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# Complicated magnetic behavior in one-dimensional nickel(III) chain complex [1-(4'-cyanobenzyl)pyridinium] $[Ni(mnt)_2]$ (mnt<sup>2-</sup> = maleonitriledithiolate)

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## Abstract

A new ion-pair complex [1-(4'-cyanobenzyl)pyridinium]  $[Ni(mnt)_2]$  (1), in which  $mnt^{2-} =$  maleonitriledithiolate, have been fabricated and its X-ray single crystal structural analyses at 293, 180 and 140 K shown that the  $[Ni(mnt)_2]^-$  anions and  $[CNB2Py]^+$  cations form a well-separated stacking column along *c*-axis direction, within which  $[Ni(mnt)_2]^-$  anions are uniformly spaced to give a one-dimensional (1-D) chain structure. Bulk magnetic properties of this complex have been investigated in the temperature range of 2–400 K and shown there exists spin kink at ~190 K. In low temperature region, weak ferromagnetic behavior occurs in 1.

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# 1. Introduction

Square-planar  $M(dithiolene)_2$  complexes have attracted extensive interests in the areas of conducting and magnetic materials, dyes, non-linear optics, catalysis [1,2]. In this series of complex, previous works shown that different counterions could induce versatile stacking modes in the solid state, furthermore, have prominent affection on molecular interaction and resultant magnetic diversity [3–9]. Recently, we fabricated and structural characterized a series of  $[BzPy]^+[M(mnt)_2]^-$ (M = Ni or Pt) complexes, where  $[BzPy]^+$  denoted benzylpyridinium derivative, and found that there are markedly different magnetic exchange properties although these complexes have extremely similar molecular and stack structures [10–14]. In order to further understand the magnetic coupling mechanism, we have systematic investigated the relationship between stack structure and magnetic

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properties for this series of complexes. Herein we report the synthesis and crystal structure of an ionpair complex (Scheme 1), [1-(4'-cyanobenzyl)py $ridinium][Ni(mnt)_2]$ , with a well-discreted stacking column. Its complicated magnetic properties show a spin kink around 190 K and following this transition, weak ferromagnetic behavior occurs in this complex in low temperature region.

# 2. Experimental

[1-(4'-cyanobenzyl)pyridinium]<sub>2</sub>[Ni(mnt)<sub>2</sub>] was prepared by the direct combination of 1:2:2 mol equiv of NiCl<sub>2</sub>  $\cdot$  6H<sub>2</sub>O, Na<sub>2</sub>mnt and 1-(4'-cyanobenzyl)pyridinium bromide in water. The resulting red precipitate product was obtained by filtration and dried. [1-(4'-cyanobenzyl)pyridinium]<sub>2</sub>[Ni  $(mnt)_2$  (729.5 mg, 1.0 mmol) was solved in 20 cm<sup>3</sup> MeCN, then a MeCN solution (10 cm<sup>3</sup>) of  $I_2$  (150 mg, 0.59 mmol) was slowly added and the mixture was stirred for 2 h. The resulting dark precipitates were recrystallized from MeCN to give pure 1 [15,16]. Yield 433 mg, 81%. Anal. Calc. for  $C_{21}H_{11}N_6NiS_4$ : C, 47.2%; H, 2.08%; N, 15.7%. Found: C, 47.0%; H, 2.09%; N, 15.8%. Infrared spectrum (cm<sup>-1</sup>): v(CN), 2207.6 vs, v(C=C) of mnt<sup>2-</sup> 1446.7 m. Elemental analyses were performed with a Perkin-Elmer 240 analytical instrument. IR spectra were recorded on a Fourier Transform Infrared Spectrometer (170SX) (KBr pellet). Magnetic susceptibility data on powdersample were collected over the temperature range of 2-400 K using a Quantum Design MPMS-5S superconducting quantum interference device (SQUID) magnetometer, and diamagnetic corrections were made estimating experimentally using Na<sub>2</sub>mnt, 1-(4'-cyanobenzyl)pyridinium bromide, NaBr. DSC experiment was performed on a Perkin-Elmer calorimeter. Thermal analysis of polycrystalline samples placed in an aluminum crucible was carried out on warming (rate of 20 K min<sup>-1</sup>) in the temperature range of -180 to 120 °C (93–393 K).

