CrystEngComm

Paper

Triple hydrogen bond directed crystal engineering of metal assembled complexes: the effect of a bifunctional ligand on supramolecular structure

Yuichi Sugiyama,[a] **Keiichi Adachi,**[a] **Satoshi Kawata,***[a] **Hitoshi Kumagai,**[b] **Katsuya Inoue,**[b]
Motomi Katada[c] **and Susumu Kitagawa**[d]

[a]*Department of Chemistry, Shizuoka University, 836 Ohya, Shizuoka 422-8529, Japan. E-mail: scskawa@ipc.shizuoka.ac.jp*
[b]*Institute for Molecular Science, Myodaiji, Okazaki 444-8585, Japan*
[c]*Department of Chemistry, Tokyo Metropolitan University, Minami Ohsawa, Hachiouji, Tokyo 192-0397, Japan*
[d]*Department of Synthetic Chemistry and Biological Chemistry, Kyoto University, Sakyo-ku, Kyoto 606-8501, Japan*

Received 2nd October 2000, Accepted 30th October 2000
Published on the Web 14th November 2000

The crystal structures of compounds $[Hmel]_2[M(tdpd)_2(OH_2)_2]\cdot 2H_2O$ ($M = Ni^{2+}$, Co^{2+}; $Hmel^+$ = melaminium cation; H_2tdpd = 1,4,5,6-tetrahydro-5,6-dioxo-2,3-pyrazinedicarbonitrile) are reported; the metal complex supramolecular structures can be rationally designed *via* hydrogen bonding interactions.

Crystal engineering has become an area of great interest in this decade.[1] So far, however, the rational design and preparation of new materials for specific applications are still at an early evolutionary stage with the current focus mainly on understanding the factors that determine crystal packing. During the last few years, several types of weak interactions, such as versatile hydrogen bonding interactions and electrostatic interactions have been recognized and used in constructing extended networks.[2] Particularly, the hydrogen bonding interaction has emerged to be a powerful tool for the design of supramolecular systems based on noncovalent synthesis.[3,4] Although many research groups have focused on the usage of melamine (mel) and its derivatives[5] to form supramolecular networks by hydrogen bonding to other organic molecules, the concepts have recently been extended into the inorganic domain.[6,7] Transition metal ions can be incorporated into hydrogen bonding networks by employing bifunctional ligands that contain, in addition to metal binding sites, hydrogen bonding functionalities that are retained on complexation.

$Tdpd^{2-}$ (H_2tdpd = 1,4,5,6-tetrahydro-5,6-dioxo-2,3-pyrazinedicarbonitrile) has attracted our interest as a potential bifunctional ligand with necessary hydrogen bonding characteristics. We have previously shown that it can construct metal-assembled complexes with triangular and rectangular lattices by coordination bonds.[8] $Tdpd^{2-}$ is a planar ligand and has both multi metal binding and hydrogen bonding sites. We now present the synthesis and structural study of the two-dimensional compounds $[Hmel]_2[M(tdpd)_2(OH_2)_2]\cdot 2H_2O$ ($M = Ni^{2+}$ (**1**), Co^{2+} (**2**)).

An aqueous solution (1 ml) of nickel(II) chloride hexahydrate ($5\ mmol\ l^{-1}$) and H_2tdpd ($5\ mmol\ l^{-1}$) was transferred to a glass tube, then an ethanolic solution of melamine (mel) ($5\ mmol\ l^{-1}$) poured into the tube without mixing the two solutions. Light green plate crystals (**1**) began to form in two weeks; yield, 70%.† One of these crystals was used for X-ray crystallography. Compound **2** was synthesized from cobalt(II) acetate tetrahydrate by a procedure similar to that employed for **1**. Orange plate crystals began to form in two weeks; yield, 60%.†

X-ray crystallography reveals that **1** and **2** are isostructural to each other (Table 1). The structure of **1** consists of mononuclear $[Ni(tdpd)_2(OH_2)_2]^{2-}$ dianions, $Hmel^+$ cations and uncoordinated water molecules. An ORTEP[9] drawing of the structure around the nickel ion in **1** with the atom numbering scheme is shown in Fig. 1. The structure of **1** shows that the desired coordination and aggregation have been

Table 1 Crystal data for $[Hmel]_2[M(tdpd)_2(OH_2)_2]\cdot 2H_2O$ ($M = Ni^{2+}$ (**1**), Co^{2+} (**2**))[a]

