Mutual Chiral Discrimination between Tricationic and Trianionic Sulfur-bridged Tricobalt(III) Complexes

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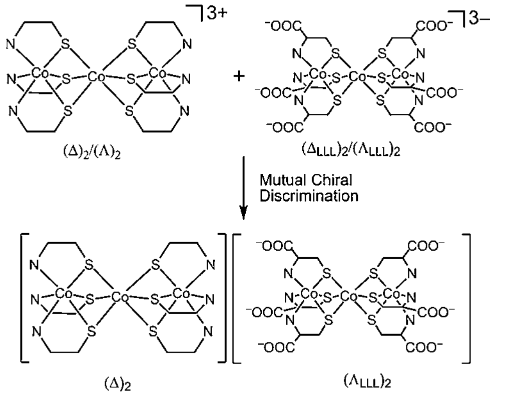
Treatment of the racemic $(\Delta)_2/(\Lambda)_2$ isomer of the tricationic complex, $[\mathrm{Co_3(aet)_6}]^{3+}$ ($[\mathbf{1}]^{3+}$), with the optically active $(\Lambda_{\mathrm{LLL}})_2$ isomer of the trianionic complex, $[\mathrm{Co_3}(\text{L-cys-}N,S)_6]^{3-}$ ($[\mathbf{2}]^{3-}$), afforded only the $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$ isomer of the complex salt, $[\mathrm{Co_3(aet)_6}][\mathrm{Co_3}(\text{L-cys-}N,S)_6]$ (**3**), the structure of which was determined by X-ray crystallography. The selective formation of this isomer was also observed when the racemic isomer of $[\mathbf{1}]^{3+}$ was treated with a 1:1 mixture of the $(\Delta_{\mathrm{LLL}})_2$ and $(\Lambda_{\mathrm{LLL}})_2$ isomers of $[\mathbf{2}]^{3-}$.

Optically active transition-metal complexes have received considerable attention not only due to their significance in fundamental coordination stereochemistry but also due to their potential applications such as asymmetric catalysis, nonlinear optics, and chiral recognition.[1] In most cases, two approaches have been applied to obtain optically active complexes; one is the asymmetric synthesis of a given enantiomer and the other is the optical resolution of a racemic complex into individual enantiomers. For the latter approach, a classical, simple technique is the fractional crystallization with the use of a suitable optically active resolving agent, which is based on the chiral recognition between a racemic complex and a resolving agent. While optically pure organic compounds, such as tartaric acids and alkaloids, have widely been used as resolving reagents for cationic and anionic metal complexes, respectively,[2,3] it has also been recognized that some optically pure ionic complexes can be used as an effective resolving agent for other metal complexes with an opposite charge.[4] However, multinuclear metal complexes have rarely been used as resolving agents, except for $[\mathrm{Sb_2}(R,R\text{-tartrato})_2]^{2-}$,[5] and furthermore, no report has appeared on the optical resolution of a racemic multinuclear complex cation with use of an optically active multinuclear complex anion. In this paper, we report that the racemic isomer ($(\Delta)_2/(\Lambda)_2$) of the tricationic tricobalt(III) complex with 2-aminoethanethiolate (aet), $[\mathrm{Co_3(aet)_6}]^{3+}$ ($[\mathbf{1}]^{3+}$),[6,7] is effectively resolved by using the $(\Lambda_{\mathrm{LLL}})_2$ isomer of the trianionic tricobalt(III) complex with L-cysteinate (L-cys), $[\mathrm{Co_3}(\text{L-cys-}N,S)_6]^{3-}$ ($[\mathbf{2}]^{3-}$),[8] thanks to the selective crystallization of the $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$ isomer of the 1:1 complex salt, $[\mathrm{Co_3(aet)_6}][\mathrm{Co_3}(\text{L-cys-}N,S)_6]$ (**3**). The selective crystallization of $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3** from the racemic $(\Delta)_2/(\Lambda)_2$-$[\mathbf{1}]^{3+}$ and a mixture of the $(\Delta_{\mathrm{LLL}})_2$ and $(\Lambda_{\mathrm{LLL}})_2$ isomers of $[\mathbf{2}]^{3-}$ due to mutual chiral discrimination, which leads to the simultaneous resolution of $[\mathbf{1}]^{3+}$ and $[\mathbf{2}]^{3-}$, is also reported (Scheme 1).



