.p. 75 °C (Found: C, 62.9; H, 4.7; N, 18.2. Calc. for $C_{12}H_{11}N_3O_2$: C, 62.9; H, 4.8; N, 18.3%); ν_{max}(KBr disc) 2978m, 1572m, 1525m (NO_2), 1431m, 1354m (NO_2) cm^{-1}; δ_H($CDCl_3$, 200 MHz) 2.55 (3 H, s, Me), 2.71 (3 H, s, Me), 7.21 (1 H, d, *J* 6.45, $H^{5'}$), 7.23 (1 H, d, *J* 6.36, $H^{3'}$), 7.30 (1 H, d, *J* 8.31, H^5), 7.75 (1 H, dd, *J* 6.36, *J* 6.45, $H^{4'}$) and 8.01 (d, 1 H, *J* 8.31 Hz, H^4); δ_C($CDCl_3$, 50.03 MHz) 24.1 (C^7), 24.6 ($C^{7'}$), 120.0, 122.7, 123.8, 132.4, 137.2 ($C^{4,5,3',4',5'}$), 144.5, 150.6, 153.7, 158.0 and 161.4 ($C^{2,3,6,2',6'}$); λ_{max}(log ε)($CHCl_3$) 282 (1.76) and 240 (1.71) nm; *m/z* 229 ($M^{\cdot+}$, 40), 199 (*M* − 2 × Me, 100), 183 (*M* − NO_2, 48), 171 (34), 156 (21), 130 (10), 92 (19), 65 (23), 53 (24), 39 (27) and 32 (22%).

3-*Amino*-6,6′-*dimethyl*-2,2′-*bipyridine* (L). *Method* 1. 6,6′-Dimethyl-3-nitro-2,2′-bipyridine (47.5 mg, 0.207 mmol) was added to a solution of tin(II) chloride dihydrate (272 mg, 1.20 mmol) and concentrated hydrochloric acid (2 cm^3). The mixture was heated at 100 °C for 22 h, basified with sodium hydroxide and the product extracted into chloroform. The combined extracts were dried over sodium sulfate and the solvent removed *in vacuo*. The crude product was distilled (125 °C, 0.07 mmHg) and recrystallized from benzene with infusion of light petroleum (b.p. 60–70 °C) yielding 3-amino-6,6′-dimethyl-2,2′-bipyridine (L) as a yellow crystalline solid (38 mg, 91%), m.p. 98 °C (Found: C, 72.7; H, 6.7; N, 21.1. Calc. for $C_{12}H_{13}N_3$: C, 72.3; H, 6.6; N, 21.1%); ν_{max}(KBr disc) 3365m, 3245m, 2910w, 1612m, 1569, 1556, 1475, 1449 and 1329 cm^{-1}; δ_H($CDCl_3$, 200 MHz) 2.49 (3 H, s, Me), 2.58 (3 H, s, Me), 6.20 (2 H, br s, NH_2), 6.93 (1 H, d, *J* 8.27, H^5), 6.97 (1 H, d, *J* 8.27, H^4), 7.05 (1 H, d, *J* 7.54, $H^{5'}$), 7.68 (1 H, dd, *J* 8.06, 7.54, $H^{4'}$) and 8.31 (1 H, d, *J* 8.06 Hz, $H^{3'}$); δ_C($CDCl_3$, 50.03 MHz) 58.9 (C^7), 59.4 ($C^{7'}$), 91.4 ($C^{3'}$), 91.9 ($C^{5'}$), 92.7 (C^5), 93.5 (C^4), 96.6 ($C^{2'}$), 97.1 ($C^{4'}$), 97.3 (C^2), 98.6 (C^6), 100.1 ($C^{6'}$) and 103.4 (C^3); λ_{max}(log ε)(MeCN) 354 (1.82) and 256 (1.92) nm; *m/z* 199 ($M^{\cdot+}$, 49), 198 (100), 184 (5), 171 (3), 119 (3), 100 (3), 92 (4), 65 (3), 53 (4) and 32 (9%).

