BULLETIN OF THE CHEMICAL SOCIETY OF JAPAN, VOL. 44, 3051—3055 (1971)

Metal Complexes Containing Six-Membered Chelate Rings. I. Preparation and Structure of 2,4-Pentanediaminetetraacetato Complexes of Cobalt(III)

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(Received May 31, 1971)

New cobalt(III) complexes with 2,4-pentanediaminetetraacetate (2,4-ptnta^{4-}) have been prepared. The optically active 2,4-ptnta^{4-} (RR or SS) forms a sexadentate complex and determines the absolute configuration around the metal ion. The *meso*-2,4-ptnta^{4-} (RS) coordinates to the metal ion as a quinquedentate with a free acetate branch. Such stereospecific formations of sexa- and quinquedentate complexes from the optically active and the *meso* 2,4-ptnta^{4-} have been attributed to the steric regulation coming from the methyl groups on the α-carbon atoms.

Recently van Saun and Douglas[1] and Ogino *et al.*[2] prepared and resolved cobalt(III) complexes of trimethylenediaminetetraacetate (trdta^{4-}), and suggested that the ligand acts as a sexadentate with less strain as compared with the sexadentate ethylenediaminetetraacetate (edta^{4-}) in an octahedral complex.

The trdta^{4-} complex involves a six-membered chelate ring with puckered skeletal structure in the trimethylenediamine part, for which the following four conformers are possible; chair, two twist (δ) and (λ), and boat form, as shown in Fig. 1. Molecular models clearly indicate that when trdta^{4-} forms a stable octahedral complex as sexadentate, the six-membered chelate should have twist form,[2] and that the δ twist should give a complex with Λ configuration and the λ twist that with Δ configuration. The trdta^{4-} in chair form can not behave as sexadentate, but does as quinquedentate ligand with a free acetate branch. (Fig. 2)

It is generally understood that methyl groups on carbon atoms in puckered chelate rings always tend to take equatorial position.[3] Hence a stereospecific or stereoselective complex formation may be expected by use of such ligands as *l*-propylenediaminetetraace-

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[1] C. W. Van Saun and B. E. Douglas, *Inorg. Chem.*, **8**, 1145 (1969).

[2] H. Ogino, M. Takahashi, and N. Tanaka, This Bulletin, **43**, 424 (1970).

[3] See for example, A. M. Sargeson, "Conformations of Coordinated Chelates" in "Transition Metal Chemistry", R. L. Carlin, Ed., Marcel Dekker, New York (1966), Vol. **3**, pp. 303—343.

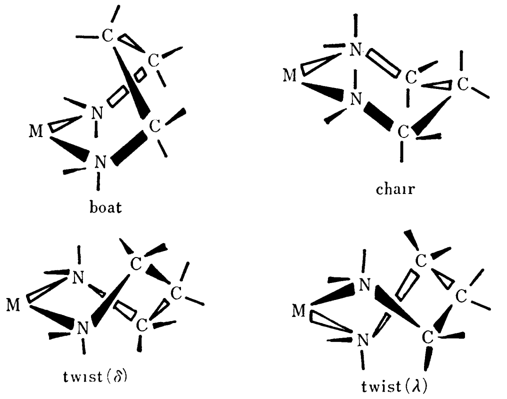

Fig. 1. Possible conformations of six-membered 1,3-diamine chelates. (The notations, δ and λ are by *Inorg. Chem.*, **9**, 1 (1970)).

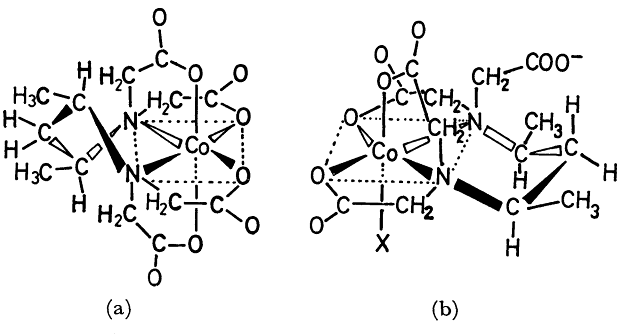
(a) (b)

Fig. 2. Cobalt(III) complexes of (a) RR-2,4-ptnta^{4-}, and (b) RS-2,4-ptnta^{4-} with equatorial methyl groups.

