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Synthesis and supramolecular networks of 5,6-dioxo-1,10-phenanthroline-2,9-dicarboxylic acid dihydrate and its first coordination compound *cis*-diaquachlorido(5,6-dioxo-1,10-phenanthroline-2,9-dicarboxylic acid-κ^4O^2,N,N',O^9)manganese(II) chloride dihydrate

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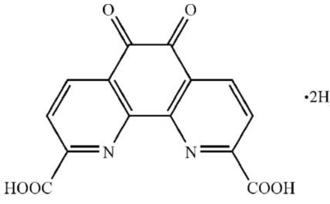
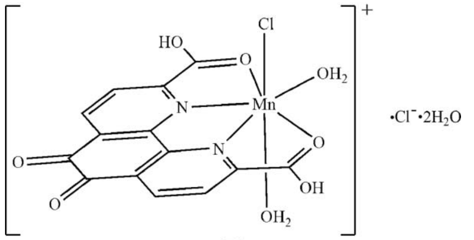
5,6-Dioxo-1,10-phenanthroline-2,9-dicarboxylic acid dihydrate (H_2pdda·2H_2O), $C_{14}H_6N_2O_6 \cdot 2H_2O$, was obtained by carbonylation of 1,10-phenanthroline-2,9-dicarboxylic acid. Its first coordination compound, $[MnCl(C_{14}H_6N_2O_6)(H_2O)_2]Cl \cdot 2H_2O$, in which the H_2pdda ligand remains protonated, was synthesized in aqueous acetic acid. H_2pdda chelates one water molecule *via* hydrogen bonds in H_2pdda·2H_2O, whereas in the coordination compound it chelates one heptacoordinate Mn^{II} atom *via* coordination bonds. The N atoms in H_2pdda·2H_2O and the Cl atoms in the coordination compound are also involved in hydrogen bonds. Extensive hydrogen bonding results in supramolecular networks in both compounds.

Comment

1,10-Phenanthroline is among the most extensively studied chelators and its numerous derivatives have played key roles in coordination and supramolecular chemistry (Bencini & Lippolis, 2010; Luman & Castellano, 2004). 1,10-Phenanthroline-5,6-dione (Ma *et al.*, 2010; Braband *et al.*, 2010; Dong *et al.*, 2010; Liu *et al.*, 2008; Wang *et al.*, 2006; Zheng *et al.*, 2010; Patel *et al.*, 2010; Goswami & Chakrabarty, 2010; Si *et al.*, 2009; Ettedgui & Neumann, 2009; Zhao *et al.*, 2008; Bodige & MacDonnell, 1997; Lenaerts *et al.*, 2005; Cardinaels *et al.*, 2008; Beaudoin & Obare, 2008) and 1,10-phenanthroline-2,9-dicarboxylic acid (Miao *et al.*, 2010; Chen *et al.*, 2010; Williams *et al.*, 2009; Harbuzaru *et al.*, 2009; Dean *et al.*, 2008; Fan *et al.*, 2008; Melton *et al.*, 2006; Garas & Vagg, 2000) are two important derivatives, whereas 5,6-dioxo-1,10-phenanthroline-2,9-dicarboxylic acid (H_2pdda), which combines both the 5,6-dicarbonyl and 2,9-dicarboxyl groups, has received little attention (Lamarque *et al.*, 2010; Echavarren & Porcel, 2006; Garas & Vagg, 2000; Evangelista & Pollak, 1986). No coordination compound of H_2pdda has been reported. Continuing our interest in polypyridine compounds and their coordination behaviour (Wu *et al.*, 1997, 2002, 2005), we discuss here the synthesis and structure of H_2pdda·2H_2O, (I), and its first coordination compound, *viz.* $[MnCl(H_2pdda)(H_2O)_2]Cl \cdot 2H_2O$, (II).



