Spin transition induced by crystal - liquid crystal transition

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Abstract. Cobalt(II) compounds \([\text{Co(C10C8C2-terpy)}_2(\text{BF}_4)_2 (1) \text{ and } \text{Co(C12C10C2-terpy)}_2(\text{BF}_4)_2 (2) \text{ (CxCyCz-terpy = 4'''-5'''-Alkyl-1'''-alkoxy-2,2':6',2''-terpyridine)}\) with branched alkyl chains, based on a terpyridine frame, were synthesized. The cobalt(II) compounds 1 and 2 exhibit the spin transition between low-spin and high-spin with thermal hysteresis loop at the liquid crystal transition temperature \((T_{1/2}^{\uparrow} = 275 \text{ K and } T_{1/2}^{\downarrow} = 250 \text{ K for } 1 \text{ and } T_{1/2}^{\uparrow} = 307 \text{ K and } T_{1/2}^{\downarrow} = 296 \text{ K for } 2)\), and the spin transition is induced by crystal – liquid crystal transition. The bifunctional materials show synchronizing both spin transition and liquid crystal transition.

1. Introduction

Liquid crystals are fascinating functional materials, and are important in the field of advanced materials such as electro optic devices. Organic liquid crystals are diamagnetic and can be easily oriented by an electric field. Liquid crystals of transition metal complexes, called metallomesogens, have attracted a great deal of attention at a point of view of multi-functionality. [1] The development of metallomesogens with multi-functions (spin-crossover, mixed-valence, magnetism, conductivity etc.) is very important in order to achieve the co-occurrence of various physical properties in the functional molecular-based materials.

The spin-crossover (SCO) phenomenon occurs when transforming between high-spin (HS) and low-spin (LS) states reversibly, stimulated by external perturbations (e.g. temperature, pressure, magnetic field or light). [2] Galyametdinov et al. reported such a SCO iron(III) compound \((S = 1/2 \leftrightarrow S = 5/2)\) with liquid-crystal properties. [3] This compound consists of an iron(III) ion coordinated to Schiff-base ligands with long alkyl chains, and exhibits a rod-like geometry. The SCO behavior was gradual in the temperature range of 50 K - 300 K, and the smectic A mesophase was observed between 380 K and 418 K. We have also observed a photo-induced spin transition (LIESST effect) below about 60 K in the SCO iron(II) compounds, which displays the mesophase above about 350 K. [4] The development of novel compounds exhibiting LIESST is one of the main challenges in this field. It may be possible that both the SCO and mesophase transition can be synchronized. Fujigaya et al. have reported a one-dimensional iron(II) compound with triazole derivatives, which exhibits SCO and liquid-crystal behavior in the same temperature region. [5] However, the supposed mesomorphism of the complexes has not been confirmed. Gaspar et al. have been investigating the possibility of synchronizing both transitions in the iron(II) complexes which are 1-D compounds based on triazole ligands. [6] They have reported that thermochromic liquid crystals operating in the room-temperature
region exhibited SCO behavior in the temperature range at which the materials show a discotic columnar mesophase. Furthermore, the controlling the SCO characteristics of 1-D iron(II) compounds by an amphiphilic phase transition have also reported. [7,8]

Hence, in order to develop a variety of switchable molecules which exhibit a spin transition induced by a crystal-mesophase transition, we propose the strategies as following; (i) the SCO compounds are necessary in order to transform the spin states even by subtle structural changes in the ligands or molecules, (ii) the SCO compounds with \( T_{1/2} \) above room temperature are necessary because the liquid-crystal transition temperature is generally higher than room temperature for the **metallomesogens** or (iii) the liquid-crystal transition temperature should be adjusted to \( T_{1/2} \) in the SCO compounds by changing the length or type of the alkyl chains. Based on the strategy (i) - (iii), we aimed at construction of the spin transition compounds which occured at liquid crystal transition temperature. The SCO **metallomesogens** have been investigated for only iron(II) or iron(III) compounds so far. The SCO **metallomesogens** for other metal compounds, cobalt(II) and so on, have been also interesting.