Properties	Values	
Complex	**1**[b]	**2**[c]
Empirical formula	$C_{18}H_{22}NiN_{20}O_8$	$C_{18}H_{22}CoN_{20}O_8$
M	705.20	705.43
Crystal system, space group	Triclinic, $P\bar{1}$ (no. 2)	Triclinic, $P\bar{1}$ (no. 2)
a/Å	9.5650(3)	9.517(3)
b/Å	9.6958(6)	9.654(4)
c/Å	9.9663(3)	9.964(1)
α/°	61.490(4)	61.68(2)
β/°	75.585(3)	75.91(2)
γ/°	62.714(4)	63.62(2)
V/Å^3	721.28(7)	721.3(4)
Z, D_c/g cm^{-3}	1, 1.623	1, 1.624
$F(000)$	362.00	361.00
$R_{collected}$ $[I > 2\sigma(I)]$	3113	3629
T/°C	23.0	23.0
2θ range/°	5.18–148.66	3–55
R, w$R2$	0.039, 0.115	0.057, 0.142

[a]Click here for full crystallographic data (CCDC no. 1350/38). [b]$\mu(CuK\alpha) = 17.05\ cm^{-1}$(graphite monochromated). An Enraf Nonius CAD-4 diffractometer was used. The structure was solved by direct methods (Rigaku TEXSAN crystallographic software package of Molecular Structure Corporation) and refined with full-matrix least-squares technique (SHELXL-93).[11] [c]$\mu(MoK\alpha) = 6.77\ cm^{-1}$ (graphite monochromated). A Mac Science MXC3 diffractometer was used. The structure was solved by direct methods (Rigaku TEXSAN crystallographic software package of Molecular Structure Corporation) and refined with full-matrix least-squares technique (SHELXL-93).

---

† Elemental analysis data for $[Hmel]_2[Ni(tdpd)_2(OH_2)_2]\cdot 2H_2O$: calc. for $C_{18}H_{22}NiN_{20}O_8$: C 30.66, H 3.14, N 39.73%; found: C 30.32, H 3.17, N 40.19%; elemental analysis data for $[Hmel]_2[Co(tdpd)_2(OH_2)_2]\cdot 2H_2O$: calc. for $C_{18}H_{22}CoN_{20}O_8$: C 30.65, H 3.14, N 39.71%; found: C 30.16, H 3.10, N 39.90%.

DOI: 10.1039/b007939l

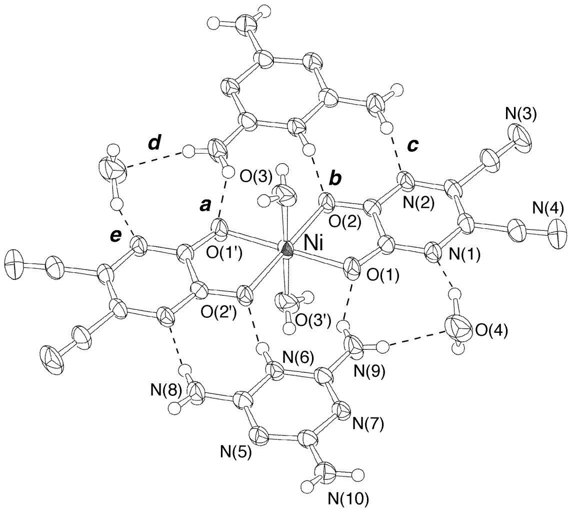

Fig. 1 ORTEP drawing of **1** with labelling scheme and thermal ellipsoids at the 50% probability level for Ni, O, N, and C atoms. Spheres of the hydrogen atoms have been arbitrarily reduced. Hydrogen bonding geometries: N···N/O, H···N/O distances (Å), N/O–H··N/O angles (°): ***a*** 2.762(4), 1.96, 152; ***b*** 2.803(3), 1.97, 170; ***c*** 2.907(3), 2.02, 175; ***d***, 2.919(3), 2.14, 162; ***e***, 2.988(4), 1.93, 158. Click image or here to access a 3D representation.

