

# CONFORMATIONAL ASPECTS OF CHELATE RINGS

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## I. INTRODUCTION

This review concerns a survey of conformational studies which have been made of metal chelate rings. Evidence for nonplanar arrangements of the atoms in five-, six-, and more-membered chelate rings, and the problems of the conformations of substituent groups on atoms in the ring will be considered. Literature is covered up through September 1963.

Five-membered chelate rings such as occur in trisethylenediaminecobalt(III) often possess great stability; racemization of the optical antipodes is slow even at 100°. Until comparatively recently it was generally assumed that five-membered chelate rings were planar, despite the deviations from planarity of other five-membered rings such as the *d*-ribose ring in cytidine (37) and the thiazolidine ring (17) in penicillin and cyclopentane and its derivatives (30b). Present evidence shows that conformational considerations may be applied to these five-membered and larger chelate rings. The implications of conformational orientation on problems of thermodynamic stability, ligand field strengths, kinetics of ring formation or breaking, or ligand exchange open new fields in the study of coordination compounds.

The conformational analysis of organic molecules has led to striking advances in our insight into organic systems. The possibilities of isomerism through restricted rotation about a single bond have been clear for some years. Many cases are now known where a conformational interaction dictates the structure

adopted by a molecule. For example, 1,2-dithiocyanatoethane adopts the *trans* conformation in the solid state; this has been shown by X-ray analysis (34) and by infrared spectroscopy (100). Ethylenediamine dihydrochloride was assigned the *trans* conformation in the solid state on the basis of its infrared spectrum (96) although the corresponding sulfate was shown by X-ray analysis (108) to adopt the *gauche* conformation, the azimuthal angle being 75.7°.

The conformations of bidentate ligands, when they form a five-membered ring, have recently been elucidated by conformational analysis (15), and evidence has accumulated that the *gauche* form of the chelate ring is favored.

It is the purpose of this review to summarize the available evidence for the conformations of chelate rings and to show that a good deal of chemical information about complex molecules may be rationalized by conformational considerations. Nearly all the physical evidence relates to chelate rings formed by diamines, though other chelating systems are discussed where appropriate.

## II. SINGLE CHELATE RING

### A. CONFORMATIONAL ANALYSIS

The first suggestion that the five-membered rings formed by ethylenediamine need not be planar appeared (105) in 1933. The four possibilities considered for the bisethylenediamineplatinum(II) cation were: Figure 1a, completely planar; Figure 1b, chair form;

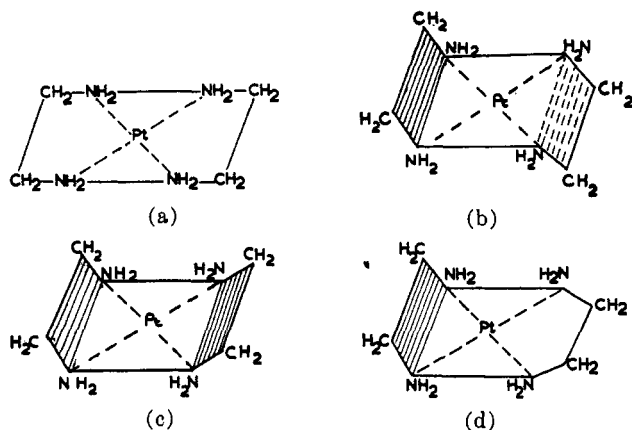


Figure 1.

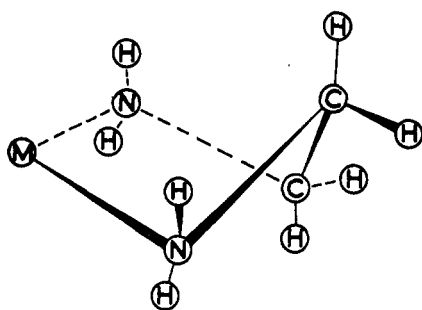


Figure 2.

Figure 1c, trough form; and Figure 1d, an angular form. Shortly afterwards, Theilacker (128) pointed out, from models, that the chelate rings themselves could well be puckered, avoiding the eclipsed conformation of the hydrogen atoms, as shown in Figure 2.

The concept of the puckered chelate ring was taken up by Mathieu (78), who discussed the structure shown by Figure 3 for bis(cyclopentanediamine)platinum(II) cation. Jaeger had previously pointed out (59), that for the molecule to contain two parallel cyclopentane rings, the two diamine molecules coordinated to one platinum atom had to be enantiomeric. Using a method superficially resembling that later used by Corey and Bailar, Mathieu (78) calculated nonbonded interactions of the methyl groups in tris-(+)-propylenediaminecobalt(III) cation and, by using the correct configuration of the D complex, arrived at the correct absolute configuration for (+)-propylenediamine.

Corey and Bailar applied (15) the novel methods of conformational analysis to chelated ethylenediamine. Assuming bond lengths M-N 2.00 Å., N-C 1.47 Å., and C-C 1.54 Å. and bond angles MNC = NCC =

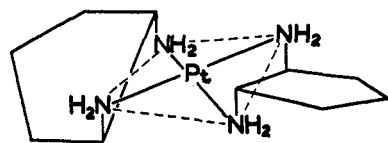


Figure 3.

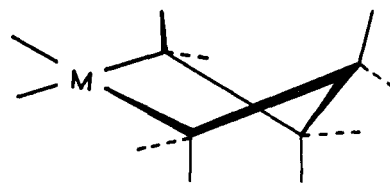


Figure 4.

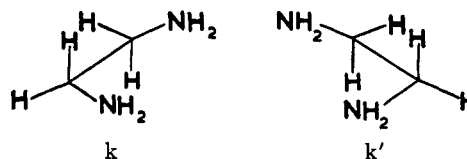


Figure 5.

109.5°, the conformation of a single chelated ethylenediamine molecule was shown to be as in Figure 4. The N-M-N angle was calculated at 86.2°, and the ring is puckered such that the azimuthal angle ( $\theta$ ) between the bonds from metal to nitrogen, viewed along the C-C bond, is 48.8° (for a planar ring, this angle is 0°). The agreement with the values found (84) for trisethylenediaminecobalt(III) cation by X-ray analysis is excellent [C-C, 1.54 Å.; C-N, 1.47 Å.; C-N, 1.47 Å.; Co-N, 2.00 Å.; CoNC, 109.5°; NCC, 109.6°; NCoN, 87.4°;  $\theta$ , 48°].

A consequence of the preferred *gauche* conformation of the chelated ethylenediamine molecule is that such a molecule has two enantiomeric forms, denoted *k* and *k'*, as shown in Figure 5. This consequence of the *gauche* conformation of a symmetrically disubstituted ethane had been realized (64) much earlier and was again pointed out in an infrared spectral study (100) of the shape of the chelate rings formed by sulfur ligands. However, to date, no evidence of stabilization of a single chelated ethylenediamine molecule in one enantiomeric conformation has been obtained. A careful examination (119) of the behavior of tetraammineethylenediaminecobalt(III) cation with optically active anions gave no indication of resolution, nor, when Rochelle salt was added to the cobalt compound, did the d-d transitions of the complex cation become optically active. This "configurational activation" had been used previously (63) to demonstrate the possibility of stabilizing one enantiomer of ethylenediaminetetraacetatocuprate(II) with (-)-quinine.

#### B. AXIAL AND EQUATORIAL SUBSTITUENTS

The most obvious consequence of the puckered nature of a single chelate ring is that substituents may be either axial or equatorial. In common with purely organic systems, it is in general true that an axial substituent is less favored than the equatorial analog.