Method 2. 6,6′-Dimethyl-3-nitro-2,2′-bipyridine (50 mg, 0.218 mmol) was dissolved in ethanol (10 cm^3). Palladium-on-charcoal catalyst was added (5 mg) and the mixture stirred under hydrogen at atmospheric pressure for 10 h. The reaction mixture was filtered through Celite and the solvent removed, to give a yellow oil which crystallized on standing. Recrystallization from benzene with infusion of light petroleum afforded 3-amino-6,6′-dimethyl-2,2′-bipyridine as a yellow crystalline solid (40 mg, 92%) which had identical spectral properties to the sample prepared in method 1.

Reactions of 3-*Amino*-6,6′-*dimethyl*-2,2′-*bipyridine* (L).—*With* $CdCl_2$. A solution of L (11.0 mg, 0.055 mmol) in acetonitrile (0.3 cm^3) was added under nitrogen to a stirred suspension of cadmium(II) chloride (10.1 mg, 0.055 mmol) in acetonitrile (0.2 cm^3). More acetonitrile (5 cm^3) was added to give a homogeneous solution. Slow ether infusion into this solution over 2 d afforded di-μ-chlorobis[(3-amino-6,6′-dimethyl-2,2′-bipyridine)chlorocadmium(II)] **1** as yellow plates, m.p. > 300 °C; ν_{max}(KBr disc) 3418s, 3337s, 3217m, 1633m, 1592m, 1572m, 1462s and 1407s cm^{-1}; δ_H(CD_3CN, 200 MHz) 2.62 (3 H, s, Me), 2.78 (3 H, s, Me), 5.10 (2 H, br s, NH_2), 7.29 (1 H, d, *J* 8.49, H^4), 7.44 (1 H, d, *J* 8.49, H^5), 7.47 (1 H, d, *J* 7.26, $H^{5'}$), 8.01 (1 H, dd, *J* 7.98, *J* 7.26, $H^{4'}$) and 8.36 (1 H, d, *J* 7.98 Hz, $H^{3'}$); λ_{max}(log ε)(MeCN) 360 (1.30), 257 (1.34), 221 (1.48) and 210 (1.52) nm. Crystals suitable for X-ray diffraction crystallized from a solution of the complex in acetone–water over a period of 5 d.

With $Zn(CF_3SO_3)_2$. A solution of L (5.4 mg, 0.027 mmol) in acetonitrile (0.2 cm^3) was added to zinc(II) triflate (10.6 mg, 0.029 mmol) in acetonitrile (0.2 cm^3) under nitrogen. Slow diethyl ether infusion over 5 d afforded (3-amino-6,6′-dimethyl-2,2′-bipyridine)zinc(II)bis(triflate) **2** as yellow needles, m.p. > 300 °C; ν_{max}(KBr disc) 3439, 3330, 3232, 1629, 1594, 1574, 1465s and 1449 cm^{-1}; δ_H(CD_3CN, 200 MHz) 2.15 (3 H, s, Me) 2.29 (3 H, s, Me), 5.37 (2 H, br s, NH_2), 7.44 (1 H, d, *J* 8.62, H^4), 7.60 (1 H, d, *J* 7.76, $H^{5'}$), 7.74 (1 H, d, *J* 8.62, H^5), 8.27 (1 H, dd, *J* 8.63, 8.62, $H^{4'}$) and 8.59 (1 H, d, *J* 8.63 Hz, $H^{3'}$); λ_{max}(log ε)(MeCN) 343.9 (0.92) and 211 (1.58) nm; *m/z* (ES) 200.0 ($[L + H]^+$).