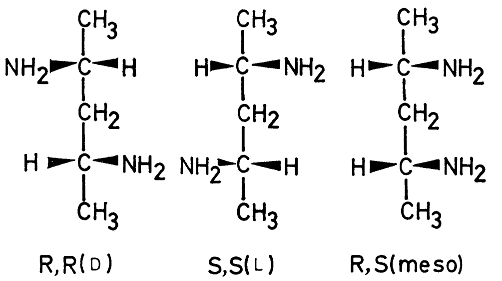

Fig. 3. Isomers of 2,4-pentanediamine.

tate.[4] In this paper, we report the preparation of cobalt(III) complexes of 2,4-pentanediaminetetraacetate (2,4-ptnta^{4-}) which has two methyl groups on the α-carbon atoms adjacent to the amino nitrogen, and discuss the relationship between the structure of these complexes and the optical isomerism of 2,4-pentanediamine, from which the 2,4-ptnta^{4-} ligand is derived.

Experimental

Preparation of Ligands. *2,4-Pentanediamine*: This diamine exists in three isomers, *meso* (RS) and a pair of racemic (RR) and (SS), as shown in Fig. 3. Very recentlyAppleton and Hall[5] reported the separation and the resolution of these isomers. The present method was almost the same as theirs.

Acetylacetone dioxim was reduced with metallic sodium in ethanol by Harries and Haga's [6] and Dippel's[7] metod, and the product was collected by steam distillation. The aqueous ethanol solution of the diamine was acidified with hydrochloric acid and evaporated almost to dryness under reduced pressure. The product, a mixture of *meso* and racemic diaminedihydrochloride, was separated by the following method; a suspension of 100 g of the mixture in 500 m*l* of 95% ethanol was heated to boiling with stirring, and then filtered in hot. The insoluble material was treated further twice with ethanol in the same way, the volume of ethanol being adjusted according to the amount of insoluble material. The residue was almost pure racemic dihydrochloride. Its purity can be examined by the PMR spectrum in deuterium oxide. (Fig. 4) The filtrate was united, cooled to room temperature, the precipitate filtered off, washed with absolute ethanol and ether, and air dried. This product consists of mostly racemate, but contains a small amount of *meso* isomer, which can be removed by repeating the method described above. Ether was added slowly to the filtrate with stirring until the solution became turbid, which was kept in a refrigerator over night. A mixture of racemic and *meso* isomer was precipitated. Here the *meso* isomer formed large prismatic crystals, while the racemate gave fine needle crystals. Thus, these two isomers can be easily separated by decanting the latters with absolute ethanol repeatedly. A small amount of almost pure *meso* isomer was obtained by evaporating all the filtrates under reduced pressure.

Found: racemic isomer C, 34.69; H, 9.27; N, 15.99%. meso isomer C, 34.19; H,9.34; N, 15.99%. Calcd for $C_5H_{16}Cl_2N_2$: C,34.30; H, 9.21; N, 16.00%

The dihydrochloride was converted into free diamine by the following method. An aqueous solution containing a slight excess of potassium hydroxide was added to the dihydrochloride in a small amount of water below 5°C with stirring. The solution was filtered to remove potassium chloride. Free diamine was obtained in aqueous solution by distilling the filtrate under reduced pressure. The concentration was determined by titrating with aqueous 0.1 N perchloric acid solution.

As was pointed out by Appleton and Hall,[5] Dippel's assignment of these isomers should be reversed; his racemic (α-isomer) is meso and his meso (β-isomer) is racemic, since his meso was resolved into optical isomers.