achieved with the nickel atom being coordinated to two tdpd^{2-} ligands which are in turn involved in an AAA≡DDD (A = hydrogen-bond acceptor, D = hydrogen-bond donor) arrangement with Hmel^{+} cations. The coordination geometry around the nickel ion in the monomer is a distorted octahedron involving the four oxygen atoms of two tdpd^{2-} anions and two water molecules in *trans* position relative to one another (Ni–O distances: 2.008(1) Å (Ni–O(1) and Ni–O(1′)), 2.046(2) Å (Ni–O(2) and Ni–O(2′)) and 2.110(2) Å (Ni–O(3) and Ni–O(3′))). The triple hydrogen bonding distances between the tdpd^{2-} and Hmel^{+} units are O(1′)···N(9′), 2.762(4) Å; O(2)···N(6′), 2.803(3) Å; N(2)···N(8′), 2.907(3) Å (***a***, ***b*** and ***c***, respectively, in Fig. 1). These complexes, to the best of our knowledge, are the first example of an AAA≡DDD system in the self assembled complexes, while theoretical calculations suggested the system AAA≡DDD is the most stable relative to ADA≡DAD and AAD≡DDA systems.[6,10] One mononuclear complex, two Hmel^{+} cations, and two uncoordinated waters form a building module. In the module, uncoordinated water molecules make two types of hydrogen bonds with ring nitrogen atoms of tdpd^{2-} and amino hydrogen atoms in Hmel^{+} cation (***d*** and ***e*** in Fig. 1). The triply hydrogen-bonded module, $[Hmel]_2[Ni(tdpd)_2(OH_2)_2]\cdot 2H_2O$ is linked to adjacent modules *via* additional N(H)···N and N(H)···O hydrogen bonds (***f***, ***g*** and ***h*** in Fig. 2) to form planar sheets. Adjacent sheets are mutually offset and linked *via* O(H)···N hydrogen bonds between terminal nitrogen atoms of tdpd^{2-}, N(4), and coordinated water oxygen atoms, O(3), which are inserted from above and below into the 'vacant' region indicated by **A** in Fig. 2.

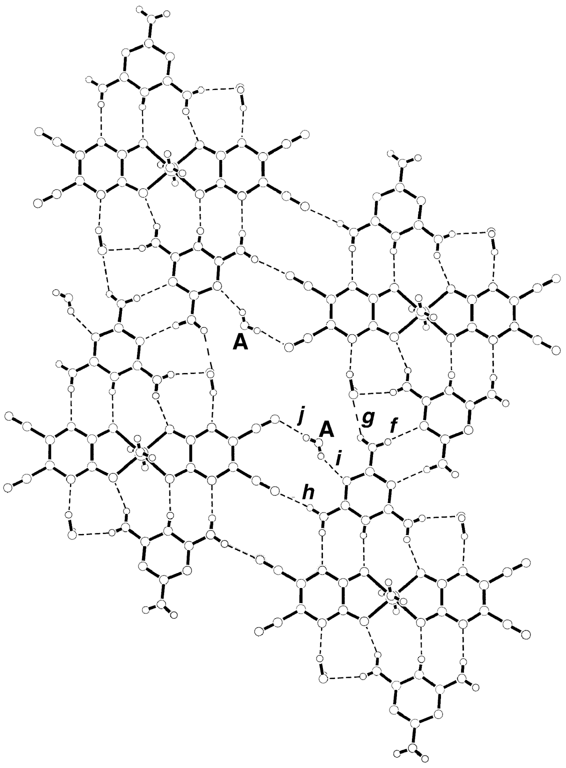

Fig. 2 Part of the hydrogen-bonded planar sheets formed by **1** showing the intermolecular interactions between adjacent module. Hydrogen bonding geometries: N···N/O, H···N/O distances (Å), N/O–H···N/O angles (°): ***f*** 3.022(2), 2.13, 171; ***g*** 3.053(4), 2.38, 132; ***h*** 3.032(4), 2.18, 161; ***i*** 2.855(3), 2.18, 147; ***j*** 2.947(3), 2.16, 176. **A** represents the region where the coordinated water oxygen atom O(3) from adjacent sheets inserts from above and below. Click image or here to access a 3D representation.

We conclude that hydrogen bonding interaction may play an important role in determining the structure of assembled complexes. Complexes $[M(tdpd)_2(OH_2)_2]^{2-}$ with AAA hydrogen bonding recognition sites have been synthesized and shown to form co-crystals with Hmel^{+} cations involved DDD motif. The ligand H_2tdpd fulfils its bifunctional role by generating a transition-metal complex as part of a multidimensional co-crystallised network, self-assembled by a combination of coordination and hydrogen bond formation. We are now extending this result by the preparation of the design of supramolecular systems based on noncovalent synthesis through variation of substituted melamine derivatives.