A most striking consequence of this inequality of the two possible isomers is that, for metal complexes of (+)-propylenediaminetetraacetic acid, (+)-H<sub>4</sub>PDTA, only one isomer is possible (25) with the methyl group

TABLE I  
STABILITY CONSTANTS OF COMPLEXES OF ISOMERIC DIAMINES

	H <sub>2</sub> L pK <sub>1</sub>	HL pK <sub>2</sub>	Cu <sup>2+</sup>		Ni <sup>2+</sup>		
			log K <sub>1</sub>	log K <sub>2</sub>	log K <sub>1</sub>	log K <sub>2</sub>	log K <sub>3</sub>
<i>dl</i> -2,3-Diaminobutane <sup>a</sup>	6.91	10.00	11.39	9.82	7.71	6.48	4.31
<i>meso</i> -2,3-Diaminobutane <sup>a</sup>	6.92	9.97	10.72	9.34	7.04	5.70	2.89
<i>dl</i> -Stilbenediamine <sup>b</sup>	3.95	8.09	10.07	9.11	7.37	6.09	4.38
<i>meso</i> -Stilbenediamine <sup>b</sup>	4.78	7.85	8.46	7.50	4.70	3.52	—

<sup>a</sup> Ref. 7. <sup>b</sup> Ref. 6.

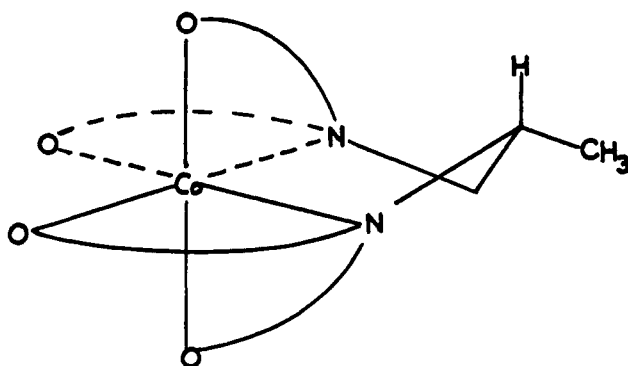


Figure 6.

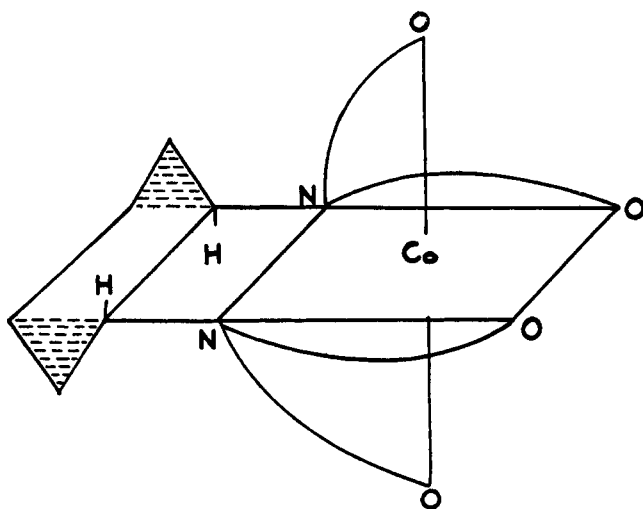


Figure 7.

equatorial. Only the L form of the cobalt(III) complex, L(-)<sub>546.1</sub>[Co(+)-PDTA]<sup>-</sup>, was isolable; this is shown in Figure 6. The stereospecificity appears to be complete (14). The absolute configuration of the complex is known because that of the ligand follows from the relationship (103) of (-)-propylenediamine to (+)-alanine. By comparison of the circular dichroism spectra of the complexes of cobalt(III) with (+)-PDTA and EDTA, the absolute configuration of (-)<sub>546.1</sub>[Co(EDTA)]<sup>-</sup> has been established (38). In a similar way, only one isomer of the *trans*-(-)-cyclohexane-1,2-diaminetetraacetatocobaltate(III) anion is stable (25). In this case, only the isomer D(+)-[Co(-)-CHXTA]<sup>-</sup> has both the C-N bonds from the cyclohexane ring equatorial, as in Figure 7.

TABLE II

STABILITY CONSTANTS OF COMPLEXES OF ISOMERIC 1,2-DIMETHYLETHYLENEDIAMINETETRAACETIC ACIDS

Ligand	Log KML			
	Ca <sup>2+</sup>	Sr <sup>2+</sup>	Ba <sup>2+</sup>	Mg <sup>2+</sup>
<i>dl</i> -DIMEDTA <sup>a</sup>	9.09	7.10	5.92	8.35
<i>meso</i> -DIMEDTA <sup>a</sup>	8.96	7.01	5.86	8.30

<sup>a</sup> DIMEDTA is 1,2-dimethylethylenediaminetetraacetic acid.

Similar examples are available for complexes of PDTA in which the ligand is quinquedentate only; these are (+)-K[Co(+)-HPDTC]Cl, (-)-[Cr(-)-PDTA](H<sub>2</sub>O)], and (-)-Ba[Rh(-)-PDTA](H<sub>2</sub>O)]<sub>2</sub>; the last may be kept at 96° for 6 hr. with no racemization (25). The use of ligands such as PDTA, where the conformational requirement of substituents on chelate rings dictate the configuration for any metal complex formed, gives a method (10) of rendering labile ions asymmetric.

Thermodynamic data are generally lacking in the conformational field, but a few examples are available of isomeric ligands which form complexes of differing stability because of a difference between equatorial or axial substituents. For the 2,3-diaminobutanes, the results (7) shown in Table I were obtained; results involving more than one chelate ring per metal atom are also given. Results available (6) for the isomeric stilbenediamines are also given in Table I. An extension (57) to the isomeric 2,3-butanediaminetetraacetic acids is shown in Table II. In all cases, the lower stability of the complex formed by the *meso* ligand is probably due to the conformationally unstable axial methyl group, or other large groups, since in the more stable complexes of the racemic ligands, there are no large groups in axial positions, as shown in Figure 8. In the preparative field, this destabilization of compounds by large axial groups in chelate rings is reflected by the ready synthesis (4) of the tris(*dl*-stilbenediamine)cobalt(III) cation; the highest complex ob-

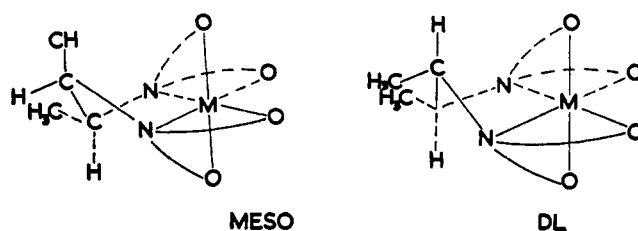


Figure 8.

TABLE III  
STABILITY CONSTANTS OF COMPLEXES OF  
ISOMERIC 1,2-DIAMINOCYCLOHEXANES

Metal	<i>trans</i> -1,2- Diaminocyclohexane			<i>cis</i> -1,2- Diaminocyclohexane		
	log $K_1$	log $K_2$	log $K_3$	log $K_1$	log $K_2$	log $K_3$
H <sup>+</sup>	6.72 <sup>a</sup>	9.89 <sup>b</sup>	—	6.41 <sup>a</sup>	9.99 <sup>b</sup>	—
Co <sup>2+</sup>	6.37	5.37	3.48	5.79	4.55	2.84
Ni <sup>2+</sup>	7.99	6.99	5.09	7.41	6.13	2.94
Cu <sup>2+</sup>	11.13	9.80	—	10.87	9.67	—
Zn <sup>2+</sup>	6.37	5.61	—	6.08	5.49	—
Cd <sup>2+</sup>	5.80	4.71	—	5.78	4.71	—

<sup>a</sup> p $K_1$ . <sup>b</sup> p $K_2$ .

tainable from the *meso* ligand contained only two molecules of diamine per cobalt atom, and even the bis-*meso*-diamine complex was prepared in far smaller yield than the bis-*dl*-diamine complex.

A very similar rationalization may be applied to the stability constant data available (114) for the isomeric 1,2-diaminocyclohexanes as ligands; they are collected in Table III. The first explanation offered (53, 73) for the formation of the more stable compounds by the *trans* ligand was that the *trans*-diamine could form complexes while the cyclohexane ring was in the chair form, whereas the *cis*-diamine had to adopt the unstable boat conformation before it could form complexes. In fact, the energy difference represented by the difference in stability constants is much lower than typical values for chair-boat isomerizations, and the N-N distances in the *cis*- and *trans*-diamines each in chair form are, of course, the same. It is probable that both diamines have the cyclohexane ring in the chair form, but that necessarily, while the amino groups in the *trans*-diamine are equatorial, one of the amino groups in the *cis*-diamine must be axial.