(I)



(II)

Two previous procedures for obtaining (I) were reported (Evangelista & Pollak, 1986; Garas & Vagg, 2000) using 2,9-dimethyl-1,10-phenanthroline-5,6-dione as the reactant, but the yields were not high and the handling procedures were somewhat complicated. Here we have employed a new synthetic route with 1,10-phenanthroline-2,9-dicarboxylic acid as the starting material. The main advantages of this route are the improved yield and simpler product separation. The normal carbonylation procedure for 1,10-phenanthroline-type compounds includes oxidation with H_2SO_4/HNO_3/KBr (or NaBr), neutralization of the resulting acidic solution, extraction of the quinone with dichloromethane, drying and distilling of the organic solution (Ma *et al.*, 2010; Braband *et al.*, 2010; Dong *et al.*, 2010; Liu *et al.*, 2008; Wang *et al.*, 2006; Zheng *et al.*, 2010; Patel *et al.*, 2010; Goswami & Chakrabarty, 2010; Si *et al.*, 2009; Ettedgui & Neumann, 2009; Zhao *et al.*, 2008; Bodige & MacDonnell, 1997; Lenaerts *et al.*, 2005; Cardinaels *et al.*, 2008; Beaudoin & Obare, 2008). For 1,10-phenanthroline-2,9-dicarboxylic acid, the solution remains acidic after oxidation and, on pouring into cold water, the product precipitated directly with a high yield. This is reasonable since the two carboxyl groups should make H_2pdda less soluble in acidic solution. The proton NMR spectrum of (I) shows three kinds of protons, including the carboxyl protons, and their integration areas are fully consistent with the structure of H_2pdda. Interestingly, the X-ray structural analysis confirms that H_2pdda preferentially exists as the dihydrate, just like the compounds reported previously without X-ray analysis (Evangelista & Pollak, 1986; Garas & Vagg, 2000).

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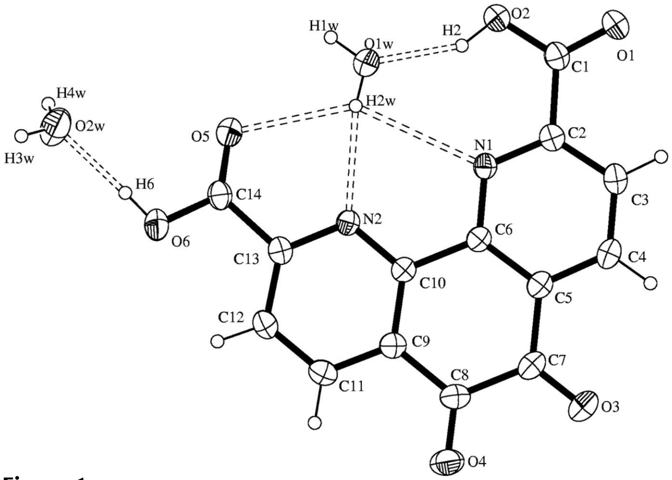

Figure 1
The asymmetric unit of (I), with displacement ellipsoids drawn at the 30% probability level. Dashed lines represent hydrogen bonds.