Resolution of racemic 2,4-pentanediamine: This was resolved by Appletonand Hall's method as *d*-tartrate. Effective resolution was also substantiated by use of *trans*-1,2-cyclohexanedicarboxylic acid. The specific rotation was the same as that by use of *d*-tartrate.

The tartrates were converted into free diamines by the following method; a small excess of aqueous barium hydroxide solution (1:1) was added to an aqueous solution of the tartrate. The precipitate was filtered off, washed with a small amount of water and the filtrate and the washings were distilled under reduced pressure. The product contained a significant amount of water, and the diamine concentration was determined by titration with 0.1 N perchloric acid solution.

The specific rotation of the enantiomers in water are as follows; $[\alpha]_D = -8.33°$ from crystalline *d*-tartrate
$[\alpha]_D = +8.46°$ from oily *d*-tartrate

$(+)_D$-Isomer can be assigned to (SS) configuration, and $(-)_D$-isomer to (RR) configuration, as discussed later.

2,4-Pentanediaminetetraacetate: Free acid and the barium salt of RR-2,4-pentanediaminetetraacetate were synthesized according to a similar method to that for trimethylenediaminetetraacetate by Weyh and Hamm.[8] Monochloroacetic

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[4] F. P. Dwyer and T. E. MacDermott, *J. Amer. Chem. Soc.*, **85**, 2916 (1963).

[5] T. G. Appleton and J. R. Hall, *Inorg. Chem.*, **9**, 1807 (1970).

[6] C. Harries and T. Haga, *Ber.*, **32**, 1191 (1899).

[7] C. J. Dippel, *Rec. Trav. Chim.*, **50**, 525 (1931).

[8] J. A. Weyh and R. E. Hamm, *Inorg. Chem.*, **7**, 2431 (1968).

acid (13.9 g) in 14 m*l* of water was neutralized with 9 g of potassium hydroxide in 15 m*l* of water below 20°C with stirring, and treated with 3.16 g of $(-)_D$-diamine in 5 m*l* of water. The solution was heated at 80°C for 2 hr and 9 g of potassium hydroxide in 10 m*l* of water was added. The solution was evaporated to about 30 m*l* at 80°C, cooled to 0°C and filtered to remove potassium chloride. To the filtrate was added 15.4 g of barium chloride dihydrate in 30 m*l* of hot water with stirring, and the solution was evaporated at 80°C to about 35 m*l*. The barium salt was filtered off, washed with hot water (80°C) several times and air dried.

Found: C, 23.38; H, 3.50; N, 4.37%. Calcd for $C_{13}H_{24}N_2O_{11}Ba_2=Ba_2(RR\text{-}2,4\text{-ptnta})\cdot 3H_2O$: C, 23.69; H, 3.67; N, 4.25%.

Barium salts of racemic- and meso-2,4-pentanediaminetetraacetate were prepared similarly, but the latter was obtained as powder by adding methanol to its concentrated aqueous solution. Both barium salts give only approximate coincidence between found and calculated analytical results, but their cobalt complexes give very satisfactory analytical results.

Preparation of Metal Complexes. Cobalt(III) complexes of isomers of $2,4\text{-ptnta}^{4-}$ were prepared from $Na_3[Co(NO_2)_6]$[9]. The yields of the complexes were rather low because cobalt(III) was reduced to cobalt(II) during the reaction. Preparation from cobalt(II) salt, $2,4\text{-ptnta}^{4-}$ and an oxydizing agent such as hydrogen peroxide and lead dioxide yielded a large amount of cobalt(II) complex, which could hardly be removed.

The racemic barium salt was treated with an equivalent amount of dilute sulfuric acid, centrifuged and the supernatant evaporated to dryness. The residue was extracted with ethanol and the ethanol evaporated off.