Scheme 1. Schematic representation of chiral selective crystallization.

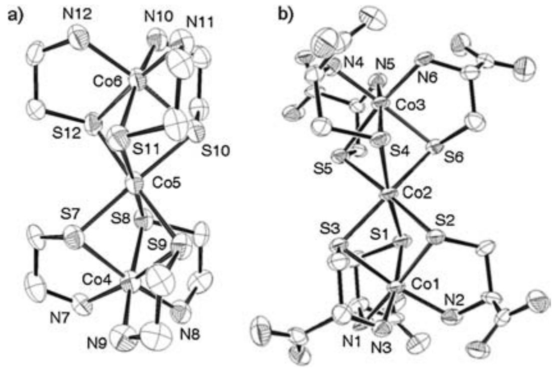


Figure 1. Perspective view of a) $(\Delta)_2$-$[\mathrm{Co_3(aet)_6}]^{3+}$ and b) $(\Lambda_{\mathrm{LLL}})_2$-$[\mathrm{Co_3}(\text{L-cys-}N,S)_6]^{3-}$ in $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3**. H atoms are omitted for clarity.

Treatment of the racemic $[\mathrm{Co_3(aet)_6}](\mathrm{NO_3})_3$ ($(\Delta)_2/(\Lambda)_2$-$[\mathbf{1}](\mathrm{NO_3})_3$) with $(\Lambda_{\mathrm{LLL}})_2$-$\mathrm{K_3}[\mathrm{Co_3}(\text{L-cys-}N,S)_6]$ ($(\Lambda_{\mathrm{LLL}})_2$-$\mathrm{K_3}[\mathbf{2}]$) in a 2:1 ratio in water, followed by allowing to stand at room temperature, gave black needle-like crystals ($(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3**).[9] The elemental analytical data of this product were in agreement with the formula for a 1:1 adduct of $[\mathrm{Co_3(aet)_6}]^{3+}$ and $[\mathrm{Co_3}(\text{L-cys})_6]^{3-}$,[10] and its electronic absorption spectrum in water was identical to that of a 1:1 mixture of $[\mathbf{1}]^{3+}$ and $[\mathbf{2}]^{3-}$.[6,8] The IR spectrum of $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3** (KBr disk) showed a strong sharp C=O stretching band at $1620\,\mathrm{cm^{-1}}$, suggestive of the deprotonated form for free L-cys carboxyl groups.[11] Single-crystal X-ray analysis demonstrated that the asymmetric unit of $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3** consists of a tricobalt complex cation ($[\mathrm{Co_3(aet)_6}]^{3+}$) and a tricobalt complex anion ($[\mathrm{Co_3}(\text{L-cys-}N,S)_6]^{3-}$), besides water molecules of crystallization.[12] The absence of nitrate anions implies that all the carboxylate groups in the complex anion are deprotonated, consistent with the IR spectrum. The $[\mathrm{Co_3(aet)_6}]^{3+}$ cation and the $[\mathrm{Co_3}(\text{L-cys-}N,S)_6]^{3-}$ anion adopt the $(\Delta)_2$ and the $(\Lambda_{\mathrm{LLL}})_2$ configurations, respectively (Figure 1). This result clearly indicates that only the $(\Delta)_2$ isomer of $[\mathbf{1}]^{3+}$ was incorporated in the crystal, together with the $(\Lambda_{\mathrm{LLL}})_2$ isomer of $[\mathbf{2}]^{3-}$. All the six carboxylate groups

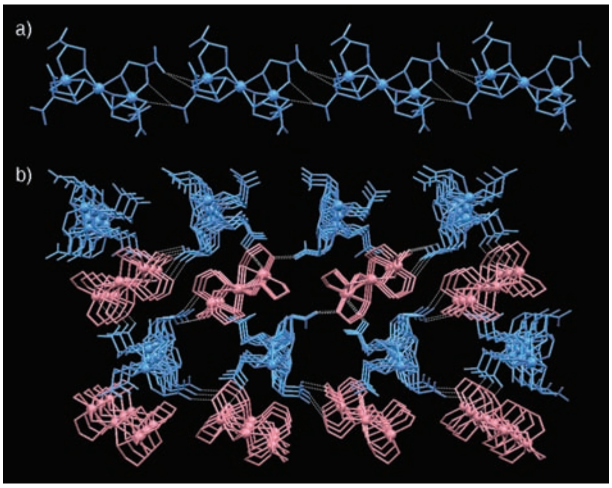


Figure 2. a) 1D and b) 3D hydrogen-bonding structures in $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3**. Pink and blue molecules represent $(\Delta)_2$-$[\mathrm{Co_3(aet)_6}]^{3+}$ and $(\Lambda_{\mathrm{LLL}})_2$-$[\mathrm{Co_3}(\textsc{l}\text{-cys-}N,S)_6]^{3-}$, respectively.