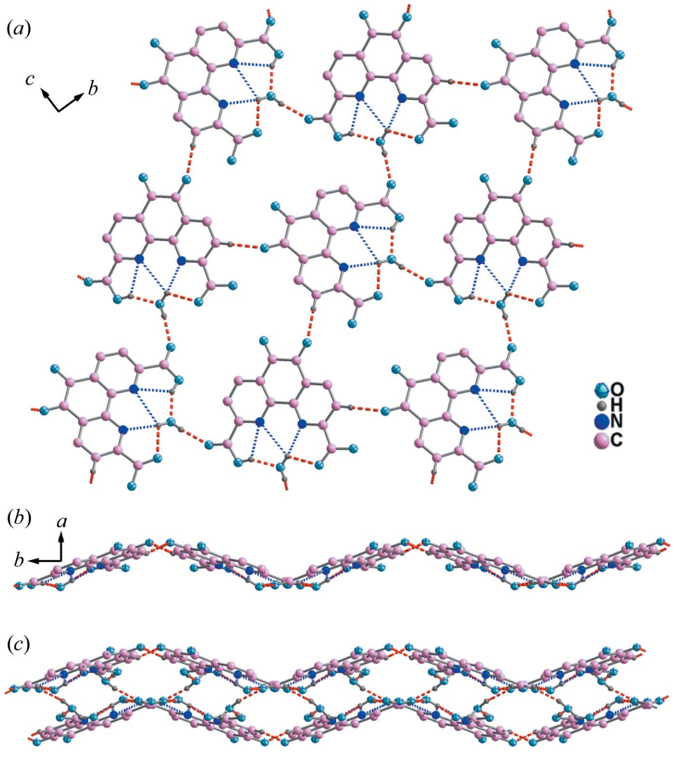

Figure 2
Three views of the hydrogen-bonding networks in (I). The H_2pdda layer and the O1*W* water molecules are shown in (*a*), viewed down the *a* axis. These layers are bridged by O2*W* water molecules to form the double layers shown in (*b*) and (*c*) viewed down the *c* axis.

Complex (II) is the first reported coordination compound of H_2pdda and it is noteworthy that this crystalline solid was obtained in acetic acid/water solution. The acidic solution favours the neutral form of H_2pdda, which is supported by the IR spectrum of the complex since the characteristic strong band around 1600 cm^{-1}, corresponding to the asymmetric stretching of a deprotonated carboxyl group (Nakamoto, 2009), was not observed. The X-ray diffraction data for both (I) and (II) are of high quality and the H atoms are generally visible in the difference Fourier maps. Therefore, we believe the detailed description of the structures (specifically the hydrogen bonding) is reliable.

The asymmetric unit of (I) is shown in Fig. 1 and consists of one H_2pdda molecule and two water molecules. The lengths of the C7—O3 and C8—O4 carbonyl bonds are 1.202 (3) and 1.210 (3) Å, respectively, comparable to the corresponding bond lengths in 1,10-phenanthroline-5,6-dione which range from 1.207 (3) to 1.214 (3) Å (Calderazzo *et al.*, 1999). This reflects the fact that the two carboxyl groups at the 2- and 9-positions do not have a significant influence on the carbonyl groups. The locations of the carboxyl H atoms which are clearly visible in the difference Fourier map are also confirmed by the C—O bond lengths: the C1═O1 and C14═O5 double-bond lengths are 1.219 (3) and 1.200 (3) Å, respectively, whereas the C1—O2 and C14—O6 single-bond lengths are significantly longer at 1.298 (3) and 1.305 (3) Å, respectively. The two carboxyl groups are approximately coplanar with the phenanthroline unit, particularly that including atom C1; the N1—C2—C1—O1 and N2—C13—C14—O5 torsion angles are 176.5 (2) and 15.3 (4)°, respectively. It is interesting that the O1*W* water molecule is situated such that the O atom and its attached H atom (H2*W*) look to be chelated by two N atoms and two carboxyl groups through O—H···O and O—H···N hydrogen bonds (Table 1, and Figs. 1 and 2). This water molecule donates the other H atom (H1*W*) to carboxyl atom O1 in an adjacent H_2pdda molecule (symmetry code: $x, -y + \frac{5}{2}, z - \frac{1}{2}$). These classical hydrogen bonds, together with nonclassical intermolecular C—H···O hydrogen bonds (Steiner, 1996) between C12 and O4($x, -y + \frac{3}{2}, z - \frac{1}{2}$), lead to the formation of a corrugated layer parallel to the (100) plane, as shown in Fig. 2. The other water molecule (O2*W*) forms three hydrogen bonds with three H_2pdda molecules. These hydrogen bonds further link two adjacent antiparallel layers, giving rise to a double-layer network (Fig. 2*b*).

