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Hg^{2+}-Sensing System Based on Structures of Complexes

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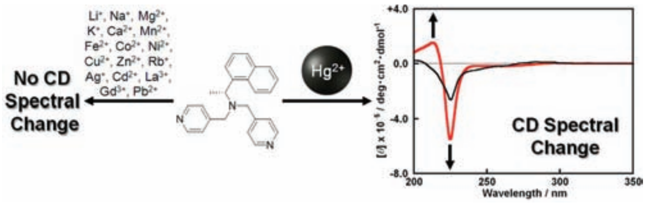
ABSTRACT



The first example of a new Hg^{2+}-sensing system based on the structures of complexes is reported. The system uses a combination of a new chiral bidentate ligand and CD spectroscopy. Significant CD spectral changes are observed when Hg^{2+} is added, whereas no CD spectral changes are observed in the cases of Li^+, Na^+, K^+, Mg^{2+}, Ca^{2+}, Mn^{2+}, Fe^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Rb^+, Ag^+, Cd^{2+}, La^{3+}, Gd^{3+}, and Pb^{2+}.

It is well-known that Hg^{2+} is a highly toxic metal ion with respect to human health and the environment.[1−4] Many Hg^{2+}-ion-sensor molecules have been reported in the past decade.[5−24] In general, sensor molecules for metal ions consist of three parts: a receptor, an active unit, and a spacer.[25] Since the selectivity of a ligand depends on the receptor, the receptor is the most important of these three parts. To develop highly selective ion-sensor molecules, we need to take factors such as the ion diameters, valence electrons, electronic configurations, and coordination modes of metal ions into consideration in the design and preparation of ligands. Much effort has been put into preparing highly designed sensor molecules.[2]

However, there is another way to develop ion-selective sensor molecules. A new way is to develop a ligand that only outputs information on the specific structure of a

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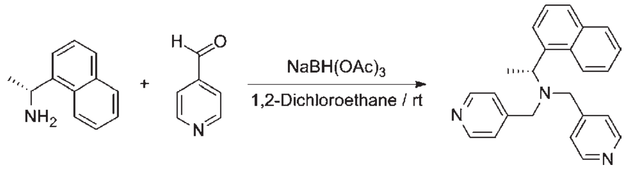
complex between a ligand and a specific metal ion. In this case, the ligand itself does not require metal-ion selectivity. If we could develop a ligand which forms a specific structure by binding to a specific metal ion, even if the ligand does not have metal-ion selectivity, this would be a new ion-sensing system. Fluorescence and UV−vis spectroscopies have been used in many ion-sensing systems. These spectroscopies do not give information on the structures of the complexes, although they give electronic information on the ligand and/or complexes.

CD spectroscopy is a powerful tool for determining the absolute configurations of chiral molecules and complexes on a microgram scale. The CD exciton chirality method provides valuable information on the spatial arrangement of the chromophores.[26] When two or more chromophores situated near each other are regularly arranged spatially, the CD spectrum changes drastically, not only in intensity but also with respect to spectral shape. In addition, no CD spectral changes are observed in the case of random arrangements of the chromophores.

When CD spectroscopy is used to detect metal complexation, it is therefore expected that drastic CD spectral changes will be observed only for specific metal-ion arrangements. Here, we report a Hg^{2+}-ion-sensing system based on the structures of complexes; the system uses a combination of CD spectroscopy and a new chiral bidentate ligand.

Scheme 1. Synthesis of (*R*)-(−)-**1a**



A new chiral bidentate ligand with a 1-(1-naphthyl) group, (*R*)-(−)-**1** (Scheme 1), was prepared in 75% yield by the reductive amination of (*R*)-(+)-1-(1-naphthyl)-ethylamine with 4-pyridinecarbaldehyde in the presence of $NaBH(OAc)_3$. We have also prepared some analogs bearing 1-(2-naphthyl), 1-phenyl, and 1-cyclohexyl groups as a chiral moiety and 3-pyridyl groups as binding sites (see the compound list in the Supporting Information). However, only (*R*)-(−)-**1** showed a significant CD spectral change on addition of Hg^{2+} ions.