H[Co(RR- and SS-2,4-ptnta)]·3H₂O: An aqueous solution (100 m*l*) containing 6.6 g of racemic $H_42,4$-ptnta (prepared from 13 g of barium salt) and 8 g of $Na_3[Co(NO_2)_6]$ was warmed at 50°C for 3 hr, cooled to room temperature and filtered. The filtrate was passed through a column of the anion exchanger Dowex 1-X4 in chloride form. The column was washed with water to remove the cobalt(II) ion and the adsorbed purple band was eluted with 0.1 N hydrochloric acid. The eluate was condensed in a vacuum desiccator over potassium hydroxide to about 10 m*l*. Purple crystals were deposited by adding ethanol under cooling, which were filtered off, washed with ethanol, air dried and recrystallized from water by cooling together with ethanol.

Found: C, 34.77; H, 5.33; N, 6.13%. Calcd for $C_{13}H_{25}N_2O_{11}Co$: C, 35.14; H, 5.67; N, 6.31%.

K[Co(RR-2,4-ptnta)]·H₂O: This complex was prepared from RR-H_4-2,4-ptnta and $Na_3[Co(NO_2)_6]$ by a similar method to that for the racemic-2,4-ptnta complex. Acid complex was converted into potassium salt by treating with aqueous potassium iodide and ethanol. The product was recrystallized from water by adding ethanol.

Found: C, 34.16; H, 4.41; N, 6.02%. Calcd for $C_{13}H_{20}N_2O_9KCo$: C, 34.98; H, 4.55; N, 6.28%.

The rotation of this complex in water shows plus sign at Na D line.

Resolution of H[Co(RR- and SS-2,4-ptnta)]·3H₂O A solution containing 1.5 g of H[Co(RR- and SS-2,4-ptnta)]·$3H_2O$ in 25 m*l* of water was stirred with a slight excess of silver oxide, and filtered. The filtrate was added to a suspension containing 1.2 g of $(+)_D$-$[Co(NO_2)_2en_2]Br$[10] in 60 m*l* of water. The mixture was stirred for 20 min, filtered to remove silver bromide, and condensed in a vacuum desiccator over phosphorus pentoxide. When the volume of the filtrate became about 50 m*l*, the first fraction of crystalline diastereomer (0.5 g) was obtained with specific rotation of +887° at Na D line (fraction 1). Recrystallization from water did not increase the rotation. The filtrate was evaporated again to decrease the volume to about 42 m*l*. The second fraction (0.5 g) was obtained with specific rotation of −696° at Na D line (fraction 2). The recrystallized sample from water showed the same specific rotation. By repeating such a fractional crystallization, three more fractions were obtained, but their specific rotations showed smaller absolute values than those of the fractions 1 and 2. Pure diastereomers were further obtained from these three fractions by repeated fractional crystallization from water.

$(+)_D$-*d*-$[Co(NO_2)_2en_2][Co(2,4\text{-ptnta})]\cdot 2H_2O$, $[\alpha]_D=+887°$, Found: C, 28.98; H, 5.36; N, 16.28%. Calcd for $C_{17}H_{38}N_8O_{14}Co_2$: C, 29.32; H, 5.36; N, 16.09%.

$(-)_D$-*d*-$[Co(NO_2)_2en_2][Co(2,4\text{-ptnta})]\cdot 6H_2O$, $[\alpha]_D=-696°$, Found: C, 26.63; H, 5.95; N, 14.71%. Calcd for $C_{17}H_{46}N_8O_{18}Co_2$: C, 26.57; H, 6.03; N, 14.58%.

These diastereomers were converted into potassium salts by the following method. A solution containing 0.67 g of either $(+)_D$- or $(-)_D$-isomer in 15 m*l* of water was treated with 0.53 g of potassium iodide, warmed at 70°C for 10 min, kept at 0°C for 2 hr and filtered to remove the precipitated $(+)_D$-$[Co(NO)_2en_2]I$. Addition of ethanol to the filtrate gave violet crystals (0.37 g), which were recrystallized from aqueous solution by adding ethanol.