The molecular structure of (II) is shown in Fig. 3. The Mn^{II} atom is seven coordinate, ligated by a tetradentate H_2pdda molecule, two water molecules and one chloride ion, forming the pentagonal–bipyramidal geometry. The H_2pdda ligand remains protonated and binds to the Mn^{II} atom in a planar

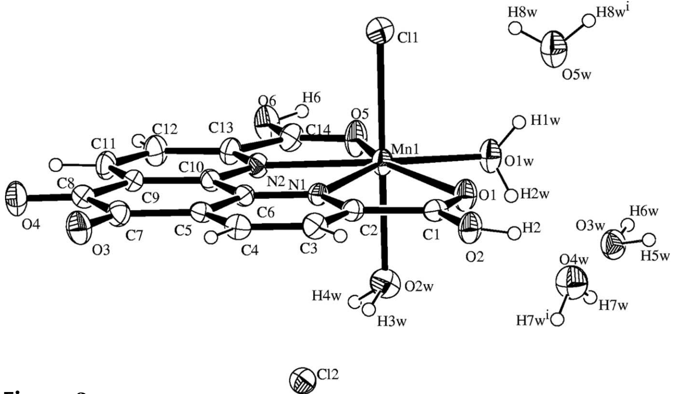

Figure 3
The molecular structure of (II), with displacement ellipsoids drawn at the 30% probability level. [Symmetry code: (i) $-x + 1, y, -z + \frac{1}{2}$.]

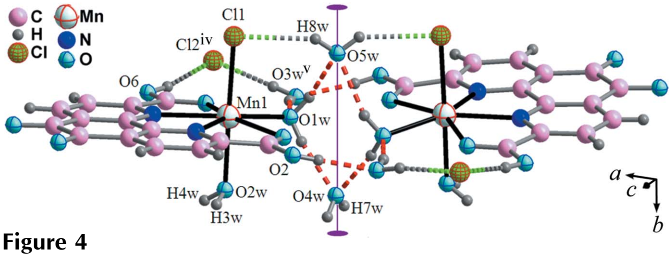

Figure 4
The dimer composed of two twofold-axis-related molecules in (II), formed by hydrogen bonds (dashed bonds). The twofold axis which bisects water molecules O4*W* and O5*W* is shown. Symmetry codes are as in Table 2.

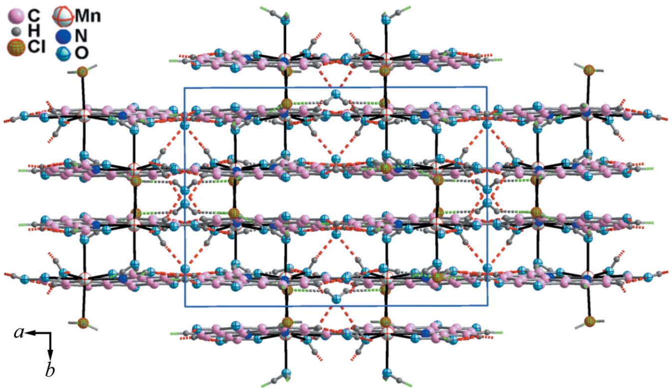

Figure 5
The pillar-layer-like hydrogen-bond network in (II).

N_2O_2 chelation manner. The rigid nature of the ligand ensures that the Mn—O(carboxyl) bond lengths [2.430 (3) and 2.461 (3) Å for O5 and O1, respectively] are longer than the Mn—O(water) bond lengths [2.204 (3) and 2.248 (3) Å for O1*W* and O2*W*, respectively], which are comparable to the Mn—N bond lengths [2.295 (3) and 2.298 (3) Å for N1 and N2, respectively]. The Mn—Cl bond length [2.4945 (15) Å] falls into the expected range. Inspection of the bond lengths for H_2pdda in (I) and (II) reveals no remarkable difference in the corresponding data, indicative of similar environments for the H_2pdda molecule in the two compounds. This is reasonable if the H_2pdda molecule in (I) is considered to 'chelate' the water molecule in a similar fashion to the binding of H_2pdda in (II), where the tetradentate H_2pdda chelates the Mn^{II} atom. The discrepancy in binding guests and bonding nature does not induce a significant change in the structure of H_2pdda.