# 3. Results and discussion

# 3.1. Crystal structure of 1 in high-temperature phase (293 K)

 $[CNBzPy][Ni(mnt)_2]$  (1) crystallizes in the monoclinic space group  $P2_1/c$  at room temperature and crystallographic details are summarized in Table 1. Selected bond lengths and bond angles are listed in Table 2. For the  $[Ni(mnt)_2]^-$  anion, the Ni(III) ion is co-ordinated to four sulfur atoms of two mnt<sup>2-</sup> ligands, and exhibits square-planar coordination geometry. The five-membered nickelcontaining rings are slightly puckered, as have been found with other  $[M(mnt)_2]^{n-}$  structures [17]. The average S-Ni-S bond angle within the five-membered ring is 92.6°, and the average Ni-S bond distance is 2.15 Å, these values are in agreement with that of  $[Ni(mnt)_2]^-$  complexes reported [10–14]. The CN groups of mnt<sup>2–</sup> ligand are bent away from the coordinating plane defined by Ni atom and four sulfur atoms. The deviations of four terminal N atoms from the plane are -0.0385, 0.0215, 0.2143, 0.0921 Å, respectively. In the 1-(4'cyanobenzyl)pyridinium cation, the dihedral angles of the C(15)–C(14)–N(5) reference plane are 80.1° for phenyl ring, 80.6° for pyridine ring, respectively.

The most notable structural feature of **1** is that the anion and cation possess the stacking structure with well-separated column along the direction of c-axis (Fig. 1a). Within an anion column, the  $[Ni(mnt)_2]^-$  anions form a 1-D uniformly spaced chain, and the slipped zig-zag configuration of  $[Ni(mnt)_2]^-$  anions are displayed in Fig. 1b. The nearest S...S, S...Ni and Ni...Ni distances are of 3.85, 3.65 and 4.54 A within the  $[Ni(mnt)_2]^$ anion chain, respectively. Obviously, there exist intermolecular interactions between neighboring  $[Ni(mnt)_2]^-$  anions within an anionic chain due to the shorter intermolecular separations. While the closest Ni ··· Ni separation between anionic chains is 8.08 A, which is significantly longer than the distance of Ni ··· Ni separation within a chain.

Table 1						
Crystal	data	and	structure	refinement	for	1

	1	1	1
Temperature	293(2) K	180(2) K	140(2) K
Empirical formula	$C_{21}H_{11}N_6NiS_4$	$C_{21}H_{11}N_6NiS_4$	$C_{21}H_{11}N_6NiS_4$
Formula weight	534.31	534.31	534.31
Wavelength	0.71073 Å	0.71073 Å	0.71073 Å
Crystal system	Monoclinic	Monoclinic	Monoclinic
Space group	$P2_1/c$	$P2_1/c$	$P2_1/c$
Unit cell dimensions			
a (Å)	15.197 (3)	15.0630(3)	15.0218(3)
b (Å)	17.796(4)	17.7252(4)	17.6926(3)
c (Å)	8.6089(17)	8.5663(2)	8.54580(10)
α (°)	90	90	90
β (°)	95.15(3)	94.6499(10)	94.5089(8)
γ (°)	90	90	90
Volume ( $\mathring{A}^3$ ), Z	2318.9(8), 4	2279.63(9), 4	2264.23(6), 4
Density (calculated)	$1.530 \text{ g/cm}^3$	1.557 g/cm <sup>3</sup>	1.567 g/cm <sup>3</sup>
Absorption coefficient	$1.219 \text{ mm}^{-1}$	$1.239 \text{ mm}^{-1}$	$1.248 \text{ mm}^{-1}$
$F(0\ 0\ 0)$	1084	1084	1084
Crystal size (mm <sup>3</sup> )	$0.15\times0.10\times0.10$	$0.15\times0.10\times0.10$	$0.15\times0.10\times0.10$
$\theta$ range for data collection	3.48–27.49°	3.51-27.48°	3.52–27.48°
Limiting indices	$-19 \leq h \leq 19$	$-19 \leq h \leq 19$	$-19 \leq h \leq 19$
	$-23 \leq k \leq 23$	$-22 \leq k \leq 22$	$-22 \leq k \leq 22$
	$-11 \leq l \leq 11$	$-11 \leq l \leq 11$	$-11 \leq l \leq 11$
Reflections collected	33282	36213	37792
Independent reflections	5303	5099	5130
	$(R_{\rm int} = 0.0427)$	$(R_{\rm int} = 0.0928)$	$(R_{\rm int} = 0.0503)$
Absorption correction	Empirical	Empirical	Empirical
Max. and min. transmission	0.886 and 0.833	0.884 and 0.830	0.883 and 0.830
Refinement method	Full-matrix least-squares		
	on $F^2$		
Data/restraints/parameters	5303/0/289	5099/0/289	5130/0/289
Goodness-of-fit on $F^2$	1.024	1.008	1.031
Final <i>R</i> indices $[I > 2\sigma(I)]$	$R_1 = 0.0332$	$R_1 = 0.0386$	$R_1 = 0.0283$
	$wR_2 = 0.0733$	$wR_2 = 0.0693$	$wR_2 = 0.0594$
R indices (all data)	$R_1 = 0.0582$	$R_1 = 0.1012$	$R_1 = 0.0511$
<u>^</u>	$wR_2 = 0.0835$	$wR_2 = 0.0823$	$wR_2 = 0.0652$
Largest diff. Peak and hole (e $\mathring{A}^{-3}$ )	0.253 and -0.342	0.317 and -0.398	0.269 and -0.298