### 2. Experimental methods

Cobalt(II) compounds \([\text{Co(C10C8C2-terpy)}_2](\text{BF}_4)_2 \) (1) and \([\text{Co(C12C10C2-terpy)}_2](\text{BF}_4)_2 \) (2) (CxCyCz-terpy = 4'-5'''-Alkyl-1'''-alkoxy-2,2':6',2''-terpyridine) with branched alkyl chains were synthesized. The ligand C12C10C2-terpy was synthesized by mixing 2-Decyl-1-bromotetradecane (1.38 g, 3.43 mmol), 2,6-bis(2-pyridyl)-4(1H)-pyridone (0.57 g, 2.29 mmol) and K2CO3 (0.63 g, 4.58 mmol) in DMF (70 ml) at 80 °C for 12 h. The ligand C10C8C2-terpy was also synthesized by the same method. The compounds 1 and 2 were obtained as brown powder by reacting Co(BF4)2 with the corresponding ligands, and the compositions for 1 and 2 were confirmed by elemental analysis. Anal. Calcd. for C70H102N6O2B2F8Co1 (1): C, 65.07 H, 7.96 N, 6.50. Found : C, 65.23 H, 8.02 N, 6.73. Anal. Calcd. for C78H118N6O2B2F8Co1 (2): C, 66.71 H, 8.47 N, 5.98. Found : C, 66.83 H, 8.72 N, 5.73. A rod-like geometry is proposed for the molecular structure of 1 and 2 (Figure 1).

![Figure 1. Chemical structure in cations of 1 and 2.](image)

### 3. Results and Discussion

Liquid-crystalline properties for 1 and 2 were confirmed by powder X-ray diffraction (XRD), and polarizing optical microscopy (POM). Powder XRD measurements for 1 and 2 were carried out to confirm this mesophase. The XRD pattern for 1 at 300 K displays a diffuse and broad scattering halo, centered at 4.2 Å (2\( \theta \) = 21.0°) in the wide-angle region, and indicative of a liquid-like order of the aliphatic chains and thus of the fluid-like nature of the phase. In the small-angle region, the XRD pattern displayed the reflections of a lamellar phase with a periodicity \( d = 21.9 \) Å (2\( \theta \) = 4.0°). The XRD pattern for 2 at 470 K displays a diffuse and broad scattering halo, centered at 4.4 Å (2\( \theta \) = 20.0°) in the wide-angle region, and indicative of a liquid-like order of the aliphatic chains and thus of the
fluid-like nature of the phase. In the small-angle region, the XRD pattern displayed the reflections of a lamellar phase with a periodicity \( d = 25.1 \, \text{Å} \) (\( 2\theta = 3.5^\circ \)).

The textures of \( 1 \) and \( 2 \) were observed at various temperature on heating and cooling mode. The typical fan-shaped textures were observed in mesophase. The mesophase was identified as a smectic A (SmA) mesophase based on the texture observed by POM and the powder XRD pattern.

Phase transition temperatures for \( 1 \) and \( 2 \) obtained by differential scanning calorimetry (DSC) measurements are summarized in Table 1. The DSC analysis showed that two mesophases, \( M_1 \) and \( M_2 \), were included in the compound \( 1 \). On heating, the crystal \( K_1 \) phase transforms to the \( M_1 \) phase (unknown) at 275 K, and transforms from \( M_1 \) phase to the \( M_2 \) phase (SmA) at 323 K. Further heating, the mesophase-to-isotropic liquid transition temperature for \( 1 \) was observed at 479 K. On the other hand, the polymorphism includes two crystal forms \( K_1 \) and \( K_2 \), and two mesophase \( M_1 \) and \( M_2 \) in the compound \( 2 \). [9] On heating, the crystal \( K_1 \) phase transforms to the \( K_2 \) phase at 298 K, and transforms from \( K_2 \) phase to the unknown \( M_1 \) phase at 307 K. Further heating, the \( M_1 \) phase transforms to the \( M_2 \) (SmA) phase at 323 K. The mesophase-to-isotropic liquid transition temperature for \( 2 \) was observed at 453 K.