With $[Cu(MeCN)_4]PF_6$. A solution of L (8.0 mg, 0.04 mmol) in acetonitrile (0.3 cm^3) was added to a solution of tetra(acetonitrile)copper(I) hexafluorophosphate (15.2 mg, 0.041 mmol) in acetonitrile (0.4 cm^3) under nitrogen. The reaction mixture immediately turned red and was stirred for 3 h. The solvent was removed to give complex **3** as a red solid, m.p. > 200 °C (decomp.); ν_{max}(KBr disc) 3461, 3385, 3221, 2959, 2915, 1629, 1607, 1567, 1487, 1460 and 1443 cm^{-1}; δ_H(CD_3CN–1 μl hydrazine, 200 MHz) 2.26 (3 H, s, Me), 2.40 (3 H, s, Me), 5.05 (2 H, br s, NH_2), 7.16 (1 H, d, *J* 8.32, H^4), 7.30 (1 H, d, *J* 8.32, H^5), 7.33 (1 H, d, *J* 7.33, $H^{5'}$), 7.87 (1 H, dd, *J* 7.96, 7.33, $H^{4'}$) and 8.29 (1 H, d, *J* 7.96 Hz, $H^{3'}$); λ_{max}(log ε)(MeCN) 358 (1.31), 256 (1.43) and 211 (1.75) nm; *m/z* (ES) 461.3 ($[CuL_2]^+$)(weak), 303.1 {$[CuL(MeCN)]^+$}, 262.0 ($[CuL]^+$)(strong) and 200.0 ($[L + H]^+$).

With $Cu(CF_3SO_3)_2$. A solution of L (5.0 mg, 0.025 mmol) in acetonitrile (1.0 cm^3) was added to a solution of copper(II) triflate (9.6 mg, 0.027 mmol) in acetonitrile (1 cm^3) under nitrogen. The solution was stirred for 14 h and the solvent then removed under reduced pressure to afford (3-amino-6,6′-dimethyl-2,2′-bipyridine)copper(II)bis(triflate) **4** as an orange-brown solid, m.p. > 300 °C; ν_{max}(KBr disc) 3477s, 3241m, 1637m, 1614m, 1492w and 1467 cm^{-1}; λ_{max}(log ε)(MeCN) 377 (1.13), 263 (1.13), 222 (sh, 1.28) and 211 (1.37) nm.

X-Ray Crystallography.—A crystal of dimensions 0.12 × 0.06 × 0.15 mm was mounted on a glass fibre with cyanoacrylate resin. Lattice parameters at 21 °C were determined by least-squares fit to the setting parameters of 25 independent reflections, measured and refined on an Enraf-Nonius CAD4F four-circle diffractometer employing graphite-monochromated Mo-Kα radiation. Intensity data were collected in the range $1 < \theta < 25°$ using an ω–2θ scan. The scan width and horizontal counter aperture employed were $(1.40 + 0.35 \tan\theta)°$ and $(2.00 + 1.05 \tan\theta)$ mm respectively. Data reduction and application of Lorentz, polarization and absorption (maximum, minimum transition 0.925, 0.810) corrections were carried out using the Enraf-Nonius Structure Determination Package.[32] The structure was solved by direct methods using SHELXS 86[33] and the solution was extended by Fourier difference methods using SHELX 76.[34] Hydrogen atoms were included at

Table 2 Positional parameters (× 10^4) for complex **1**

Atom	*x*	*y*	*z*
Cd	1110(1)	996(1)	54(1)
Cl(1)	752(1)	−19(1)	2001(1)
Cl(2)	30(1)	2095(1)	905(1)
N(2)	3762(4)	980(2)	712(4)
N(1)	1390(4)	1555(2)	−2062(4)
N(3)	6175(5)	1414(3)	−1287(6)
C(1)	135(5)	1774(2)	−3440(5)
C(2)	214(6)	1760(3)	−4855(6)
C(3)	1528(6)	1469(3)	−4868(5)
C(4)	2822(6)	1243(3)	−3471(6)
C(5)	2752(5)	1317(2)	−2045(5)
C(6)	4106(5)	1144(2)	−479(5)
C(7)	5691(5)	1189(3)	−187(5)
C(8)	6866(6)	982(3)	1333(6)
C(9)	6498(6)	819(3)	2494(6)
C(10)	4915(5)	848(3)	2189(6)
C(11)	4475(6)	750(4)	3476(6)
C(12)	−1332(6)	2019(4)	−3410(7)