The effect of changing the ring size in saturated cyclic ligands on chelate stabilities has not received much attention; *trans*-1,2-cycloheptanediamine forms (9) less stable complexes with nickel, zinc, or cadmium than does *trans*-1,2-cyclohexanediamine. The reason for this is not yet clear, and further information is necessary before the influence of conformations in cyclic diamines can be rationalized.

The results of some studies of the kinetics of certain reactions may be explained by the idea that increasing

conformational instability increases the rate of nucleophilic substitution; results (93) for the aquation at pH 1 and the replacement (94) of chloride by thiocyanate in aqueous methanol in some *trans*-dichlorobisdiaminecobalt(III) cations are given in Table IV.

While little work has appeared which is directly concerned with complex compounds formed by oxygen ligands, conformational effects in chelate rings formed by diols are clear in a number of physicochemical studies. Cuprammonium solutions are well known (116) to dissolve cellulose and to form complexes with many hydroxylated compounds. The large values for the optical rotatory power for the resultant solutions (67) are attributed to the formation of asymmetric five-membered chelate rings. The chemistry underlying these effects is not altogether clear, but the complex formed from diols and cupriethylenediamine cations is known (118) to contain one chelated diol per copper atom. The same kind of conformational effects are found as with diamine compounds; the lower stability of complexes where large axial substituents are present on the chelate rings is exemplified by the observation (102) that D-(or L-) 2,3-butanediol affects the conductance of a cuprammonium solution much more than does *meso*-2,3-butanediol. The conformational instability of a six-membered ring is shown by the absence of complexing with trimethylenediol.

Although the most striking effects of conformation on stabilities of chelated compounds involve transition metals, similar effects are found in several cases where diols form chelate rings with nonmetals. (–)-Butane-2,3-diol forms (13, 20) a much more stable complex with periodate than does the *meso*-diol. This is due to the fact that the chelate ring formed by the *meso*-diol has an axial methyl group, whereas in the case of the *levo*-diol, both methyl groups are equatorial. In view of the cyclic transition states (30) which occur in glycol oxidations, many other observations on relative rates of oxidations of this kind can be interpreted in terms of the relative conformational stabilities of the intermediate cyclic states.

A large amount of scattered information is available for complexes of diols with borate systems. For example, the equilibrium constants (110) for complex

TABLE IV  
KINETIC DATA FOR *trans*-DICHLOROBISDIAMINECOBALT(III) CATIONS  
(Diamines were of the type NH<sub>2</sub>CVX·CYZ·NH<sub>2</sub>)

Compound	V	X	Y	Z	Aquation	[SCN] <sup>-</sup>	SCN <sup>-</sup> attack
					$k \times 10^4$ , min. <sup>-1</sup> ; 15°		$k \times 10^4$ , min. <sup>-1</sup> ; 25°
1	H	H	H	H	0.46	0.08	3.6
2	CH <sub>2</sub>	H	H	H	0.84	0.10	3.9
3 ( <i>dl</i> )	CH <sub>2</sub>	H	CH <sub>2</sub>	H	2.1	0.10	8.1
4 ( <i>meso</i> )	CH <sub>2</sub>	H	CH <sub>2</sub>	H	82.0	0.20	88.0
5	CH <sub>2</sub>	CH <sub>2</sub>	H	H	30.0	—	—
6	CH <sub>2</sub>	CH <sub>2</sub>	CH <sub>2</sub>	CH <sub>2</sub>	Instant. <sup>a</sup>	0.01	Instant.

<sup>a</sup> At 10°.

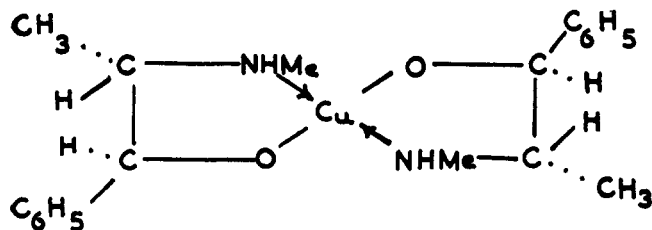


Figure 9.

formation by the isomeric 2,3-butanediols are 1.18 for the *meso* isomer and 8.41 for the *dl* isomer. The axially substituted chelate ring formed by the *meso*-diol is less stable than the equatorially substituted ring from the *dl*-diol; this is also clear from a preparative study by Dale (19), who has started the task of systematizing complex formation between diols and borates (18, 52) in terms of the conformation of the cyclic compounds obtained. Much of the earlier work on the subject is of dubious value, since it appears not to have been commonly realized that the species present in borate solutions vary with pH. However, a good deal of information can be interpreted qualitatively. For example, a major factor contributing to the separation by paper ionophoresis of diols (36) and sugars (35) in borate buffers is the stability of the chelated compound formed, which is in turn controlled by the conformation of substituents.

Just as the stabilities of the chelate rings formed from diamines and diols are controlled by the conformation of substituents, so are those of amino alcohols. A particularly elegant use of this was in deriving information on the conformations of certain alkaloids by examining (32) the relative stabilities of their copper compounds. The chelate rings in the complex of  $\psi$ -ephedrine with copper(II) are stable, all substituents being equatorial, as shown in Figure 9. By contrast, the complex from ephedrine is very much less stable, readily decomposing in the presence of a little water because of the presence of axial substituents. When a 1:1 mixture of ( $\pm$ )- $\psi$ -ephedrine and ( $\pm$ )-ephedrine was treated with sufficient copper acetate to form a compound with only one isomer, the complex of  $\psi$ -ephedrine was isolated in 87% yield. This was advanced as a useful route to the separation of diastereoisomeric 2-amino alcohols. Similar observations were made on the 2-amino-1- $\beta$ -nitrophenylpropane-1,3-diols. Alkaloids with tertiary amine groups are also capable of chelation; a copper compound was obtained from ( $\pm$ )-*N*-methylephedrine. In a similar study of the conformation of cinchona bases, it was found (33) that stable copper chelates were obtainable from epiquinine and epiquinidine, whereas no chelates were obtained from quinine, quinidine, cinchonine, or cinchonidine. This provides extremely good evidence that the *threo* configuration assigned (129) to the epibases on other grounds is correct.

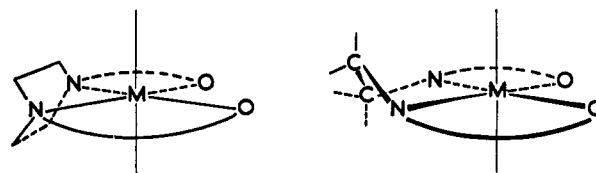


Figure 10.

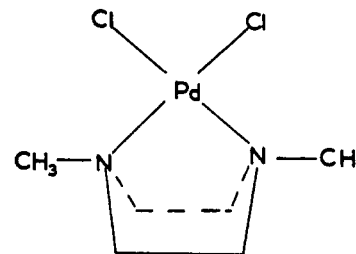


Figure 11.

C. *cis*-CHELATE RINGS

A further consequence of the puckering of the chelate ring in the most thermodynamically favored case is that *cis* conformations about the C-C bond in diamine chelate rings are uncommon. However, in certain cases, they must exist. For example, in any compound containing piperazine (or a similar 1,4-diheterocyclohexane) acting as a bidentate ligand, when it must adopt the boat conformation, there are two chelate rings for each piperazine, each of which necessarily has a *cis* conformation about the C-C bond.

Cyclic diamines which are constrained to adopt the boat form for chelation form less stable complexes than the corresponding straight-chain diamines. The stability constants (115) for the complexes of silver with both piperazine and triethylenediamine are considerably lower than those for straight-chain diamines. Similarly, in order to form *N,N'* chelate rings, piperazine-*N,N'*-diacetic acid (PIPDA) must adopt the boat conformation. Ethylenediaminediacetic acid (EDDA) can form unstrained *gauche* chelate rings, as shown in Figure 10. The stability constants (56) for some metals are given in Table V.