Therefore, the magnetic interaction between two anionic columns separated by a sizable diamagnetic cationic column is generally weak, and **1** is a 1-D magnetic chain system from the viewpoint of the structure analysis.

# 3.2. Crystal structures of **1** in low-temperature phase (180 and 140 K)

The molecular structures of 1 in low-temperature phase (180 and 140 K) are crystallographically indistinguishable with that in high-temperature phase (Table 1). The lattice contraction with decreasing temperature change to a much less extent, i.e., the cell parameters of *a*, *b*, *c*,  $\beta$  and *V* decrease 0.134 Å, 0.071 Å, 0.043 Å, 0.50°, 39.3 Å<sup>3</sup> at 180 K, and 0.175 Å, 0.103 Å, 0.063 Å, 0.64°, 54.7 Å<sup>3</sup> at 140 K, respectively. The corresponding bond lengths and bond angles in 1 at 180 and 140 K are in agreement well with the values at room temperature, the separations between adjacent molecules gradually decreases as the temperature decreasing, and see also in Table 2. Complex 1 preserve the stacking structure with well-separated column along the direction of *c*-axis and the [Ni(mnt),]<sup>-</sup> anions also form a 1-D uniformly

	1 (293 K)	1 (180 K)	1 (140 K)	
Bond distances (Å)				
Ni(1)–S(1)	2.1388(7)	2.1517(7)	2.1506(5)	
Ni(1)–S(2)	2.1495(7)	2.1394(7)	2.1490(5)	
Ni(1)–S(3)	2.1493(7)	2.1498(7)	2.1413(5)	
Ni(1)–S(4)	2.1471(7)	2.1508(7)	2.1517(5)	
Bond angles (°)				
S(1)-Ni(1)-S(2)	92.50(3)	92.63(3)	92.771(18)	
S(1)-Ni(1)-S(3)	87.10(3)	87.73(3)	86.874(18)	
S(3)-Ni(1)-S(4)	92.69(3)	92.72(3)	92.651(18)	
S(2)-Ni(1)-S(4)	87.73(3)	86.97(3)	87.753(19)	
Intrachain distances (Å)				
Ni···Ni	4.539	4.517	4.506	
Ni···S	3.652	3.629	3.619	
$S \cdots S$	3.845	3.804	3.789	
(the nearest separation)				
Interchain distances (Å)				
Ni···Ni	8.080	8.045	8.029	
(the nearest separation)				

Table 2 Selected bond parameters and intermolecular contacts for 1



Fig. 1. (a) The packing diagram of a unit cell for 1. (b) 1-D  $[Ni(mnt)_2]^-$  anion chain with equal  $Ni \cdots Ni$  distant viewing along the *c*-axis.



Fig. 2. Variable temperature X-ray powder patterns in the temperature range 113-278 K exhibit no change for complex 1.

spaced chain at 180 and 140 K. Within the  $[Ni(mnt)_2]^-$  chain, the nearest  $S \cdots S$ ,  $S \cdots Ni$  and  $Ni \cdots Ni$  distances are of 3.80 Å at 180 K (3.79 Å at 140 K), 3.63 Å at 180 K (3.62 Å at 140 K) and 4.52 Å at 180 K (4.51 Å at 140 K), respectively. The corresponding closest  $Ni \cdots Ni$  separation between anion chains is 8.05 Å at 180 K (8.03 Å at 140 K). In a word, there are not notable changes for the molecular and stacking structures of 1 between high- and low-temperature phases, and the

results are in agreement with that of the variabletemperature X-ray powder diffraction measured in the temperature ranges 113–278 K (Fig. 2).