The complexing properties of (*R*)-(−)-**1** toward several metal ions were examined, based on metal-ion-induced CD and UV−vis spectral changes in methanol (Figure 1a and 1b). In the CD spectra (Figure 1a), free (*R*)-(−)-**1** exhibits a negative Cotton effect at λ_{ext} 225 nm. When equimolar amounts of Hg^{2+} were added, drastic spectral changes were observed at λ_{ext} 225 and 214 nm, whereas no CD spectral changes were observed upon addition of equimolar amounts of Li^+, Na^+, K^+, Mg^{2+}, Ca^{2+}, Mn^{2+}, Fe^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Rb^+, Ag^+, Cd^{2+}, La^{3+}, Gd^{3+}, and Pb^{2+} ions. On the other hand, a slight UV−vis spectral change was observed on addition of Hg^{2+} ions (Figure 1b), although no spectral changes were observed on addition of the other metal ions. These results indicate that a sensing system using CD spectroscopy with (*R*)-(−)-**1** provides complete Hg^{2+} selectivity.

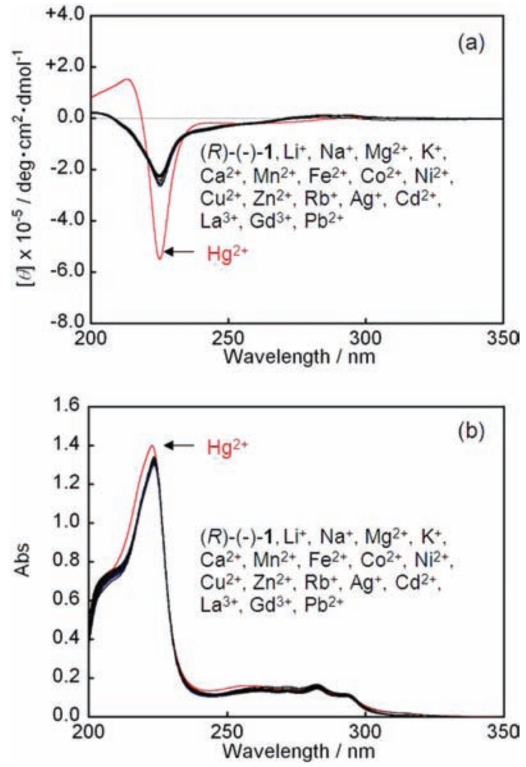


Figure 1. Metal-ion-induced CD ([metal salts] = [(*R*)-(−)-**1**] = 2.0×10^{-4} M) (a) and UV−vis spectral changes ([metal salts] = [(*R*)-(−)-**1**] = 1.9×10^{-5} M in methanol) (b).

To clarify the reasons for this selectivity toward Hg^{2+} ions by (*R*)-(−)-**1**, the structure of the (*R*)-(−)-**1**−Hg-$(CF_3SO_3)_2$ complex was confirmed by cold ESI-MS and ^1H NMR spectroscopy. Cold ESI-MS is an excellent tool for confirming the presence of unstable species and/or species with large molecular weights, and the data reflect the structures in solution (Figure 2). The cold ESI-MS of a 1:1 mixture of (*R*)-(−)-**1** and $Hg(CF_3SO_3)_2$ was measured in methanol.

The fragment ion peaks arising from [(*R*)-(−)-**1** + Hg^{2+} − H^+]$^+$, [2(*R*)-(−)-**1** + $2Hg^{2+}$ + $2OTf^-$]$^{2+}$, [2(*R*)-(−)-**1** + $2Hg^{2+}$ + $3OTf^-$]$^+$, [4(*R*)-(−)-**1** + $4Hg^{2+}$ + $7OTf^-$]$^+$, and [6(*R*)-(−)-**1** + $6Hg^{2+}$ + $10OTf^-$]$^{2+}$ were observed at m/z = 554, 703, 1555, 3259, and 2408, respectively. The patterns of the fragment ion peaks agree with the theoretical distributions (see Figure S1d and S1e in the Supporting Information). The mass data suggest that the $Hg(CF_3SO_3)_2$ complex with (*R*)-(−)-**1** is a $(1:1)_n$ coordination polymer. ^1H NMR titration experiments were carried out in methanol-d_4 (see Figure S1f in the Supporting Information).