of the $[\mathrm{Co_3}(\textsc{l}\text{-cys-}N,S)_6]^{3-}$ anion in $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3** have an axial orientation with *lel* (δ for Λ) conformational N,S-chelate rings. The same stereochemical behavior has been found in $(\Lambda_{\mathrm{LLL}})_2$-$[\mathrm{Co_3}(\textsc{l}\text{-cys-}N,S)(\textsc{l}\text{-Hcys-}N,S)_5](\mathrm{NO_3})_2$,[8b] in which five of six carboxylate groups are protonated. In the crystal $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3**, two of six carboxylate groups in each $(\Lambda_{\mathrm{LLL}})_2$-$[\mathrm{Co_3}(\textsc{l}\text{-cys-}N,S)_6]^{3-}$ anion are hydrogen-bonded to amine groups of two adjacent anions (av N···O = 2.950(10) Å) to form a 1D chain structure (Figure 2a). The other three carboxylate groups of each anion are hydrogen-bonded to amine groups of three adjacent $(\Delta)_2$-$[\mathrm{Co_3(aet)_6}]^{3+}$ cations (av N···O = 2.946(10) Å) such that each cation is connected to three anions through N–H···O hydrogen bonds (Figure 2b). As a result, anionic and cationic parts are alternately arranged to construct a 3D hydrogen-bonding network.

To investigate whether only the $(\Delta)_2$ isomer of $[\mathbf{1}]^{3+}$ was incorporated in **3**, an aqueous solution of the bulk sample of $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3** was chromatographed on an anion-exchange column (QAE-Sephadex A-25). When the column was treated with water, a brownish green band containing $[\mathbf{1}]^{3+}$ was eluted, while a brownish green band containing $[\mathbf{2}]^{3-}$ was absorbed on the top of the column, which was eluted with a 0.3 M aqueous solution of NaCl. From the absorption and CD spectral measurements, it was confirmed that the eluate of $[\mathbf{1}]^{3+}$ contains only the $(\Delta)_2$ isomer, manifesting the enantioselective uptake of $(\Delta)_2$-$[\mathbf{1}]^{3+}$ into **3**.

Compatible with the chiral selective uptake of the $(\Delta)_2$ isomer of $[\mathbf{1}]^{3+}$ by $(\Lambda_{\mathrm{LLL}})_2$-$[\mathbf{2}]^{3-}$ into the crystalline state, treatment of $(\Lambda)_2$-$[\mathbf{1}](\mathrm{NO_3})_3$ with $(\Lambda_{\mathrm{LLL}})_2$-$\mathrm{K_3}[\mathbf{2}]$ gave no crystalline solid containing $[\mathbf{1}]^{3+}$ and $[\mathbf{2}]^{3-}$. Furthermore, no crystalline solid appeared when the racemic $[\mathbf{1}](\mathrm{NO_3})_3$ was treated with $(\Delta_{\mathrm{LLL}})_2$-$\mathrm{K_3}[\mathbf{2}]$ under the same conditions. Prompted by these results, the racemic $[\mathbf{1}](\mathrm{NO_3})_3$ was then treated with a 1:1 mixture of the $(\Delta_{\mathrm{LLL}})_2$ and $(\Lambda_{\mathrm{LLL}})_2$ isomers of $\mathrm{K_3}[\mathbf{2}]$ in a 1:1 ratio, which resulted in the formation of black needle-like crystals.[9,13] The anion-exchange column chromatography, together with the single-crystal X-ray crystallography, revealed that this product is identical with $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3**. Thus, the diastereomeric pure salt of $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3** consisting of $(\Delta)_2$-$[\mathbf{1}]^{3+}$ and $(\Lambda_{\mathrm{LLL}})_2$-$[\mathbf{2}]^{3-}$ was selectively isolated, though four diastereomers, $(\Delta)_2(\Delta_{\mathrm{LLL}})_2$, $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$, $(\Lambda)_2(\Delta_{\mathrm{LLL}})_2$, and $(\Lambda)_2(\Lambda_{\mathrm{LLL}})_2$, are possible to be formed for **3**.