There are also extensive hydrogen bonds (Table 2) in (II). As shown in Fig. 4, water molecules O4*W* or O5*W* are located on the same twofold axis. They connect two symmetry-related manganese complexes *via* hydrogen bonds to form a dimer. The O3*W* water molecule and the Cl^- counter-ion are also involved in the formation of the dimer. Continuous hydrogen-bonding linkage among the dimers throughout the crystal lattice leads to a pillar-layer-like three-dimensional supramolecular network, as illustrated in Fig. 5.

Experimental

For the synthesis of (I), cold concentrated H_2SO_4 (20 ml) and then concentrated HNO_3 (10 ml) were added dropwise to a three-necked reaction flask loaded with 1,10-phenanthroline-2,9-dicarboxylic acid (De Cian *et al.*, 2007) (2.68 g, 10 mmol) and potassium bromide (1.78 g, 15 mmol) in an ice–salt bath. After stirring for a further 30 min, the mixture was heated to 358 K and refluxed for 4 h. The condenser tube was then removed and the solution allowed to cool to room temperature. The solution was poured into ice water (200 ml). The yellow precipitate was collected and washed (yield 2.70 g, 8.1 mmol, 81%). Recrystallization from acetone afforded crystals (m.p. 478 K) suitable for X-ray crystallographic analysis. ^{1}H NMR (d_6-DMSO): δ 13.70 (*br*, 2H, COOH), 8.60 (*d*, 2H, *J* = 8.0 Hz, 3-H), 8.27 (*d*, 2H, *J* = 8.0 Hz, 4-H). IR (KBr, ν cm^{-1}): 3514 (*s*), 3092 (*m*), 1927 (*m*), 1701 (*vs*), 1630 (*m*), 1570 (*s*), 1431 (*m*), 1385 (*s*), 1294 (*m*), 1229 (*m*), 1155 (*m*), 992 (*m*), 931 (*m*), 726 (*m*), 531 (*s*).

For the synthesis of (II), a solution of $MnCl_2 \cdot 4H_2O$ (19.8 mg, 0.1 mmol) in water (5 ml) was added dropwise to a solution of $H_2pdda \cdot 2H_2O$ (33.4 mg, 0.1 mmol) in glacial acetic acid (10 ml). The mixture was stirred for 2 h at 358 K and the resulting clear solution was evaporated for two weeks at room temperature to yield yellow crystals. IR (KBr, ν cm^{-1}): 3414 (*b s*), 2466 (*m*), 1876 (*m*), 1703 (*vs*), 1608 (*m*), 1575 (*s*), 1468 (*m*), 1389 (*m*), 1262 (*s*), 1242 (*m*), 936 (*m*), 812 (*m*), 714 (*m*), 528 (*m*).

Compound (I)

Crystal data

$C_{14}H_6N_2O_6 \cdot 2H_2O$
M_r = 334.24
Monoclinic, $P2_1/c$
a = 7.206 (2) Å
b = 15.968 (6) Å
c = 13.055 (3) Å
β = 115.049 (13)°
V = 1360.9 (7) Å^3
Z = 4
Mo *Kα* radiation
μ = 0.14 mm^{-1}
T = 296 K
0.20 × 0.13 × 0.12 mm

Data collection

Bruker APEXII CCD area-detector diffractometer
Absorption correction: multi-scan (*SADABS*; Bruker, 2002)
T_{min} = 0.973, T_{max} = 0.984
6770 measured reflections
2517 independent reflections
1610 reflections with $I > 2\sigma(I)$
R_{int} = 0.034

Refinement

$R[F^2 > 2\sigma(F^2)]$ = 0.048
$wR(F^2)$ = 0.138
S = 1.03
2517 reflections
217 parameters
H-atom parameters constrained
$\Delta\rho_{max}$ = 0.18 e Å^{-3}
$\Delta\rho_{min}$ = −0.29 e Å^{-3}