Preparatively, it has repeatedly been found that chelated complexes of piperazine are not easily formed. Piperazine (P) itself gives a palladium complex of the type  $Pd^{2+}$ , presumably chelated. 1,4-Dimethylpiperazine (MP) forms (72) complexes of the type (MP)- $MX_2$ , where M = Pd and Pt, and X = Cl or Br. No

TABLE V  
STABILITY CONSTANTS FOR COMPLEXES OF  
DIAMINE-*N,N'*-DIACETIC ACIDS

Acid	Log $K_{MY}$			
	Mg <sup>2+</sup>	Zn <sup>2+</sup>	Cu <sup>2+</sup>	Ni <sup>2+</sup>
PIPDA	1.5	5.6	8.25	6.0
EDDA	3.9	11.1	16.2	13.5

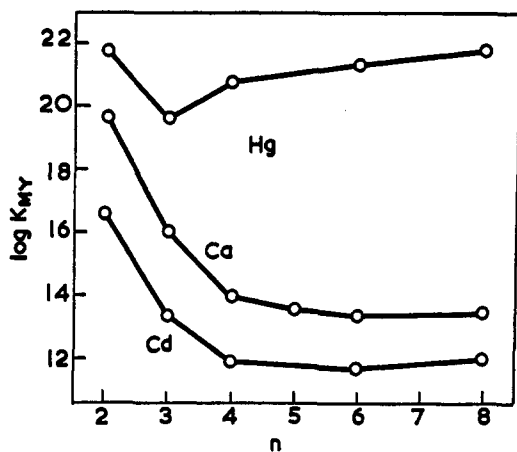


Figure 12.

chelated compounds could be made with cobalt, rhodium, nickel, copper, or cadmium. The complex of palladium chloride has been shown (47) by X-ray analysis to contain the ligand molecules in the boat form required for bidentate chelation, as in Figure 11. Infrared spectral evidence had previously shown that the usual chair form of 1,4-dimethylpiperazine is no longer present in the compound of palladium, which has a much more complicated spectrum.

The more heavily substituted the carbon atoms in piperazine, the less ready the product is to adopt the boat form, because of the increasing size of axial groups, and therefore, to form *cis* chelate rings. 1,2,2,4,5,5-Hexamethylpiperazine (71b) readily gave salts with 2 equiv. of alkyl halides but did not cyclize with ethylene dibromide, which does cause cyclization of the chelating ligand 1,4-dimethylpiperazine. Analogs of piperazine containing other group V elements have been studied preparatively, but no chelated compounds are known; the product, for example, from the system (71a) palladium bromide-1,4-diphenyl-1,4-azaphosphine (L) was  $L_2PdBr_2$ .

Other 1,4-diheterocyclohexanes which could form chelated compounds, which would necessarily contain five-membered rings with the *cis* conformation, are dioxane and its analogs. However, only one compound of dioxane appears to contain boat-form molecules (*i.e.*, chelate rings with the *cis* conformation). This is the red 1:1 adduct (104) with titanium tetrabromide, with which monoethers form 2:1 adducts. The C-O-C ring-stretching frequency is absent from the infrared spectrum of the adduct of dioxane, indicating that both oxygen atoms coordinate, and the compound is monomeric in dioxane solution. Although addition compounds of dioxane with transition metal halides with the formula  $MX_2 \cdot \text{dioxane}$  have been described (62), nothing is known of their structures. It is probably relevant that both infrared (125) and X-ray studies (46) show the presence of chair-form dioxane molecules in  $HgCl_2 \cdot C_4H_8O_2$  and  $HgBr_2 \cdot C_4H_8O_2$  (infrared).

1,4-Dithiane does form compounds (11) of stoichiometry indicating possible *cis* chelation, *e.g.*,  $CuX_2 \cdot C_4H_8S_2$ , but nothing is known of the structures. The case of 1,4-diselenane has been examined recently by infrared spectroscopy (49); the only cases where the spectrum is significantly different from that of the free ligand are  $(C_4H_8Se_2)PdCl_2$  and  $(C_4H_8Se_2)PtCl_2$ , which may therefore, like the analogous 1,4-dimethylpiperazine compound of palladium, contain chelate rings with the *cis* conformation.

It is abundantly clear that the *cis* conformation for chelated ligands is extremely rare and not likely to occur except under exceptional circumstances. The only suggestion of *cis* chelate rings occurring in complexes of acyclic diamines was based on the infrared spectra of a series of compounds of ethylenediamine, when it was suggested (97) that two types of conformation of the chelate rings (*cis* and *gauche*) were distinguishable. The suggestion was later withdrawn (99) since it did not agree with X-ray structural results.

#### D. SIZE OF CHELATE RING

From conformational analysis of diamine chelate rings, Corey and Bailar conclude that a six-membered ring of this type is conformationally less stable than a five-membered ring, which provides an explanation of the well-known fall (58) in stability constants on increasing the size of the chelate ring from five to six members. The same fall in stability from five- to six-membered rings has been noted preparatively for other chelating systems, such as dithiols and their S-ethers (126). Certain exceptions to this generalization are known, involving cations which form linear bonds most easily. For the stability constants (115) of silver complexes with diamines  $H_2N(CH_2)_nNH_2$ , the effect of increasing the value of  $n$  is shown in Table VI. The

TABLE VI

STABILITY CONSTANTS FOR $NH_2(CH_2)_nNH_2$ WITH SILVER IONS				
$n$	2	3	4	5
Log $K_{Ag-diamine}$	4.77	5.85	5.90	5.95

increase of formation constant with  $n$  may well be due to the increasing possibility of the silver ion being able to form linear sp-hybridized bonds. Schwarzenbach (113) studied diaminetetracarboxylic acids of the type  $(HO_2CCH_2)_2N(CH_2)_nN(CH_2CO_2H)_2$  which give rise to N-N chelate rings with  $(n + 3)$  members. The results are shown graphically in Figure 12.

These results appear to be due to the ease with which the mercuric ion forms linear bonds; the acids giving rise to large rings ( $n \geq 4$ ) can span linear positions without conformational strain. The octahedrally bonding calcium ions show a decrease in stability with increasing N,N' chelate ring size, owing to the buckling necessary to bring the nitrogen atoms into *cis* positions. The preference of the mercuric ion for linear bonds is

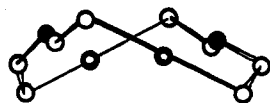


Figure 13.—“Mercury diethylene oxide”: ●, mercury; ○, oxygen; ○, carbon.

rather well exemplified by the compound (109) “mercury diethylene oxide,” which has been shown by X-ray diffraction (42) to be a dimer, based on a twelve-membered ring, as shown in Figure 13.

The positional isomers of cyclohexanediaminetetraacetic acids were examined by Schwarzenbach and Ackermann, who found (112) the values given in Table VII for the stability constants. The 1,2-acid

TABLE VII  
STABILITY CONSTANTS FOR COMPLEXES OF  
CYCLOHEXANEDIAMINETETRAACETIC ACIDS

Metal	Log $K_{MY}$		
	1,2 <sup>a</sup>	1,3	1,4
Ca <sup>2+</sup>	12.5	4.77	4.19
Mg <sup>2+</sup>	10.3	4.64	4.30

<sup>a</sup> The numbers refer to the relative positions of the substituents on the cyclohexane rings.

can chelate with the nitrogen atoms in the diequatorial position, forming a five-membered *gauche* chelate ring; the 1,3-acid can only form a six-membered N,N' chelate ring in a very strained conformation; and the 1,4-acid can chelate only in the boat conformation, forming a seven-membered ring.

### III. TWO OR MORE RINGS

#### A. CONFORMATIONAL ANALYSIS

It was early realized that there are two possible forms of the bisethylenediamineplatinum(II) cation, shown in Figure 14. The *meso* form (A) has a center of symmetry and should give rise to fewer infrared-active fundamentals than the *dl* form (B), which has no center of symmetry. Both infrared and Raman spectra were interpreted (77) to indicate that the compound is in the *meso* form (A).

A more recent treatment of this problem in terms of the conformation of the chelate rings, led to the conclusion that there are three possibilities: the enantiomeric (and energetically equivalent) *kk* and *k'k'* forms, and a *kk'* form, as shown in Figure 15. The *kk* form is, of course, the *dl* form (B) of Figure 14, and the *kk'*

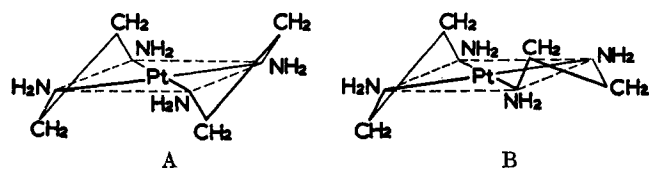


Figure 14.