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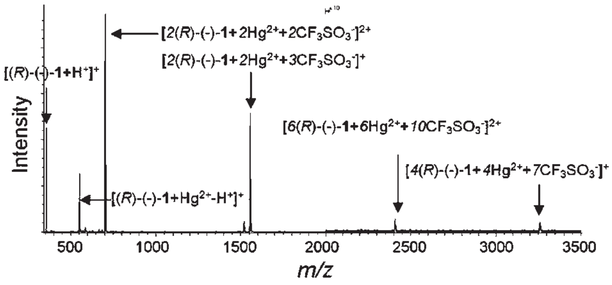

Figure 2. Cold ESI-MS of a mixture of (*R*)-(−)-**1** and Hg-$(CF_3SO_3)_2$ (1:1) in methanol (298 K).

The naphthalene protons in the complex were assigned using $^1H-^1H$ COSY and 1D ^1H NOE difference spectroscopies (see Figure S1g and S1h in the Supporting Information). When equimolar amounts of $Hg(CF_3SO_3)_2$ were added, (i) the signal widths of the pyridine protons broadened and (ii) the signals of the 8-position proton of the naphthalene and the methine proton of the chiral center shifted to lower field by about 0.7 ppm. These results suggest that the complex is a coordination polymer, and the naphthalene and methine protons are located in a deshielding area of the pyridine rings.

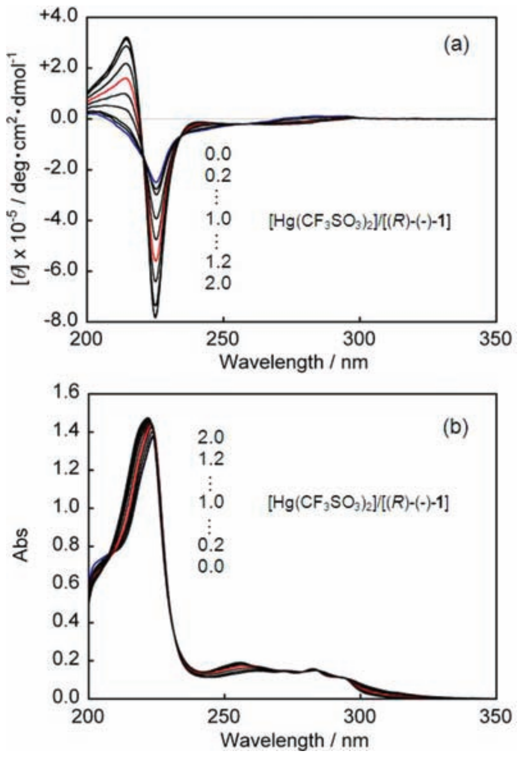

Figure 3. Hg^{2+}-induced CD ($[Hg(CF_3SO_3)_2]$ = [(*R*)-(−)-**1**] = 2.0×10^{-4} M (a) and UV−vis spectral changes ($[Hg(CF_3SO_3)_2]$ = [(*R*)-(−)-**1**] = 2.0×10^{-5} M in methanol) (b).

To obtain stereochemical information on the Hg^{2+} complex, titration experiments using UV−vis and CD spectroscopies were carried out (Figure 3a and 3b). These titration experiments indicate the following: (i) the absorbance at the λ_{max} arising from the ^1B_b transition of the naphthalene unit increases about 1.05 times with the addition of $Hg(CF_3SO_3)_2$ (Figure 3b); (ii) the first (λ_{ext} 225 nm) and second (λ_{ext} 214 nm) Cotton effects in the CD spectra appear in the region of the ^1B_b transition, and small CD spectral changes are observed around λ_{ext} 270 nm, arising from the pyridines (Figure 3a). These results clearly suggest that the CD spectral pattern shows exciton coupling between the naphthalene units.[26] It is well-known that a pair of first negative and second positive Cotton effects indicates the counterclockwise screw sense between two or more axe; therefore the arrangement between the naphthalene units in the (*R*)-(−)-**1**−$Hg(CF_3SO_3)_2$ complex would be the counterclockwise screw sense. In addition, plotting the absorbance at 250 nm vs $[Hg(CF_3SO_3)_2]$/[(*R*)-(−)-**1**] ratios showed a sigmoidal curve which fits a logistic function (see Figure S1i, S1j, and S1k in the Supporting Information). The sigmoidal curve indicates that the binding of (*R*)-(−)-**1** to $Hg(CF_3SO_3)_2$ is autoaccelerative. It is well-known that the cooperative guest binding profile can be analyzed with the Hill equation, $\log[y/(1 - y)] = n \log[\text{guest}] + \log K$, where n and K are the Hill coefficient and overall association constant between the ligand and Hg^{2+}, respectively.[27−30] From the slope and intercept of the linear plot, we obtained $n = 2.09$ and $\log K = 10.8$ (correlation coefficient $R^2 = 0.97$). The n value is nearly 2, meaning that two binding sites of (*R*)-(−)-**1** work cooperatively.