$(+)_D$-$[Co(2,4\text{-ptnta})]\cdot H_2O$, $[\alpha]_D=+1446°$, Found; C, 34.40; H, 4.55; N, 6.31%.

$(-)_D$-$[Co(2,4\text{-ptnta})]\cdot H_2O$, $[\alpha]_D=-1420°$, Found: C, 34.61; H, 4.53; N, 6.27%. Calcd for $C_{13}H_{20}N_2O_9KCo$: C, 34.98; H, 4.55; N, 6.28%.

H[CoCl(RS-2,4-ptntaH)]: Barium salt of *meso*-2,4-ptnta was similarly converted into $H_42,4$-ptnta. When an aqueous solution containing 7 g of this *meso*-$H_42,4$-ptnta and 8 g of $Na_3[Co(NO_2)_6]$ was warmed at 60°C for 3 hr, a reddish brown solution was obtained. This was treated with dilute hydrochloric acid at 60°C for 30 min to give a blue solution. This was evaporated almost to dryness in a vacuum desiccator over potassium hydroxide. The residue was dissolved in a small amount of water and passed through a column containing the anion exchanger Dowex 1-X4 in chloride form. The column was washed with water and the adsorbed blue band was eluted with 0.1 N hydrochloric acid. The eluate was condensed in a vacuum desiccator over potassium hydroxide and treated with ethanol. Blue crystals were precipitated on cooling, filtered off, washed with ethanol, air dried and recrystallized from 0.1 N hydrochloric acid by adding ethanol.

Found: C, 36.35; H, 5.58; N, 6.55%. Calcd for $C_{13}H_{19}N_2O_8ClCo$: C, 36.59; H, 4.72; N, 6.57%.

When the reddish brown solution was submitted to the anion exchange and then treated with 0.1 N hydrochloric acid *in situ*, the brown band changed the color into blue with evolution of bubbles and eluted. The same blue crystals were obtained on a similar treatment of the eluate.

K[CoCl(RS-2,4-ptntaH)]: H[CoCl(RS-2,4-ptntaH)] was dissolved in a small amount of 0.1 N hydrochloric acid and an excess of potassium acetate was added. Blue crystals obtained on adding ethanol to the solution were filtered off, washed with ethanol, air dried and recrystallized from 0.1 N hydrochloric acid by adding ethanol.

Found: C, 33.35; H, 4.07; N, 6.06%. Calcd for $C_{13}H_{19}N_2O_8ClKCo$: C, 33.59; H, 4.12: N, 6.03%.

Elemental analysis and the pH measurement of the aqueous solution suggest that the product is in the given form with free acetic acid branch.

Measurements. Visible and ultraviolet absorption spec-

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9) E. Billman, *Z. Anal. Chem.*, **39**, 284 (1900).

10) *Inorganic Syntheses*, **6**, 194 (1960).