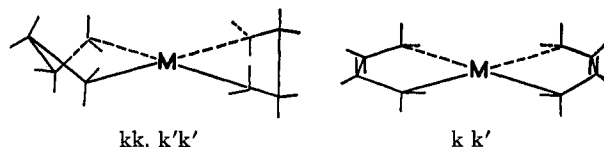


Figure 15.

form is the *meso* form (A). The only significant differences between the *kk* and *kk'* forms are the hydrogen-hydrogen interactions between the two rings (effectively between the NH<sub>2</sub> groups). The hydrogen-hydrogen potential function of Mason and Kreevoy (75) was used to calculate the energy difference  $E_{kk'} - E_{kk}$  as about 1 kcal./mole, implying that the *kk* form should predominate at room temperatures to the extent of about 85%.

It seems likely that the *kk* and the *kk'* forms may well give rise to different ligand field strengths in the plane; this could have marked consequences in equilibrium between planar and octahedral complexes with weak interaction along the *z*-axis. It has not previously been suggested that the phenomena associated with “Lifschitz salts” could be explained by just such an energy difference between conformational isomers. The only available structure is that (88) for blue Ni(*meso*-stien)<sub>2</sub>(H<sub>2</sub>O)<sub>2</sub>(Cl<sub>2</sub>CH·COO)<sub>2</sub>, which does not give details of the chelate rings. The small change in ligand field strength with temperature, observed (48) as the cause of the thermochromism in bis(N,N-diethylethylenediamine)copper(II) perchlorate, has been tentatively explained as due to changing conformations of the chelate ring, which would give changes of ligand field of the right order.

For an octahedral trisethylenediamine complex, with a given configuration at the metal, four forms are possible: *kkk*, *k'kk*, *k'k'k*, and *k'k'k'* (corresponding for an optically active diamine to *ddd*, *ldd*, *lld*, and *lll*, or the mirror images, depending on the configuration at the metal). A calculation based on the hydrogen-hydrogen potential of Mason and Kreevoy led to the conclusion that  $E_{k'k'k'} - E_{kkk} \approx 1.8$  kcal./mole. The two types of complex *kkk* and *k'k'k'* were designated “*lel*” and “*ob*”; the C–C bonds in the stable “*lel*” form are roughly parallel to the short trigonal axis, whereas in the “*ob*” form, the C–C bonds are oblique to this axis, as shown in Figure 16.

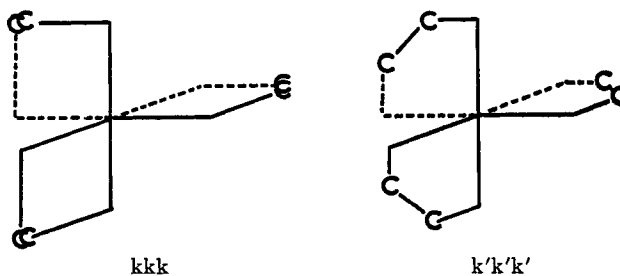
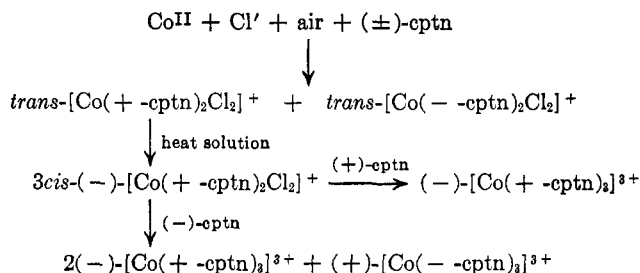


Figure 16.

## B. STEREOSPECIFICITY

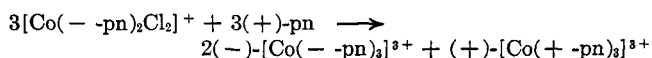
Stereospecific effects in the formation of complexes of optically active diamines with metals, notably cobalt(III), have been recognized for many years. An explanation of the principal features (given in section IIIA) has been obtained by means of conformational analysis, which accords well with the physical evidence available (given in section IV). Most of the early observers on stereospecific coordination of optically active ligands were able to detect only the major products. The early work is briefly summarized, while more recent work is reviewed in greater detail.

When racemic *trans*-cyclopentanediamine forms (60) complexes with cobalt(III), in the presence of chloride ion, the isolable products are the *trans*-bis complexes with either two (-) or two (+)-diamine ligands. No mixed product was obtained. Further, on heating the solution of the *trans*-dichlorobis-(+)-diamine compound, the complex (-)-*cis*-dichlorobis-(+)-diaminecobalt(III) cation is formed, which reacted with a further mole of the (+)-base to give the tris complex. If (-)-base is added to the bis-(+)-base complex, a mixture of the "all (+)" and "all (-)" tris complexes was obtained; *cptn* represents *trans*-1,2-cyclopentanediamine in the summary of these results given below.



Similar results were obtained using rhodium(III). Subsequently, *trans*-1,2-cyclohexanediamine was also shown (61) to exert similar stereospecificity. It should be mentioned that Ferrone (31) was able to obtain what appeared to be *D*<sup>+++</sup> and *L*<sup>+++</sup> isomers of the tris-(+)-stilbenediaminecobalt(III) cation by the reaction of *trans*-[Co(+stien)<sub>2</sub>Cl<sub>2</sub>]<sup>+</sup> with (+)-stilbenediamine. He also made the *D*<sup>---</sup> and *L*<sup>---</sup> isomers; no quantitative information is available. A more extensive study of the ligand would be valuable.

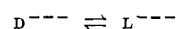
The diamine most commonly used in stereospecific work has been propylenediamine (1,2-diaminopropane, *pn*). From the reaction of cobalt chloride with (±)-propylenediamine, Smirnov (120) was able to isolate only two cations: (+)-[Co(-*pn*)<sub>3</sub>]<sup>3+</sup> and (-)-[Co(+*pn*)<sub>3</sub>]<sup>3+</sup>. The following reaction has also been reported (127) and checked (3) more recently. The



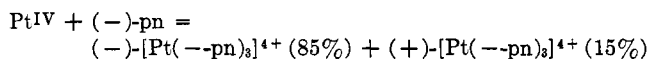
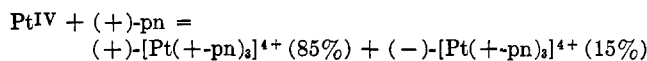
suggestion was made that the results could be accounted for by assuming the disproportionation of an unstable

intermediate "mixed" trisdiamine. Dwyer (26) objected to a similar scheme for compounds of rhodium on the ground that they are in general too robust. He pointed out that, although complex compounds of cobalt(III) are also robust, labile cobalt(II) intermediates are possibly responsible for equilibration.

Dwyer and his school (26) recently performed some careful experiments on allegedly stereospecific reactions and obtained more isomers than had previous workers. Trispropylenediaminecobalt(III) iodide has been obtained as a mixture of the *L*<sup>---</sup>, *D*<sup>---</sup>, *D*<sup>+++</sup>, and *L*<sup>+++</sup> forms,<sup>1</sup> and the reaction



using a charcoal catalyst, has been shown to have an equilibrium constant  $K = 5.75$ , whence  $F^\circ = -1.02 \pm 0.05$  kcal./mole. This is of the right order for conversion for the *kkk* form to a less conformationally stable form. It is probably relevant that (+)-tris-ethylenediaminecobalt(III) cation racemizes very rapidly in the presence of charcoal, suggesting labile cobalt(II) species as intermediates in this equilibration. Dwyer pointed out that preparative difficulties among cobalt(III) complexes may be due to seven or eight coordinated intermediates, and the presence of labile cobalt(II) compounds. These difficulties are not present in complexes of platinum. The reactions of (+)- or (-)-propylenediamine with chloroplatinic acid have been studied (24) recently. The pairs of



isomers were separated by fractional crystallization of the sparingly soluble oxalates. Again, the proportions of the stable and unstable isomers formed imply a value for their energy of interconversion of about the order expected for a (*kkk*) → (*k'k'k'*) change.