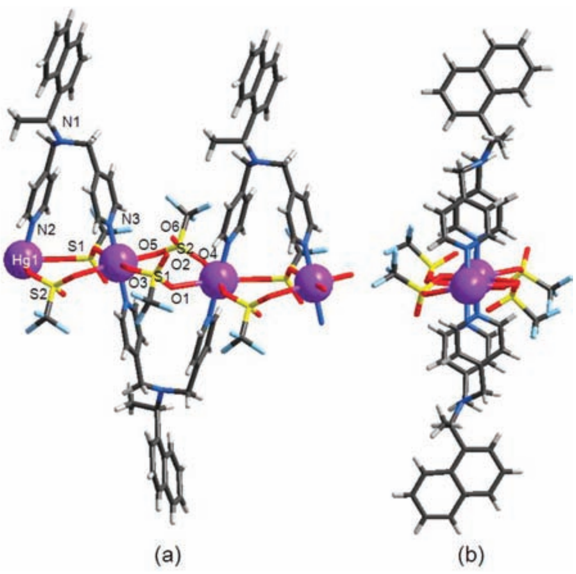

Figure 4. Partial X-ray crystal structure of the $Hg(CF_3SO_3)_2$ complex. Front view (a) and side view (b).

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(*R*)-(−)-**1** in chloroform was treated with equimolar amounts of $Hg(CF_3SO_3)_2$ in methanol to give the (*R*)-(−)-**1**-$Hg(CF_3SO_3)_2$ complex in quantitative yield. The structure of the $Hg(CF_3SO_3)_2$ complex with (*R*)-(−)-**1** was determined by X-ray crystallography. Figure 4 shows tube and line diagrams of the complex (Figure S11 shows selected distances and angles). The complex is a zigzag polymer-like complex. The Hg^{2+} ion is six-coordinated by the pyridine N2 and N3 atoms, and the O1, O3, O4, and O5 atoms of the CF_3SO_3 anions. Interestingly, opposite CF_3SO_3 anions bridge two Hg^{2+} ions to form a looped one-dimensional network structure. It is important to note that the bidentate double-bridging anions play a crucial role as a backbone in the assembly of this unique and robust supramolecular network. The 8-position hydrogen in the naphthalene (colored red in Figure S11) and the methine hydrogen are located in the deshielding area of two pyridines. The X-ray structure therefore supports the predictions of a polymer-like structure made on the basis of the cold ESI-MS and the chemical shift changes in the ^{1}H NMR titration experiments. We have tried to make other metal complexes with (*R*)-(−)-**1**, but no crystals suitable for X-ray analysis were obtained. The naphthalene units in the solid state are arranged in an eclipsed form, which should not give exciton coupling in the CD spectrum. This result could be caused by a packing effect in the solid state.

In summary, we demonstrated a Hg^{2+}-ion-sensing system based on the structures of complexes, using CD spectroscopy and a chiral bidentate ligand. The Hg^{2+}-specific CD spectral changes are the result of exciton coupling between the naphthalene units of the chiral coordination polymer. This system provides a route to new sensing systems using chiral ligands and CD spectroscopy. Investigations of the effects of counteranions of Hg^{2+} on the CD and UV−vis spectral changes are now in progress.

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Supporting Information Available. Experimental details and detailed spectroscopic data of all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

The authors declare no competing financial interest.