**Table 1.** Phase transition temperatures of \( 1 \), \( 2 \) and \( 3 \).

| Compound | Phase | \( T / \text{K} \) | Phase |
|----------|-------|----------------|-------|
| 1        | \( K_1 \) | 275K | \( M_1 \) | 323K | SmA | 479K | L.L. |
| 2        | \( K_1 \) | 298K | \( K_2 \) | 307K | \( M_1 \) | 323K | SmA | 453K | L.L. |

Phase nomenclature: \( K = \) crystal, \( L.L. = \) isotropic liquid

\( M_1 = \) unknown mesophase, \( \text{SmA} = \) smectic A mesophase

**Figure 2.** \( \chi_m T \) versus \( T \) plots (▲: heating mode, and ▼:cooling mode) for \( 1 \) and \( 2 \). The insert graph shows the derivative \( \partial \chi_m T / \partial T \) plot as a function of the temperature.

Spin transition between the high-spin and low-spin states for \( 1 \) and \( 2 \) was followed by measurements of the molar magnetic susceptibility \( \chi_m \) as a function of temperature (Figure 2). The \( \chi_m T \) value for \( 1 \) is equal to 0.53 cm\(^3\)Kmol\(^{-1}\) at 5 K, which is in the range of values expected for LS cobalt(II) ions. As the temperature is increased from 5 K, the \( \chi_m T \) product remained practically constant from 5 K to 80 K, then abruptly increased around \( T_{1/2} = 275 \) K. The \( \chi_m T \) value at 400 K was 1.80 cm\(^3\)Kmol\(^{-1}\), showing that the spin transition from the LS to the HS state was induced. The spin transition is directly related to the mesophase transition. On cooling, the \( \chi_m T \) value for \( 1 \) was decrease
gradually from 400 K to 300 K, then abruptly dropped at around $T_{1/2} = 250$ K, showing that the HS moieties were restored to the LS state with hysteresis loop ($\Delta T = 25$ K). Additional thermal cycles did not modify the thermal hysteresis loop. The $\chi_m T$ value for 2 is equal to 0.52 cm$^3$/Kmol$^{-1}$ at 5 K, which is in the range of values expected for LS cobalt(II) ions. As the temperature is increased from 5 K, the $\chi_m T$ product remained practically constant from 5 K to 70 K, then abruptly increased around $T_{1/2} = 307$ K. The $\chi_m T$ value at 400 K was 1.95 cm$^3$/Kmol$^{-1}$, showing that the spin transition from the LS to the HS state was induced. The spin transition is also directly related to the mesophase transition. On cooling, the $\chi_m T$ value for 2 was decrease gradually from 400 K to 310 K, then abruptly dropped at around $T_{1/2} = 296$ K, showing that the HS moieties were restored to the LS state with hysteresis loop ($\Delta T = 11$ K). Additional thermal cycles did not modify the thermal hysteresis loop.

The insert of Figure 2 shows the extreme of the derivative $\partial \chi_m T / \partial T$ in the spin transition behavior and DSC curves measured at scan rate the same as magnetic measurement (2 K min$^{-1}$) for 1 and 2. The extremes of the derivative $\partial \chi_m T / \partial T$ agree with the peaks in DSC curves. On heating, the spin transition temperature was observed at 275 K for 1 and 307 K for 2, and the temperature agrees with crystal-to-mesophase transition temperature. On the other hand, the extremes of the derivative $\partial \chi_m T / \partial T$ were observed at 250 K for 1 and 296 K for 2 on cooling, and the mesophase-to-crystal transitions occur in the same temperature range. It has been known that the cobalt(II) compounds with terpy derivative ligands exhibit gradual SCO behavior between $S = 1/2$ and $S = 3/2$. Therefore, it has been thought that the LS specie transforms to HS species induced by crystal-mesophase transition. These results demonstrate that the spin transitions for 1 and 2 are triggered by crystal-mesophase transition. At low temperatures, the branched alkyl chains in the compounds are in the crystal state, and the Co-N bond distance in LS state is hold. On heating, the branched alkyl chains melt, and the spin transition from LS to HS states occurs by permitting elongation of the Co-N bond.

4. Conclusion

In summary, we have succeeded in synchronizing mesophase and spin transitions for the cobalt(II) compounds [Co(C10C8C2-terpy)$_2$](BF$_4$)$_2$ (1) and [Co(C12C10C2-terpy)$_2$](BF$_4$)$_2$ (2) by using branched alkyl chains in the ligand around room temperature. In this way, the phenomenon that one phase transition causes another phase transition is very interesting, and will become important in future in the field of materials science. Furthermore, metalomesogens with multi functions will play an important role in the field of materials science in next generation.

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