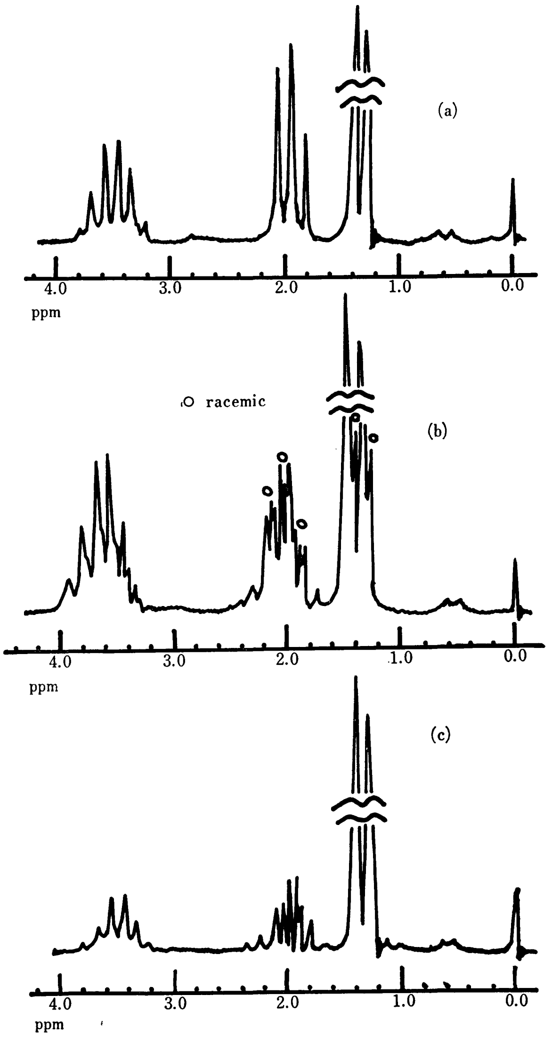

Fig. 4. PMR spectra of (a) racemic 2,4-ptn·2HCl, (b) mixture of racemic- and *meso*-2,4-ptn·2HCl, (c) *meso*-2,4-ptn·2HCl, in D_2O (60 MHz).

tra were recorded with a Hitachi 124 recording spectrophotometer. The CD curves were recorded with a Model ORD/UV-5 spectrophotometer of Japan Spectroscopic Co. with its CD attachment. PMR spectra were obtained with a Varian T-60 spectrometer using Na-TMS as an internal standard. Infrared spectra were recorded with a Hitachi EPI-2G spectrophotometer. All the measurements were made at room temperature.

Table 1. Numerical data of absorption (AB) and circular dichroism (CD) $\tilde{\nu}$ in 10^3 cm^{-1}, (log ε) and (ε_l-ε_r)

Complex	AB	CD
$(+)_D$-Δ-K[Co(RR-2,4-ptnat)]·H_2O	18.02(2.09)	17.04(−2.19) 18.94(+2.02)
	26.18(2.00)	24.55(−0.70) 32.26(+0.13)
	43.86(4.38)	40.32(−6.38) 44.44(+8.30)
$(-)_{546}$-Δ-Na[Co(trdta)]·$3H_2O$[a]	18.20(2.12)	17.00(+1.91) 19.00(−2.41)
	26.40(2.06)	24.60(+0.69)
$(-)_{546}$-Δ-K[Co(edta)]·$2H_2O$[a]	18.60(2.54)	17.10(+1.50) 19.80(−0.69) 23.80(+0.28)
	26.65(2.39)	25.60(−0.09) 27.60(+0.29)
K[CoCl(RS-2,4-ptntaH)]	17.24(2.16)	
	25.71(2.21)	
	42.55(4.30)	
K_2[CoCl(edta)][b]	17.09(2.38)	
	24.83(2.43)	
	41.50(4.27)	

a) Ref. 1)
b) J. Fujita and Y. Shimura, This Bulletin, **36**, 1281 (1963).