## 3.3. Magnetic properties

Magnetic susceptibilities of a polycrystalline sample of complex 1 were measured at a field of 1 T in the temperature range from 400 to 2 K, the  $\chi_m$ versus T plot is displayed in Fig. 3. At 400 K, the



Fig. 3. The plot of  $\chi_m$  of 1 measured at 10 kOe field (the solid line represents the best fit at high- and low-temperature range). Inset: derivative  $d(\chi_m)/dT$  versus *T*.



Fig. 4. Hysteresis loop exhibited for 1 at 2 K. The inset shows the M–H curve.

value of the effective moment  $\mu_{eff}$  equals to 1.023  $\mu_{\rm B}$ , which is significantly less than the spin-only value of 1.732  $\mu_{\rm B}$  expected for a non-interaction Ni(III) ion with S = 1/2, indicating that there exists antiferromagnetic exchange interactions between neighbor Ni(III) ions. As the temperature decreases, the value of  $\chi_{\rm m}$  gradually decreases, and a prominent kink is observed around 190 K, which may be estimated from the extreme of  $d(\chi_{\rm m})/dT$  versus T plot (inset of Fig. 3). Hereafter, the value of  $\chi_{\rm m}$  decreases more sharply and reaches a minimum  $(1.04 \times 10^{-4} \text{ emu mol}^{-1})$  at ~60 K. Below 60 K, upturn in  $\chi_{\rm m}$  values is observed at lower temperature as T approaches to 0 K and do not simply attributed to Currie-tail due

to magnetic impurity. Cycling the applied field between +10 and -10 kOe at 2 K generates a hysteresis loop as shown in Fig. 4, as expected for a material exhibiting weak ferromagnetic behavior. The weak ferromagnetism of 1 at low temperature may be due to a consequence of canted spin antiferromagnetism. Spin canting arises through a Dzyaloshinsky–Moriya interaction [18–20], which minimizes the coupling energy when two spins are perpendicular to one another. Moreover, the assumption is supported by the fact which shown in the inset of Fig. 4 that the highest magnetization of 10.56 emu G mol<sup>-1</sup> (at 2 K and 50 kOe) is significantly smaller than the theoretical saturation value of 5585 emu G mol<sup>-1</sup> [18].

The magnetic susceptibility anomaly around 190 K is very interesting, the variable-temperature crystallographic structural analyses of both single crystal and powder shown that there is not distinct structural change between the high- and low-temperature phases, which means this phase transition is only magnetic but not structural transition character. To obtain more information about the thermodynamic properties of the phase transition, DSC measurements of 1 were performed in the temperature range of 93 to 393 K. There are no any obvious exothermic or endothermic phenomena except base-line shift of the DSC curve (Fig. 5). So the phase transition observed  $\sim 190$  K is expected to be a second-order phase transition [21,22]. The phase transition observed is phenomenally similar to spin-Peierls transition, which



Fig. 5. Differential scanning calorimetry of 1 showing base-line shift.

occurs below a critical temperature  $(T_{sp})$  in uniform Heisenberg spin chain system with S = 1/2due to spin–lattice interaction, is a thermodynamic second-order transition. Additionally, **1** meet two conditions required for spin–Peierls transition. Firstly, **1** is a 1-D antiferromagnetic chain system. Secondly, the structure of **1** is flexible, in the sense that the dimerization should not require too large an energy. Experimentally, there are a knee in plot of  $\chi_m - T$  at  $T_{sp}$  and rather abrupt fall of  $\chi_m$  below  $T_{sp}$ , which is one feature of the spin–Peierls transition [23].