Table 3 Bond lengths (Å) and angles (°) for complex **1**

Cl(1)–Cd	2.674(1)	Cl(2)–Cd	2.444(1)
N(2)–Cd	2.303(3)	N(1)–Cd	2.364(3)
Cl(1')–Cd*	2.535(1)	C(6)–N(2)	1.358(6)
C(10)–N(2)	1.336(5)	C(1)–N(1)	1.346(5)
C(5)–N(1)	1.355(5)	C(7)–N(3)	1.390(6)
C(2)–C(1)	1.393(6)	C(12)–C(1)	1.476(6)
C(3)–C(2)	1.355(7)	C(4)–C(3)	1.376(7)
C(5)–C(4)	1.404(6)	C(6)–C(5)	1.472(6)
C(7)–C(6)	1.406(6)	C(8)–C(7)	1.397(7)
C(9)–C(8)	1.344(7)	C(10)–C(9)	1.399(6)
C(11)–C(10)	1.489(7)		
Cl(2)–Cd–Cl(1)	92.3(0)	N(2)–Cd–Cl(1)	106.9(1)
N(2)–Cd–Cl(2)	120.1(1)	N(1)–Cd–Cl(1)	163.5(1)
N(1)–Cd–Cl(2)	102.8(1)	N(1)–Cd–N(2)	71.4(1)
Cl(1')–Cd–N(1)	85.3(1)	Cl(1')–Cd–N(2)	118.8(1)
Cl(1')–Cd–Cl(2)	120.0(1)	Cl(1')–Cd–Cl(1)	81.3(1)
C(6)–N(2)–Cd	116.3(3)	C(10)–N(2)–Cd	122.6(3)
C(10)–N(2)–C(6)	121.1(4)	C(1)–N(1)–Cd	122.6(3)
C(5)–N(1)–Cd	111.7(2)	C(5)–N(1)–C(1)	119.8(3)
C(2)–C(1)–N(1)	121.0(4)	C(12)–C(1)–N(1)	118.1(4)
C(12)–C(1)–C(2)	121.0(4)	C(3)–C(2)–C(1)	119.6(5)
C(4)–C(3)–C(2)	120.1(4)	C(5)–C(4)–C(3)	119.0(4)
C(4)–C(5)–N(1)	120.3(4)	C(6)–C(5)–N(1)	116.5(3)
C(6)–C(5)–C(4)	123.2(4)	C(5)–C(6)–N(2)	116.7(4)
C(7)–C(6)–N(2)	120.8(4)	C(7)–C(6)–C(5)	122.4(4)
C(6)–C(7)–N(3)	125.4(4)	C(8)–C(7)–N(3)	117.8(4)
C(8)–C(7)–C(6)	116.8(4)	C(9)–C(8)–C(7)	121.1(5)
C(10)–C(9)–C(8)	120.2(5)	C(9)–C(10)–N(2)	119.6(4)
C(11)–C(10)–N(2)	118.6(4)	C(11)–C(10)–C(9)	121.8(4)

* Cl(1') related to Cl(1) by the symmetry operation $-x, -y, -z$.

calculated sites with group isotropic thermal parameters and all other atoms were refined anisotropically.

Scattering factors and anomalous dispersion terms used for Cd were taken from ref. 35 and all others used were those supplied in SHELX 76.[34] All calculations were carried out using SHELX 76[34] and plots were drawn using ORTEP.[36] The atom numbering scheme is given in Fig. 6. Final atomic coordinates, bond lengths and angles are listed in Tables 2 and 3.

Additional material available from the Cambridge Crystallographic Data Centre comprises H-atom coordinates and thermal parameters.

Crystal data. $C_{24}H_{26}Cd_2Cl_4N_6$, $M = 765.14$, monoclinic, space group $P2_1/n$, $a = 9.560(2)$, $b = 16.886(2)$, $c = 9.577(3)$ Å, $\beta = 118.37(2)°$, $U = 1360.3$ Å^3, D_c ($Z = 2$) = 1.868 g cm^{-3}, μ(Mo-Kα) = 15.78 cm^{-1}, λ(Mo-Kα) = 0.7107 Å, $F(000)$ = 752. Specimen: yellow prisms, $N = 2211$, $N_o = 1895$ [$I > 2.5\sigma(I)$], hkl -11 to -11, 0–20, 0–11, $R = 0.027$, $R' = 0.030$, $w = 1.26/[\sigma^2(F_o) + 0.000\,203F_o^2]$, residual extrema +0.4 and −0.6 e Å^{-3}.

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