When less than three molecules of the optically active diamine are present in the complex molecule, the stereospecific effects, while still marked, are not so spectacular, as might be expected from the lower energy difference between *cis*-*kk* and *cis*-*kk'* forms.

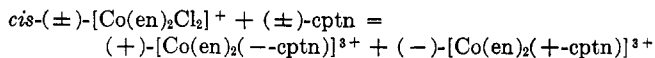
Both (+) and (-) forms of carbonatobis(-)-propylenediaminecobalt(III) salts are known (2); they are interconvertible, and, on standing, a solution of either at room temperature gives (1) an equilibrium mixture. However, in view of the participation of the aquated form [Co(A)<sub>4</sub>(HCO<sub>3</sub>)(OH)] in reactions of other carbonatotetraminecobalt(III) species, the nature of this isomerism is not entirely sure. The corresponding oxalato complex has recently been resolved (27), the

(1) *L* and *D* refer to configuration at the cobalt, and + or - to the sign of rotation of the *pn*. No ambiguity arises from the use of *L* and *D*, because the *D* complex in this case has the same configuration as the known *D*(+)-[Co(en)<sub>3</sub>]<sup>3+</sup>.

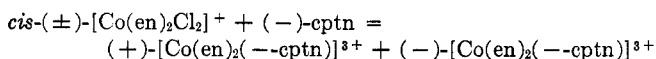


+ [(-)(-)] isomer predominating over the (-)[- -].

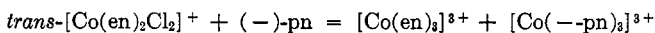
A considerable effort has been devoted to attempts at making isomers such as D(+ + -)-trisdiaminecobalt(III) cation. Ferrone (31) obtained D- and L-[Co(+stien)<sub>2</sub>(-stien)]Cl<sub>3</sub> by allowing (-)-stilbenediamine to react with *trans*-dichlorobis-(+)-stilbenediaminecobalt(III) ion. However, in view of the apparently easy rearrangements of such mixed tris diamine complexes of cobalt(III), this and other work on mixed trisdiamines is dubious. For example, the reactions



and



have been reported (60). However, doubt has been cast on this work by the finding (27) that in water, methanol, or dimethylformamide



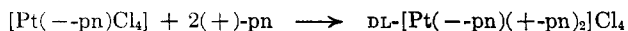
Although no "mixed" trisdiamines were then detected, a more refined technique (23) gave the results shown in Table VIII. The similar reactions described as forming bisethylenediaminepropylenediaminecobalt(III) cation (95) and bisethylenediamine-*trans*-1,2-cyclopentanediaminecobalt(III) cation (60) also need re-examination.

TABLE VIII

COMPOSITION OF "MIXED" TRISDIAMINE SPECIES

	Product %			
	From [Co(en) <sub>2</sub> - Cl <sub>2</sub> ]Cl	From [Co(en) <sub>2</sub> - (NO <sub>2</sub> ) <sub>2</sub> ]Cl	Direct synthesis	
			(-)-pn/ en = 1:2	(-)-pn/ en = 2:1
(-)-[Co(en) <sub>2</sub> (-pn)]	27	28	27	15
(-)-[Co(en)(-pn) <sub>2</sub> ]	10	17	18	37
(-)-[Co(-pn) <sub>3</sub> ]	13	4	6	30
(+)-[Co(en) <sub>2</sub> (-pn)]	17.5	15.5	13	7
(+)-[Co(en)(-pn) <sub>2</sub> ]	1	3.5	3	5
(+)-[Co(-pn) <sub>3</sub> ]	1	1	1	2
(±)-[Co(en) <sub>3</sub> ]	31	31	32	4

The sole case in which trisdiamine complexes have undoubtedly been prepared containing both (+)- and (-)-diamine molecules coordinated to the same metal atom is for platinum(IV). In particular, the reaction (29)



was performed. The optical isomers were separated by fractional crystallization of the tartrates and showed no evidence of disproportionation or racemization in boiling aqueous solution. Unfortunately, no thermodynamic data are available for these isomers, or for their more usual analogs (28), such as [Pt(+pn)<sub>3</sub>]<sup>4+</sup>.

A most useful corollary of the higher stability of the (kkk) form is that, given the absolute configuration of the optically active diamine, the configuration of the

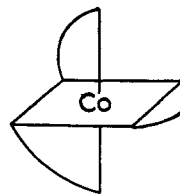


Figure 17.

more stable (kkk) form of a trisdiamine metal complex follows. The configuration of (+)-propylenediamine is known from its relation (103) to L-alanine, and the configuration thereby determined (15) for the stable isomer of tris-(+)-propylenediaminecobalt(III) cation is shown in Figure 17. This most stable isomer is found experimentally (26) to be (+)-[Co(+pn)<sub>3</sub>]<sup>3+</sup>, which shows Cotton effects (78) (in both circular dichroism and rotatory dispersion) exactly parallel with those of (+)-[Co(en)<sub>3</sub>]<sup>3+</sup>, already known from X-ray studies (85) to possess the absolute configuration shown in Figure 17. In the same way, the most stable isomer of tris(-)-propylenediaminerhodium(III) cation (which has the configuration enantiomorphous with that shown in Figure 17) has been found recently (21) to show a negative circular dichroism band at 315 mμ. Since (-)-[Rh(en)<sub>3</sub>]<sup>3+</sup> shows a positive circular dichroism for the corresponding transition (<sup>1</sup>E<sub>a</sub> ← <sup>1</sup>A<sub>1</sub>), it has the configuration shown in Figure 17. It is possible in this way to deduce configurations for analogous complexes of cobalt(III) and rhodium(III). The method is capable of extension to complexes of other metals such as chromium(III). From work of this kind, the other criteria (such as rotatory dispersion and the method of least soluble diastereoisomers) available for assignments of configuration to trisdiamine complexes of cobalt(III), rhodium(III), iridium(III), chromium(III), and platinum(IV) have been rationalized. It has been shown (22) from this method of stereospecific induction of configuration at a metal atom by optically active diamines that the complexes having the absolute configuration of Figure 17 are (+)-[Co(en)<sub>3</sub>]<sup>3+</sup>, (-)-[Rh(en)<sub>3</sub>]<sup>3+</sup>, (-)-[Ir(en)<sub>3</sub>]<sup>3+</sup>, (+)-[Cr(en)<sub>3</sub>]<sup>3+</sup>, and (+)-[Pt(en)<sub>3</sub>]<sup>3+</sup>.

A further consequence of the interplay of ligand configuration with that of the complex as a whole is that, knowing the absolute configuration of the complex ion, that of the ligand may be deduced; this has been done (15) for *trans*-1,2-cyclopentanediamine; unfortunately, the conclusion was based on comparison of signs of rotation of (+)-[Co(en)<sub>3</sub>]<sup>3+</sup> and (+)-[Co(-cptn)<sub>3</sub>]<sup>3+</sup> at the sodium D-line. More recently, the optical rotatory dispersion curves of the pairs of complexes, (a) *trans*-(+)-[Co(+pn)<sub>2</sub>Cl<sub>2</sub>]<sup>+</sup> and *trans*-(+)-[Co(+cptn)<sub>2</sub>Cl<sub>2</sub>]<sup>+</sup> (b) (+)-[Co(+pn)<sub>3</sub>]<sup>3+</sup> and (-)-[Co(+cptn)<sub>3</sub>]<sup>3+</sup>, have been shown (22) to correspond exactly, so that the true relative configurations are (+)-pn ≡ (+)-cptn. The configuration of (+)-

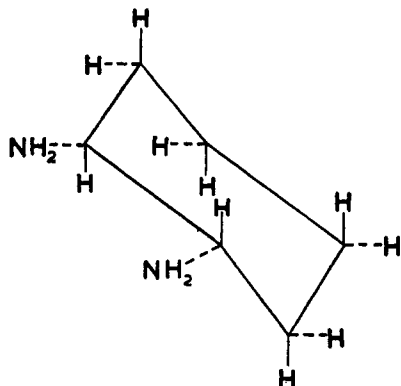
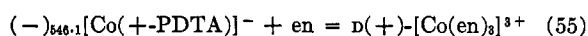
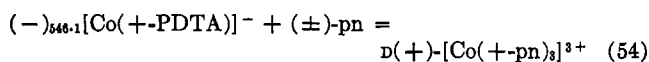
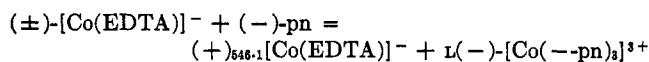
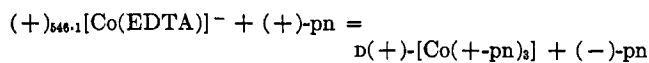
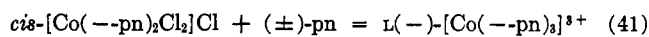


Figure 18.