Compound (II)

Crystal data

$[MnCl(C_{14}H_6N_2O_6)(H_2O)_2]Cl \cdot 2H_2O$
M_r = 496.11
Orthorhombic, *Pbcn*
a = 17.195 (6) Å
b = 12.411 (5) Å
c = 17.569 (6) Å
V = 3750 (2) Å^3
Z = 8
Mo *Kα* radiation
μ = 1.05 mm^{-1}
T = 296 K
0.42 × 0.40 × 0.30 mm

Data collection

Bruker APEXII CCD area-detector diffractometer
Absorption correction: multi-scan (*SADABS*; Bruker, 2002)
T_{min} = 0.667, T_{max} = 0.744
17437 measured reflections
3372 independent reflections
2021 reflections with $I > 2\sigma(I)$
R_{int} = 0.082

Table 1
Hydrogen-bond geometry (Å, °) for (I).

D—H···A	D—H	H···A	D···A	D—H···A
C12—H12···O4$^{\rm i}$	0.93	2.45	3.367 (1)	170
O1W—H1W···O1$^{\rm ii}$	0.84	2.03	2.865 (3)	170
O2—H2···O1W	0.82	1.81	2.561 (2)	152
O1W—H2W···O5	0.83	2.44	2.917 (3)	117
O1W—H2W···N2	0.83	2.15	2.968 (3)	169
O2W—H3W···O1$^{\rm iii}$	0.86	1.96	2.805 (3)	169
O2W—H4W···O3$^{\rm iv}$	0.86	2.53	3.053 (3)	120
O6—H6···O2W	0.82	1.76	2.574 (3)	176

Symmetry codes: (i) $x, -y+\frac{3}{2}, z-\frac{1}{2}$; (ii) $x, -y+\frac{5}{2}, z-\frac{1}{2}$; (iii) $-x, y-\frac{1}{2}, -z+\frac{1}{2}$; (iv) $x, y, z-1$.

Refinement

$R[F^2 > 2\sigma(F^2)] = 0.046$
$wR(F^2) = 0.121$
$S = 0.98$
3372 reflections
265 parameters
H-atom parameters constrained
$\Delta\rho_{\max} = 0.48$ e Å^{-3}
$\Delta\rho_{\min} = -0.33$ e Å^{-3}

H atoms attached to C atoms were positioned geometrically and allowed to ride on their parent atoms, with $U_{\rm iso}({\rm H}) = 1.2U_{\rm eq}({\rm C})$. H atoms bound to O atoms were located from difference Fourier maps and treated in the riding-model approximation, with $U_{\rm iso}({\rm H}) = 1.5U_{\rm eq}({\rm O})$. The method described by Cooper *et al.* (2010) was applied to assist the location of the H atoms, especially H3W and H4W, for more rational hydrogen bonds and short contacts.

For both compounds, data collection: *APEX2* (Bruker, 2004); cell refinement: *APEX2*; data reduction: *APEX2*; program(s) used to solve structure: *SHELXS97* (Sheldrick, 2008); program(s) used to refine structure: *SHELXL97* (Sheldrick, 2008); molecular graphics: *ORTEP-3* (Farrugia, 1997); software used to prepare material for publication: *PLATON* (Spek, 2009).

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Supplementary data for this paper are available from the IUCr electronic archives (Reference: TP3010). Services for accessing these data are described at the back of the journal.

Table 2
Hydrogen-bond geometry (Å, °) for (II).