The experimental data in high-temperature phase for **1** are analyzed with the general expression [24]:

$$\begin{split} \chi(T) &= \chi_0 + \chi^{\rm CW}(T) + \chi^{\rm spin}(T) \\ \chi_0 &= \chi^{\rm core} + \chi^{\rm VV}, \\ \chi^{\rm CW}(T) &= \frac{C_{\rm imp}}{T - \theta}, \\ \chi^{\rm spin}(T) &= \frac{Ng^2 \mu_{\rm B}^2}{J} \bar{\chi}^* \left(\frac{k_{\rm B}T}{J}\right), \end{split}$$

where  $\chi_0$  is the sum of a temperature independent and isotropic orbital diamagnetic core contribution and a usually anisotropic and temperature independent orbital paramagnetic Van Vleck contribution,  $\bar{\chi}^*$  is the reduced spin susceptibility. Because the magnetic coupling interactions in this series of compounds are sensitive to the intermolecular contacts, that is, J is dependent on temperature, so the relationship between J and temperature,  $J = J_0(1 + a_1T + a_2T^2)$ , is assumed [24]. The best fit parameters are attained as follows using a magnetic susceptibility simulation program edited by R.K. Kremer et al. [25]:  $J_0/k_B = 295.6$  K,  $C_{\rm imp} = 1.34 \times 10^{-3}$  emu K mol<sup>-1</sup>,  $\theta = -2.48$  K,  $\chi_0 = 4.68 \times 10^{-4}$  emu mol<sup>-1</sup>,  $zJ/k_{\rm B} = -5.5 \times 10^{-2}$ K,  $a_1 = 2.48 \times 10^{-3}$  K<sup>-1</sup>,  $a_2 = -8.9 \times 10^{-6}$  K<sup>-2</sup>, and g factor of 2.06 was fixed, which is the average value of EPR measurement.

Below the transition temperature, the magnetic susceptibility of 1 gradually decreases with decreasing temperature to indicate the magnetic susceptibility being activated [26], so the magnetic

susceptibility may be fitted by  $\chi_{\rm m} = [\alpha(1-P)\exp(\alpha t)]$  $(-\Delta/k_{\rm B}T)]/T + PNg^2\mu_{\rm B}^2/4k_{\rm B}T + \chi_0$ , where  $\alpha$  is a constant value corresponding to the dispersion of excitation energy,  $\Delta$  is the magnitude of spin gap, P is the uncoupling impurities content,  $\chi_0$  is the constant term caused by diamagnetism of core electron shell and Van Vleck paramagnetism and other signs have their usual meaning. The best fit curve is shown in Fig. 3, and the corresponding parameters are given as following: g = 2.079 which is near the value measured by EPR,  $P = 2.8 \times 10^{-4}$ ,  $\alpha = 0.48, \ \Delta/k_{\rm B} = 614.2 \ {\rm K}, \ \chi_0 = 1.1 \times 10^{-4} \ {\rm emu}$ mol<sup>-1</sup> and agreement factor  $R = 6.67 \times 10^{-8}$  $[R = \sum (\chi_m^{obs} - \chi_m^{calc})^2 / \sum (\chi_m^{obs})^2]$ . The obtained value of the parameter,  $2\Delta/k_{\rm B}T_{\rm sp}$  ( $T_{\rm sp}$  is the transition temperature of 190 K), is 6.47 and significantly larger than the ideal value of 3.53 derived from the BCS formula in a weak coupling regime. These results mean that the short-range magnetic correlations within the chain are not fully developed and intrinsic magnetoelastic instability of a 1-D system cannot be considered as a driving force for the transition, namely, the transition is not a pure spin–Peierls transition but an exotic one [13].

#### 4. Conclusion and outlook

In this contribution, an ion-pair complex [1-(4'cvanobenzyl)pyridinium] [Ni(mnt)<sub>2</sub>], in which  $mnt^{2-} = maleonitriledithiolate$ , have been fabricated and its single crystal X-ray structural analyses at 293, 180 and 140 K show that the molecular and stacking structures have not notable change, and  $[Ni(mnt)_2]^-$  anions are uniformly spaced along crystallographic c-axis direction. Its temperature dependence magnetic susceptibilities shown there exists a phase transition  $\sim 190$  K, but both DSC and variable-temperature X-ray powder diffraction measurements further reveal no structural transition. Although this transition is phenomenally similar to spin-Peierls transition, the magnetic data analysis in low-temperature phase and weak ferromagnetic behavior at  $\sim 2$  K indicate this transition is not a pure spin-Peierls transition but an exotic one. Therefore lots of investigations should continue in order to understand the complex magnetic behavior of 1, the intensive

researching in the aspects of novel physical properties is in progress.

### Supplementary material

The detail crystallographic data of 1 have been deposited at the Cambridge Crystallographic Data Center as supplementary publication No. CCDC-182195 for 293 K, CCDC-186340 for 180 K and CCDC-186341 for 140 K data. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB21EZ, UK, Fax: +44-1223-336-033; e-mail: deposit@ ccdc.cam.ac.uk.