*trans*-1,2-cyclohexanediamine has been deduced (40) in a similar way and is shown in Figure 18.

Stereospecific reactions of optically active complexes with optically active ligands are well known. Examples are



Although kinetic studies on the last reaction have been performed (14), the conformational implications of the transition states are not clear.

#### IV. PHYSICAL EVIDENCE FOR CONFORMATIONS OF CHELATE RINGS

##### A. SPECTROSCOPIC EVIDENCE

The most obvious correlation to be associated with the conformation of a ring system is the variation in infrared stretching frequencies between axial and equatorial substituents. In a brief study (39) of C-H stretching frequencies in complexes of ethylenediamine, no reliable correlation could be established; for example, while *D*(+)-trisethylenediaminecobalt(III) chloride showed only two bands at 3040 and 2930  $\text{cm}^{-1}$ , *D*- and *L*-dinitrobisethylenediaminecobalt(III) bromide showed three absorptions, at 2988, 2962, and 2890  $\text{cm}^{-1}$ .

In view of the higher symmetry of the *trans* conformation of a disubstituted ethane than the *cis* or *gauche* conformation, the number of infrared active fundamentals expected for each conformational isomer differs. This has been the basis of a number of investigations; oddly enough, more positive evidence is available for S-S chelate rings than N-N. 1,2-Dithiocyanatoethane exists in both *trans* and *gauche* forms in the vapor and liquid states, but only in the *trans* conformation in the solid. By comparison with the

spectrum of these states as standards, the S-S chelate ring in dichloro(1,2-dithiocyanatoethane)platinum(II) was shown (100) to contain a *gauche* chelate ring. In a similar way, the chelated compounds formed by ethylenedithiol-S,S'-dimethyl ether with palladium, platinum, copper, nickel, cadmium, and mercury,  $\text{MCl}_2(\text{CH}_3\text{-S-CH}_2\text{CH}_2\text{-S-CH}_3)$ , were also shown (123) to contain *gauche* chelate rings. The infrared spectrum of ethane-1,2-dithiol shows (132) that the molecules in the solid have the *trans* conformation; the liquid is an equilibrium mixture of *trans* and *gauche* forms. Similar work has established (79) the *gauche* conformation of free and chelated succinonitrile.

Infrared evidence on complexes of ethylenediamine has so far been inconclusive; despite the large number of papers discussing the spectra, the only isotopic substitution so far carried out has been the deuteration of the amino groups. The problem is not easy; one set of compounds led (97) to a fortuitous separation into two types of spectra, thought to correspond to differing conformations of the chelate ring. This criterion was soon withdrawn (99). From an extensive study (5) of complexes of cobalt(III), the *gauche* conformation of the chelate rings was thought likely, as in another examination (80) of salts of the *cis*- and *trans*-dichlorobisethylenediaminecobalt(III), *cis*- and *trans*-dinitrobisethylenediaminecobalt(III), and trisethylenediaminecobalt(III) cations, where the low-frequency rocking mode of the *cis* conformation of the diamine expected at 740  $\text{cm}^{-1}$  was not observed.

The most valuable result to accrue from such infrared studies is the realization that ethylenediamine molecules functioning as bridging groups adopt the *trans* conformation, with a very individual infrared spectrum. Molecules containing bridging ethylenediamine can, in a way, be regarded as disubstituted ethanes; compounds so far studied are  $\text{M}(\text{en})\text{Cl}_2$  ( $\text{M} = \text{Zn}, \text{Cd}, \text{and Hg}$ ), probably containing polymeric chains (86),  $(\text{HgCl}_2)\text{en}$  (89),  $(\text{C}_2\text{H}_4)\text{PtCl}_2 \cdot \text{en} \cdot \text{PtCl}_2(\text{C}_2\text{H}_4)$  (98), and  $\text{ClAg} \cdot \text{en} \cdot \text{AgCl}$  (87); on the other hand,  $[\text{Ag}(\text{en})_2][\text{PtCl}_4]$  is thought to contain two *gauche* ethylenediamine molecules bridging the two silver ions.

Nuclear magnetic resonance spectra (97) at 40 Mc./sec. revealed little of value; the chief conclusion was that the chelate rings are effectively *cis* through rapid inversion. Recent work (at 56.43 Mc./sec.) substantiates this conclusion; evidence of fine structure was obtained for several complexes of cobalt(III); however, the only compounds giving sharp lines were those of ethylenediaminetetraacetic acid, where the conformation of the chelate rings is fixed (39).

##### B. X-RAY DIFFRACTION

Several studies have been made of *trans*-dihalobisethylenediaminecobalt(III) cations; these are summarized in Table IX. The chelate rings are all *gauche*, and sub-

TABLE IX  
STRUCTURAL DATA FOR COMPOUNDS OF THE TYPE  $trans-[M(AA)_2X_2](H_5O_2)Cl_2$

Compound	Conformation of diamine	Relation of rings	Position of substituents	Ref.
$trans-[Co(en)_2Cl_2](H_5O_2)Cl_2$	<i>gauche</i>	kk'	—	81
$trans-[Co(en)_2Br_2](H_5O_2)Br_2$	<i>gauche</i>	kk'	—	91
$trans-[Co(en)_2Cl_2](H_5O_2)Cl_2$	<i>gauche</i>	kk'	—	90
$trans-[Co(-pn)_2Cl_2](H_5O_2)Cl_2$	<i>gauche</i>	kk	Equatorial	106
$trans-[Co(+pn)(-pn)Cl_2](H_5O_2)Cl_2$	<i>gauche</i>	kk'	Equatorial	66
$trans-[Co(en)_2Cl_2]Cl$	<i>gauche</i>	kk'	—	8

stituents, where present, are equatorial. The analogous compounds of rhodium(III),  $trans-[Rh(en)_2Cl_2](H_5O_2)Cl_2$  and  $trans-[Rh(en)_2Br_2](H_5O_2)Br_2$ , have recently been prepared; their infrared spectra (40a) are extremely similar to those of the corresponding compounds of cobalt(III), and they presumably also contain *gauche* chelate rings. Deviations from the predicted kk form have been explained as due to packing considerations or to hydrogen bonding in the crystal. A distinction arises here between bisethylenediamine compounds, where the kk' form predominates (in addition to the compounds in Table IX, it was pointed out (76) that, on the basis of the center of symmetry found (16) by X-ray methods for bisethylenediamineplatinum(II), that cation had the *meso*-(kk') configuration), and the bis active diamine compounds, where the kk form predominates.

Several other bisethylenediamine cations have been examined, notably those of copper(II) and nickel(II). The compound of copper(II) has been studied both as the tetrathiocyanatomercurate(II), when the chelate rings were said (117) to be nonplanar, and as the nitrate when the chelate rings were found (65) to be *gauche*.

A two-dimensional analysis of nitrobisethylenediaminenickel(II) perchlorate, mainly concerned with the coordination number of the nickel, showed (70) that both chelate rings were *gauche*. The crystal structure of bisthiocyanatobisethylenediaminenickel(II) shows (12) that the chelate rings are *gauche*; the perpendicular separation of the carbon atoms above and below the  $MN_2$  plane is 0.68 Å. The corresponding distance in tetraaquoethylenediaminenickel(II) nitrate (122), with only one chelate ring, is 0.72 Å. The values for trisethylenediaminenickel(II) nitrate (124) and *trans*-dichlorobisethylenediaminecobalt(III) bis-aquohydrogen chloride (81) are 0.56 and 0.68 Å, respectively.