Acknowledgements

This research was supported by a Grant-in-Aid for Scientific Research (No. 12640537) and by a Grant-in-Aid for Scientific Research on Priority Areas (No. 12023216, Metal-assembled Complexes) from the Ministry of Education, Science, Sports and Culture, Japan.

References

1 J.-M. Lehn, *Supramolecular Chemistry, Concepts and Perspectives*, VCH, Weinheim, 1995.

2 J.-M. Lehn, *Angew Chem., Int. Ed. Engl.*, 1988, **27**, 89; G.R Desiraju, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 2331; G. R. Desiraju, *Chem. Commun.*, 1997, 1475; D. Philip and J. F. Soddart, *Angew. Chem.*, Int. Ed. Engl. 1996, **35**, 1155.

3 A. D. Burrows, C.-W. Chan, M. M. Chowdhry, J. E. McGrady and D. M. P. Mingos, *Chem. Soc. Rev.*, 1995, 329.

4 C. B. Aakeröy and K. R. Seddon, *Chem. Soc. Rev.*, 1993, 397; D. S. Lawrence, T. Jiang and M. Levett, *Chem. Rev.*, 1995, **95**, 2229; S. R. Batten and R. Robson, *Angew. Chem., Int. Ed.*, 1998, **37**, 1460; S. Kawata, H. Kumagai, K. Adachi and S. Kitagawa, *J. Chem. Soc., Dalton Trans.*, 2000, 2409;.

5 J. P. Mathias, C. T. Seto, E. E. Simanek and G. M. Whitesides, *J. Am. Chem. Soc.*, 1994, **116**, 1725; G. M. Whitesides, E. E. Simanek, J. P. Mathias, C. T. Seto; D. N. Chin, M. Mammen and D. M. Gordon, *Acc. Chem. Res.*, 1995, **28**, 37; R. F. M. Lange, F. H. Beijer, R. P. Sijbesma, R. W. W. Hooft, H. Kooijman, A. L. Spek, J. Kroon and E. W. Meijer, *Angew. Chem., Int. Ed. Engl.*, 1997, **36**, 969; H. Tukada and Y. Mazaki, *Chem. Lett.*, 1997, 441; A. Ranganathan, V. R. Pedireddi and N. R. Rao, *J. Am. Chem. Soc.*, 1999, **121**, 1752.

6 M. M. Chowdhry, D. M. P. Mingos, A. J. P. White and D. J. Williams, *Chem. Commun.*, 1996, 899; S. L. James, D. M. P. Mingos, X. Xu A. J. P. White and D. J. Williams, *J. Chem. Soc., Dalton Trans.*, 1998, 1335; X. Xu, M. Hynes, S. L. James and

D. M. P. Mingos, *Mol. Cryst. Liq. Cryst.*, 2000, **342**, 15; H. Kitamura, T. Ozawa, K. Jitsukawa, H. Masuda and H. Einaga, *Mol. Cryst. Liq. Cryst.*, 2000, **342**, 69.

7 D. M. L. Goodgame, I. Hussain, A. J. P. White and D. J. Williams, *J. Chem. Soc., Dalton Trans.*, 1999, 2899.

8 K. Adachi, S. Kawata, M. K. Kabir, H. Kumagai, K. Inoue and S. Kitagawa, *Chem. Lett.*, 2000, in the press; K. Adachi, Y. Sugiyama, H. Kumagai, K. Inoue, S. Kitagawa and S. Kawata, *Polyhedron*, in the press.

9 C. K. Johnson, *ORTEP, Report ORNL-5138*, Oak Ridge National Laboratory, Oak Ridge, TN, 1976.

10 L. Jorgensen, J. Pranata, J. Am. Chem. Soc., 1990, 112, 2008; J. Pranata, S. G. Wierschke and W. L. Jorgensen, *J. Am. Chem. Soc.*, 1991, 113, 2008; T. J. Murray, S. C. Zimmerman, J. Am. Chem. Soc., 1992, **114**, 4010; G. M. Sheldrick, SHELXL-93, Program for X-Ray Crystal Structure Refinement, Göttingen University, 1993.