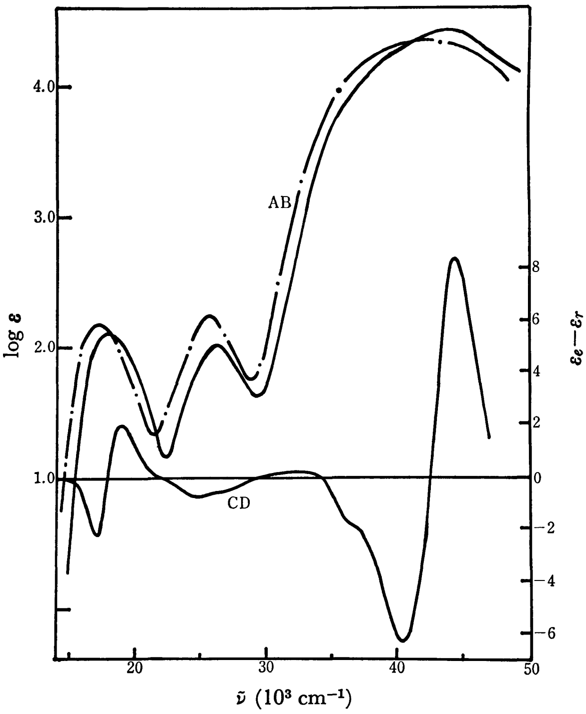

Fig. 5. Absorption (AB) and circular dichroism (CD) spectra of (+)D-K[Co(RR-2,4-ptnta)]·H_2O in H_2O (——), and AB spectrum of H[CoCl(RS-2,4-ptntaH)] in dil. HCl (—·—·).

Results and Discussion

Structure of the Complexes

As Fig. 5 and Table 1 show, the absorption spectrum of [Co(RR- and SS-2,4-ptnta)]$^-$ is very similar to that of [Co(trdta)]$^-$ [1,2], in which the trdta^{4-} coordinates to the cobalt(III) ion as a sexadentate ligand. The infrared spectrum of H[Co(RR- and SS-2,4-ptnta)]·$3H_2O$ exhibits no absorption of free carboxylate. It is thus clear that the complex contains sexadentate ligand (RR- or SS-ptnta^{4-}) with twist form of the six-membered chelate as stated previously. Studies with molecular models made it clear that both RR- and SS-2,4-ptnta^{4-} could form two possible configurational isomers, Δ and Λ-complex. The orientation of both methyl groups of the Δ complex of RR-2,4-ptnta^{4-} is equatorial to the six-membered ring (λ twist), while that of its Λ complex is axial to the chelate ring (δ twist) (Table 2). However, the existence of the diastereoisomer with the axial methyl groups has not been known so far in such chelate complexes. Thus, the complex which was prepared from racemic 2,4-ptnta^{4-} consists most likely of only a racemic pair, Δ-[Co(RR-2,4-

TABLE 2. CONFORMATIONS OF DIAMINE PART IN 2,4-PENTANEDIAMINETETRAACETATES

Ligand	Conformation		
	chair	δ-twist	λ-twist
RR-2,4-ptnta^{4-}	a,e	a,a	e,e
SS-2,4-ptnta^{4-}	a,e	e,e	a,a
RS-2,4-ptnta^{4-}	a,a e,e	a,e	a,e

e: methyl equatorial, a: methyl axial

ptnta)]$^-$ and Δ-[Co(SS-2,4-ptnta)]$^-$. Fig. 5 shows the CD spectrum of $(+)_D$-[Co(2,4-ptnta)]$^-$ in water. This isomer gives a CD pattern very similar to that of Δ-[Co(trdta)]$^-$ in the region of the first absorption band (18000 cm^{-1})[1,2]. It seems that the $(+)_D$-isomer has Δ-configuration and the 2,4-ptnta^{4-} ligand must have RR-configuration. The reaction of $Na_3[Co(NO_2)_6]$ with 2,4-ptnta^{4-} which was prepared from $(-)_D$-2,4-pentanediamine produced only $(+)_D$-Δ-[Co(2,4-ptnta)]$^-$ under the given condition. These results indicate that the complex formation between the cobalt(III) ion and the optically active ptnta^{4-} is stereospecific. It is also clear that the absolute configuration of the carbon atoms of the $(-)_D$-2,4-pentanediamine could be assigned to RR.