The first example of a trisethylenediamine complex to be studied (130) by X-ray analysis was trisethylenediaminenickel(II) nitrate; the three-dimensional structure analysis of the compound was later completed, when it was found (124) that the only possible structure was that comprising equal amounts of *dlll* and *lddd* forms (*i.e.*, the kkk forms for each band of the metal). The azimuthal angle was found to be  $45.8 \pm 2.0^\circ$  between the planes determined by the C-C and C-N

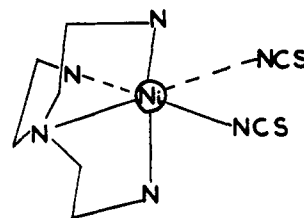


Figure 19.

bonds. The major effort in this direction has been expended on the trisethylenediaminecobalt(III) cation, which has been examined in a variety of environments. In every case, the kkk form is found. Structural data are collected in Table X.

TABLE X  
STRUCTURAL DATA ON  
TRISETHYLENEDIAMINECOBALT(III) CATION

Compound	Chelate conformation	3 ring relationship	Notes	Ref.
$dL-[Co(en)_3]Cl_3 \cdot 3H_2O$	<i>gauche</i>	kkk		83
$2D-[Co(en)_3]Cl_3 \cdot NaCl \cdot 6H_2O$	<i>gauche</i>	kkk	<sup>a</sup>	84
$2D-[Co(en)_3]Br_3 \cdot H_2O$	<i>gauche</i>	kkk		82

<sup>a</sup> A later paper (85) contains the same data with absolute configuration added.

The determination of absolute configuration of (+)- $[Co(en)_3]^{3+}$ , in (+)- $[Co(en)_3]Cl_3 \cdot NaCl \cdot 6H_2O$  (85, 107) and (+)- $[Co(en)_3]Br_3 \cdot H_2O$  (82), has given a reference point for configurational correlations among the Werner complexes, but a good deal of other information is desirable in this field. Since optical methods for deducing absolute configuration depend on knowing at least the optic axis of the crystalline complex, the only method independent of direct X-ray analysis is that using the absolute configuration of the ligand, which must itself rest on an X-ray determination. So far, no *cis*-bisdiamine compound has been studied. An interesting *cis* compound of slightly different type is dithiocyanato-N,N-di( $\beta$ -aminoethylethylenediamine)-nickel(II), whose structure (101), containing *gauche* chelate rings, is shown in Figure 19.

The *gauche* diamine chelate ring has also been found in compounds of two other types of ligand, the diamine-tetracarboxylic acids, typified by ethylenediaminetetraacetic acid ( $H_4EDTA$ ), and the tetradentate Schiff bases, typified by bisacetylaceton-N,N'-ethylenedi-

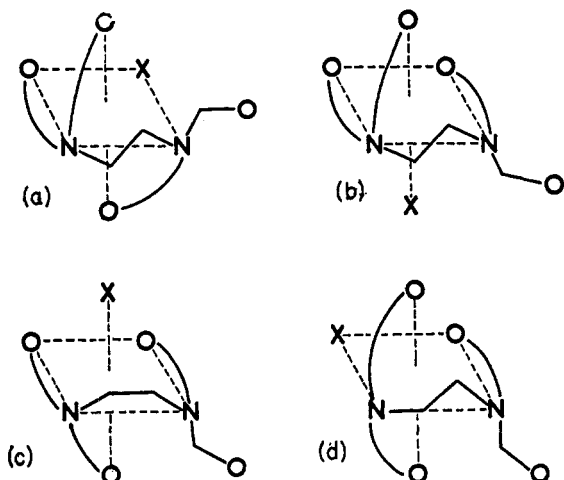


Figure 20. Possible structures for an octahedral complex containing quinquedentate EDTA.

imine. A number of complex compounds of EDTA have been studied by X-ray methods; the compound  $\text{NH}_4[\text{Co}(\text{EDTA})\text{H}_2\text{O}]$  contains (131) sexadentate EDTA; the diamine (N-N) chelate rings are *gauche*, the perpendicular distance between the carbon atoms above and below the  $\text{MN}_2$  plane being 0.58 Å. The infrared spectrum (40a) of the anion is exactly the same (apart from the usual solid-state effect) in the solid and in aqueous solution, suggesting that the conformation of the compound in solution is hardly changed from that in the solid. The compounds  $(\text{NH}_4)[\text{Cr}(\text{EDTA})\text{H}_2\text{O}]$  and  $(\text{NH}_4)[\text{Al}(\text{EDTA})\text{H}_2\text{O}]$  are isostructural (51) with  $(\text{NH}_4)[\text{Co}(\text{EDTA})\text{H}_2\text{O}]$ , and presumably also contain *gauche* N-N chelate rings. This conclusion is reinforced by the observation that  $\text{Rb}[\text{Cr}(\text{EDTA})\text{H}_2\text{O}]$  is isostructural with  $\text{Rb}[\text{Co}(\text{EDTA})\text{H}_2\text{O}]$ . *Gauche* N-N chelate rings are also present (121) in a compound where the ligand is quinquedentate,  $\text{Ni}[\text{H}_2(\text{EDTA})(\text{H}_2\text{O})]$ . The analogous compound of copper(II) is isomorphous. The possible structures for an octahedral complex containing quinquedentate EDTA are shown in Figure 20; the structure found for the compound of nickel(II) was of type (a). The perpendicular C-C distance through the  $\text{MN}_2$  plane was 0.73 Å. More recently, the heptacoordinate compound of iron(III) has been studied (50, 51) in  $\text{Rb}[\text{Fe}(\text{EDTA})(\text{H}_2\text{O})]$ . Despite the long Fe-N bonds the N-N chelate ring is puckered, approximating to a *gauche* conformation.

The compounds of the tetradentate Schiff bases which have been studied are summarized in Table XI. Where the X-ray analysis has been carried through as far as possible, the *gauche* nature of the ethylenediamine rings becomes increasingly obvious. Despite the varied environments of the metal atoms, the diamine rings retain the favored *gauche* conformations. In the one case where the diamine component of the ligand is propylenediamine, the methyl substituent is equatorial.

TABLE XI  
COMPOUNDS OF TETRADENTATE SCHIFF BASES

Compound	N,N' chelate ring	Notes	Ref.
N,N'-Ethylenebis(acetylacetonimine)copper(II)	<i>gauche</i>	—	44
N,N'-Disalicylideneethylenediaminecopper(II)	—	<sup>a</sup>	92
N,N'-Disalicylideneethylenediaminecopper(II)	<i>gauche</i>	—	45
N,N'-Disalicylideneethylenediaminezinc(II) monohydrate	<i>gauche</i>	<sup>b</sup>	43
Chloro-N,N'-disalicylideneethylenediamineiron(III)	—	—	111
N,N'-Disalicylidenepropane-1,2-diaminecopper(II) monohydrate	<i>gauche</i>	<sup>c</sup>	69

<sup>a</sup> Based on packing considerations. <sup>b</sup> The zinc is square-pyramidal. <sup>c</sup> The copper is pentacoordinate, and the methyl group is equatorial.

## V. CONCLUSION

The numerous facets of inorganic chemistry in which the conformations of chelate rings are important have been reviewed above. It is perhaps worthwhile to lay some stress on the use of chelation as a method of deducing relative stereochemistries of isomeric ligands and on the configurational implications for optically active ligands. The quite general puckering of saturated chelate rings needs to be borne in mind in many fields. In particular, it may well be that conformational aspects of biological inorganic chemistry will prove increasingly important; such observations as the greater stability (68) of complexes of zinc, nickel, and copper with D-leucyl-L-tyrosine than with L-leucyl-L-tyrosine may be interpreted on this basis.

Shibata (118a) used (–)-chloroamminebisethylenediaminecobalt(III) bromide as a catalyst in the oxidation by air of the enantiomers of 3,4-dihydroxyphenylalanine, and found that the (–)-amino acid was oxidized more readily than its enantiomer. This and related observations by the same author have been ignored. Work on mechanisms of such stereospecific effects would be extremely interesting.

As was pointed out (74) some years ago, "There is an analogy between the behavior of simple chelates of metals with optically active donors, and behavior of metal-enzyme-substrate structures."

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