D—H···A	D—H	H···A	D···A	D—H···A
C11—H11···Cl2$^{\rm i}$	0.93	2.89	3.799 (3)	166
C12—H12···O6$^{\rm ii}$	0.93	2.47	3.283 (5)	146
C4—H4···Cl1$^{\rm iii}$	0.93	2.72	3.640 (4)	171
O5W—H8W···Cl1	0.82	2.45	3.1625 (16)	145
O4W—H7W···O4$^{\rm iv}$	0.82	2.22	2.947 (3)	149
O3W—H6W···O5$^{\rm v}$	0.81	2.69	3.230 (4)	125
O3W—H6W···O1$W^{\rm v}$	0.81	2.10	2.888 (4)	164
O3W—H5W···Cl2$^{\rm vi}$	0.83	2.40	3.217 (3)	169
O2W—H4W···Cl1$^{\rm vii}$	0.82	2.51	3.315 (3)	172
O2W—H3W···Cl2	0.84	2.53	3.371 (3)	172
O1W—H2W···O4W	0.82	1.94	2.751 (4)	172
O1W—H1W···O5W	0.85	2.08	2.858 (5)	151
O6—H6···Cl2$^{\rm iv}$	0.82	2.19	3.004 (3)	170
O2—H2···O3W	0.82	1.81	2.625 (4)	174

Symmetry codes: (i) $x+\frac{1}{2}, -y+\frac{1}{2}, -z+1$; (ii) $-x+2, y, -z+\frac{1}{2}$; (iii) $x, -y, z+\frac{1}{2}$; (iv) $-x+\frac{3}{2}, -y+\frac{1}{2}, z-\frac{1}{2}$; (v) $-x+1, y, -z+\frac{1}{2}$; (vi) $x-\frac{1}{2}, -y+\frac{1}{2}, -z+1$; (vii) $-x+\frac{3}{2}, y+\frac{1}{2}, z$.

References

Beaudoin, D. S. & Obare, S. O. (2008). *Tetrahedron Lett.* **49**, 6054–6057.

Bencini, A. & Lippolis, V. (2010). *Coord. Chem. Rev.* **254**, 2096–2180.

Bodige, S. & MacDonnell, F. M. (1997). *Tetrahedron Lett.* **38**, 8159–8160.

Braband, H., Imstepf, S., Felber, M., Spingler, B. & Alberto, R. (2010). *Inorg. Chem.* **49**, 1283–1285.

Bruker (2002). *SADABS*. Bruker AXS Inc., Madison, Wisconsin, USA.

Bruker (2004). *APEX2*. Bruker AXS Inc., Madison, Wisconsin, USA.

Calderazzo, F., Marchetti, F., Pampaloni, G. & Passarelli, V. (1999). *J. Chem. Soc. Dalton Trans.* pp. 4389–4396.

Cardinaels, T., Ramaekers, J., Nockemann, P., Driesen, K., Van Hecke, K., Van Meervelt, L., Lei, S., De Feyter, S., Guillon, D., Donnio, B. & Binnemans, K. (2008). *Chem. Mater.* **20**, 1278–1291.

Chen, Q., Zeng, M.-H., Wei, L.-Q. & Kurmoo, M. (2010). *Chem. Mater.* **22**, 4328–4334.

Cooper, R. I., Thompson, A. L. & Watkin, D. J. (2010). *J. Appl. Cryst.* **43**, 1100–1107.

Dean, N. E., Hancock, R. D., Cahill, C. L. & Frisch, M. (2008). *Inorg. Chem.* **47**, 2000–2010.

De Cian, A., DeLemos, E., Mergny, J.-L., Teulade-Fichou, M.-P. & Monchaud, D. (2007). *J. Am. Chem. Soc.* **129**, 1856–1857.

Dong, H.-Z., Li, M. & Li, B.-Z. (2010). *Asian J. Chem.* **22**, 4950–4952.

Echavarren, A. M. & Porcel, S. (2006). *Sci. Synth.* **28**, 507–560.

Ettedgui, J. & Neumann, R. (2009). *J. Am. Chem. Soc.* **131**, 4–5.

Evangelista, R. A. & Pollak, A. (1986). Patent EP0171978A1.

Fan, L.-L., Li, C.-J., Meng, Z.-S. & Tong, M.-L. (2008). *Eur. J. Inorg. Chem.* pp. 3905–3909.