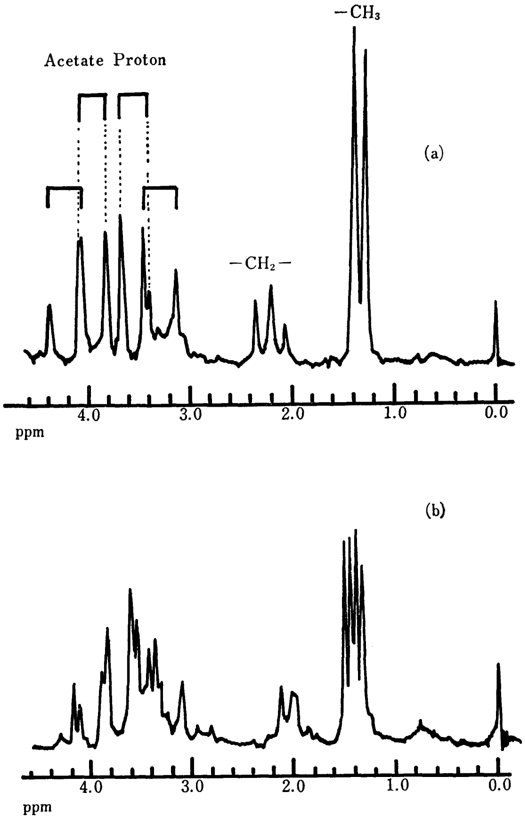

Fig. 6. PMR spectra of (a) [Co(RR- and SS-2,4-ptnta)]$^-$ (D_2O), (b) [CoCl(RS-2,4-ptntaH)]$^-$ (DCl-D_2O), (60 MHz).

The PMR spectrum of the [Co(RR- and SS-2,4-ptnta)]$^-$ in deuterium oxide provides useful information. The spectrum exhibits only one methyl signal and two kinds of acetate methylene signal. (Fig. 6). In this figure is given a tentative assignment for the observed signals.[2] The complex ion, [Co(RR- and SS-2,4-ptnta)]$^-$ has a two-fold axis through the cobalt ion and the β-carbon atom of the six-membered ring, and therefore, the two methyl groups are in an equivalent environment.

The complex, [CoCl(RS-2,4-ptntaH)]$^-$ on the other hand, is considered to involve a quinquedentate ligand. Its infrared absorption spectrum at about 1600 cm^{-1} is much broader than that of the violet complex with sexadentate RR- or SS-2,4-ptnta^{4-}. The free carboxylate absorption may overlap the strong band due to the coordinated carboxyl stretching vibration.

Figure 5 compares the visible and ultraviolet absorption spectra of the quinquedentate and the violet sexadentate complex. The first absorption band of the former complex shows at lower wave number than that of the latter complex. This is in good accord with the spectrochemical series,[11] indicating that the chloride ion coordinates to the cobalt(III) ion in the meso-2,4-ptnta complex.

The PMR spectrum of the chloro complex will also support the quinquedentate coordination of RS-ptnta^{4-}. As Fig. 6 shows, the [CoCl(RS-2,4-ptntaH)]$^-$ in DCl-D_2O gives two kinds of methyl signal, and the signals of acetate methylenes are much more complicated than those of the violet sexadentate complex with racemic or optically active 2,4-ptnta^{4-}. Such a quinquedentate coordination of the meso ligand may be caused by a steric requirement due to the methyl groups on the six-membered ring as stated previously. Molecular models indicate that so far as the methyl groups orientate equatorially to the chelate ring, the six-membered ring should take the chair form and only three out of four acetate branches seem to be allowed to coordinate to the cobalt(III) ion. Figure 2 illustrates this structure schematically. Its structure has no symmetry element and gives a racemic pair which depends on the coordination of either of the two out-of-plane acetate branches. Attempts for optical resolution of this pair have been unsuccessful so far.

Such a stereospecific formation of sexa- and quinquedentate complex from racemic and meso ptnta^{4-} clearly indicates that the steric regulation coming from the methyl group on the α-carbon atom is very strong in the six-membered rings as well as in the five-membered rings

We wish to thank the Ministry of Education for the financial support granted to this research.

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[11] Y. Shimura and R. Tsuchida, This Bulletin, **29**, 311 (1956).