In summary, we showed that the $(\Lambda_{\mathrm{LLL}})_2$ isomer of the trianionic tricobalt(III) complex, $[\mathrm{Co_3}(\textsc{l}\text{-cys-}N,S)_6]^{3-}$ ($[\mathbf{2}]^{3-}$), selects the $(\Delta)_2$ isomer of the tricationic tricobalt(III) complex, $[\mathrm{Co_3(aet)_6}]^{3+}$ ($[\mathbf{1}]^{3+}$), producing only the $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$ isomer of the complex salt, $[\mathrm{Co_3(aet)_6}][\mathrm{Co_3}(\textsc{l}\text{-cys-}N,S)_6]$ (**3**), upon crystallization. This result is most likely due to the tight 3D hydrogen-bonding network between $[\mathbf{1}]^{3+}$ and $[\mathbf{2}]^{3-}$ formed in the $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$ isomer of **3**. Remarkably, $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3** was also selectively produced from the racemic $((\Delta)_2/(\Lambda)_2)$ $[\mathbf{1}]^{3+}$ and the pseudo-racemic $((\Delta_{\mathrm{LLL}})_2/(\Lambda_{\mathrm{LLL}})_2)$ $[\mathbf{2}]^{3-}$. This means that $(\Lambda_{\mathrm{LLL}})_2$-$[\mathbf{2}]^{3-}$ discriminates the $(\Delta)_2$ isomer of $[\mathbf{1}]^{3+}$ from a mixture of the $(\Delta)_2$ and $(\Lambda)_2$ isomers, while $(\Delta)_2$-$[\mathbf{1}]^{3+}$ discriminates the $(\Lambda_{\mathrm{LLL}})_2$ isomer of $[\mathbf{2}]^{3-}$ from a mixture of the $(\Delta_{\mathrm{LLL}})_2$ and $(\Lambda_{\mathrm{LLL}})_2$ isomers. As far as we know, such a mutual chiral discrimination between cationic and anionic multinuclear species is unprecedented. Note that $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3** is easily separated into $(\Delta)_2$-$[\mathbf{1}]^{3+}$ and $(\Lambda_{\mathrm{LLL}})_2$-$[\mathbf{2}]^{3-}$ by ion-exchange column chromatography using water as an eluent. Thus, this work showed an effective, simultaneous resolution of both the cationic and anionic complexes upon crystallization, which has never been reported so far.

This work was partially supported by Grants-in-Aid for Young Scientists B (No. 20750047) from Japan Society for the Promotion of Science.

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9 Supporting Information is available electronically on the CSJ-Journal Web site, http://www.csj.jp/journals/chem-lett/index.html.

10 Calcd for $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3**$\cdot 16\mathrm{H_2O}$: C, 19.87; H, 5.45; N, 9.27%. Found: C, 19.84; H, 5.34; N, 9.23%. Yield: 58%.

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12 Crystal data for $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3**$\cdot 18\mathrm{H_2O}$: fw 1849.54, Orthorhombic, $P2_12_12_1$, $a = 11.8661(6)$, $b = 23.0133(10)$, $c = 25.8311(13)$ Å, $V = 7053.9(6)$ Å^3, $Z = 4$, $D_{\mathrm{calcd}} = 1.742\ \mathrm{g\,m^{-3}}$, 69557 reflections measured, 16053 independent. $R_1 = 0.0644$ ($I > 2\sigma(I)$), $wR_2 = 0.1864$ (all data). CCDC: 727692.

13 Calcd for $(\Delta)_2(\Lambda_{\mathrm{LLL}})_2$-**3**$\cdot 16\mathrm{H_2O} = \mathrm{C_{30}H_{98}Co_6N_{12}O_{28}S_{12}}$: C, 19.87; H, 5.45; N, 9.27%. Found: C, 19.77; H, 5.27; N, 9.25%. Yield: 61%.