Farrugia, L. J. (1997). *J. Appl. Cryst.* **30**, 565.

Garas, A. M. S. & Vagg, R. S. (2000). *J. Heterocycl. Chem.* **37**, 151–158.

Goswami, S. & Chakrabarty, R. (2010). *Eur. J. Org. Chem.* pp. 3791–3795.

Harbuzaru, B. V., Corma, A., Rey, F., Jorda, J. L., Ananias, D., Carlos, L. D. & Rocha, J. (2009). *Angew. Chem. Int. Ed.* **48**, 6476–6479.

Lamarque, L., Bazin, H. & Blanche, E. (2010). Patent WO2010070232.

Lenaerts, P., Storms, A., Mullens, J., D'Haen, J., Goerller-Walrand, C., Binnemans, K. & Driesen, K. (2005). *Chem. Mater.* **17**, 5194–5201.

Liu, G.-X., Huang, R.-Y., Xu, H., Kong, X.-J., Huang, L.-F., Zhu, K. & Ren, X.-M. (2008). *Polyhedron*, **27**, 2327–2336.

Luman, C. R. & Castellano, F. N. (2004). *Phenanthroline Ligands*, Vol. 1, *Comprehensive Coordination Chemistry II*, edited by J. McCleverty & T. J. Meyer, pp. 25–39. Amsterdam: Elsevier.

Ma, Q., Zhu, M., Yuan, C., Feng, S., Lu, L. & Wang, Q. (2010). *Cryst. Growth Des.* **10**, 1706–1714.

Melton, D. L., Derveer, D. G. V. & Hancock, R. D. (2006). *Inorg. Chem.* **45**, 9306–9314.

Miao, Y.-L., Liu, J.-L., Lin, Z.-J., Ou, Y.-C., Leng, J.-D. & Tong, M.-L. (2010). *Dalton Trans.* **39**, 4893–4902.

Nakamoto, K. (2009). In *Infrared and Raman Spectra of Inorganic and Coordination Compounds*, 6th ed. New York: John Wiley & Sons.

Patel, D. G., Paquette, M. M., Kopelman, R. A., Kaminsky, W., Ferguson, M. J. & Frank, N. L. (2010). *J. Am. Chem. Soc.* **132**, 12568–12586.

Sheldrick, G. M. (2008). *Acta Cryst.* A**64**, 112–122.

Si, Z., Li, X., Li, X., Pan, C. & Zhang, H. (2009). *Inorg. Chem. Commun.* **12**, 1016–1019.

Spek, A. L. (2009). *Acta Cryst.* D**65**, 148–155.

Steiner, T. (1996). *Crystallogr. Rev.* **6**, 1–57.

Wang, X.-X., Sun, F., Zhan, Q.-G. & Wu, J.-Z. (2006). *Acta Cryst.* E**62**, m3380–m3382.

Williams, N. J., Dean, N. E., Derveer, D. G. V., Luckay, R. C. & Hancock, R. D. (2009). *Inorg. Chem.* **48**, 7853–7863.

Wu, J. Z., Li, H., Zhang, J. G. & Xu, J. H. (2002). *Inorg. Chem. Commun.* **5**, 71–75.

Wu, J. Z., Ye, B. H., Wang, L., Ji, L. N., Zhou, J. Y., Li, R. H. & Zhou, Z. Y. (1997). *J. Chem. Soc. Dalton Trans.* pp. 1395–1401.

Wu, J. Z., Yuan, L. & Wu, J. F. (2005). *J. Inorg. Biochem.* **99**, 2211–2216.

Zhao, Y.-L., Hu, L., Gruner, G. & Stoddart, J. F. (2008). *J. Am. Chem. Soc.* **130**, 16996–17003.

Zheng, R. H., Guo, H. C., Jiang, H. J., Xu, K. H., Liu, B. B., Sun, W. L. & Shen, Z. Q. (2010). *Chin. Chem. Lett.* **21**, 1270–1272.