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#### References

- N. Robertson, L. Cronin, Coord. Chem. Rev. 227 (2002) 93.
- [2] P. Cassoux, L. Valade, H. Kobayashi, R.A. Clar, A.E. Underhill, Coord. Chem. Rev. 110 (1991) 115.
- [3] A.T. Coomber, D. Beljonne, R.H. Friend, J.L. Brédas, A. Charlton, N. Robertson, A.E. Underhill, M. Kurmoo, P. Day, Nature 380 (1996) 144.
- [4] A.E. Pullen, C. Faulmann, K.I. Pokhodnya, P. Cassoux, M. Tokumota, Inorg. Chem. 37 (1998) 6714.

- [5] M. Uruichi, K. Yakushi, Y. Yamashita, J. Qin, J. Mater. Chem. 8 (1998) 141.
- [6] D. Arcon, A. Lappas, S. Margadonna, K. Prassides, E. Ribera, J. Veciana, C. Rovira, R.T. Henriques, M. Almeida, Phys. Rev. B 60 (1999) 4191.
- [7] G.R. Lewis, I. Dance, J. Chem. Soc. Dalton Trans. (2000) 3176.
- [8] J.S. Miller, J.C. Calabrese, A.J. Epstein, Inorg. Chem. 28 (1989) 4230.
- [9] M. Hobi, S. Zürcher, V. Gramlich, U. Burckhardt, C. Mensing, M. Spahr, A. Tongi, Organometallics 34 (1996) 5342.
- [10] J.L. Xie, X.M. Ren, Y. Song, W.J. Tong, C.S. Lu, Y.G. Yao, Q.J. Meng, Inorg. Chem. Commun. 5 (2002) 395.
- [11] J.L. Xie, X.M. Ren, Y. Song, Y. Zou, Q.J. Meng, J. Chem. Soc. Dalton Trans. (2002) 2868.
- [12] J.L. Xie, X.M. Ren, Y. Song, W.W. Zhang, W.L. Liu, C. He, Q.J. Meng, Chem. Commun. (2002) 2346.
- [13] X.M. Ren, Q.J. Meng, Y. Song, C.S. Lu, C.J. Hu, X.Y. Chen, Inorg. Chem. 41 (2002) 5686.
- [14] X.M. Ren, Q.J. Meng, Y. Song, C.J. Hu, C.S. Lu, X.Y. Chen, Z.L. Xue, Inorg. Chem. 41 (2002) 5931.
- [15] S.B. Bulgarevich, D.V. Bren, D.Y. Movshovic, P. Finocchiaro, S. Failla, J. Mol. Struct. 317 (1994) 147.
- [16] A. Davison, H.R. Holm, Inorg. Synth. 10 (1967) 8.
- [17] K.W. Plumlee, B.M. Hoffman, J.A. Ibers, J. Chem. Phys. 63 (1975) 1926.
- [18] R.L. Carlin, Magnetochemistry, Springer-Verlag, Berlin, 1986.
- [19] A.J. Banister, N. Bricklebank, I. Lavender, J.M. Rawson, C.I. Gregory, B.K. Tanner, W. Clegg, M.R.J. Elsegood, F. Palacio, Angew. Chem. Int. Ed. Engl. 35 (1996) 2533.
- [20] N. Robertson, C. Bergemann, H. Becker, P. Agarwal, S.R. Julian, R.H. Friend, N.J. Hatton, A.E. Underhill, A. Kobayashi, J. Mater. Chem. 9 (1999) 1713.
- [21] R. Nicholson, Y. Fujii, X. Chen, R. Willett, J. Phys. Chem. Solids 61 (2000) 2025.
- [22] T. Hashimoto, T. Katsube, Y. Morito, Solid State Commun. 116 (2000) 129.
- [23] O. Kahn, in: Molecular Magnetism, VCH Publishers, New York, 1993, p. 263.
- [24] D.C. Johnston, R.K. Kremer, M. Troyer, X. Wang, A. Klümper, S.L. Bud'ko, A.F. Panchula, P.C. Canfild, Phys. Rev. B 61 (2000) 9558.
- [25] Magnetic susceptibility fit program, named as EGASUP and edited by Dr. R.K. Kremer, et al., Max-Plank-Solids-Research-Institute in Stuttgart, Germany.
- [26] L.C. Isett, D.M. Rosso, G.L. Bottger, Phys. Rev. B 22 (1980) 4739.