and trifluoroacetato complexes in the carboxylate series. Warning has already been issued against use of specific rates alone as criteria for judging the position of attack in reductions involving ligand transfer.[2a] In the same way, caution must be exercised in using reaction rates to choose between the outer- and inner-sphere mechanisms for reduction. Examination of reaction products generally tells a more reliable story, provided that observations are speedy and separation methods are gentle.

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Diastereoisomeric Four-Coordinate Complexes. IV.[1] Zinc(II) Complexes with Three Asymmetric Centers and Ligand Racemization in Bis[N-(alkoxycarbonylalkyl)-salicylaldimino]metal(II) Complexes

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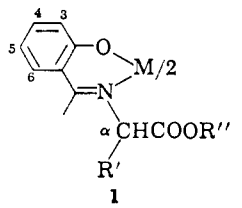
Abstract: An earlier report of the formation of optically inactive bis[N-(alkoxycarbonylalkyl)salicylaldimino]-copper(II) complexes in the reaction of the bis(salicylaldehydo) complex with an optically active amino acid ester has been confirmed and found also to occur in the preparation of Co(II), Pd(II), and Zn(II) complexes. The results of deuterium labeling and exchange experiments, which were followed by proton resonance, have revealed that loss of optical activity proceeds by racemization at the α-carbon of the N-alkoxycarbonylalkyl group and that a previously proposed tautomeric exchange path cannot be significant in the over-all racemization reaction. A transient carbanion intermediate produced by loss of the α-hydrogen is concluded to be the probable intermediate through which racemization proceeds in all cases. The pmr spectrum of optically inactive bis[N-(1-ethoxycarbonylethyl)salicylaldimino]zinc(II) revealed the presence of active and *meso* diastereoisomeric complexes produced in nonstatistical amounts in the racemization reaction. The analogous nickel(II) complex has been prepared for the first time. The two active isomers ((+,+) and (−,−)) of bis[N-(α-phenethyl)salicylaldimino]zinc(II) have been prepared and have been shown to undergo ligand exchange in chloroform to yield the *meso* complex. Pmr studies have demonstrated that the spectra of the active and *meso* forms of this complex are resolvably different and that the *meso* form is somewhat more stable in chloroform solution. Probable conformations of the phenethyl groups in the *meso* and active isomers have been deduced by steric arguments. From a comparison of the pmr spectra of the two forms, it is proposed that the synthesis of the (+,+) or (−,−) form from the active amine is nearly or totally stereospecific with respect to the absolute configuration at the metal (Δ,Λ), the more stable active isomers being $\Delta(-,-)$ and $\Lambda(+,+)$.

Schiff base complexes derived from salicylaldehyde and amino acids and their derivatives are commonly of two structural types, **1** and **2**. Of the tremendous number and variety of salicylaldimine complexes known,[4] these complexes are of particular significance because of a number of reactions undergone by the coordinated ligands, which are well defined in terms of product characterization although not necessarily completely specified mechanistically. The nitrogen substituents in the bis[N-(alkoxycarbonylalkyl)salicylaldimino]metal(II) complexes **1** (R′, R″ = alkyl), originally prepared by Pfeiffer, Offermann, and Werner,[5] may be transesterified,[5-8] amidated,[6] hydrolyzed (to yield **2**),[7] and racemized.[5] The N-(α-substituted acetato)salicylaldiminometal(II) complexes **2** (L = H_2O, py, etc.), and the recently synthesized anionic bischelate metal(III) analogs,[9] are structurally closely related to N-substituted pyridoxylideneamino, hydroxypyridinealdimino, and certain ring-substituted salicylaldimine complexes whose intermediacy in the



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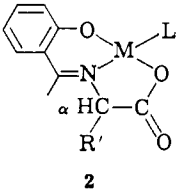

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(2) National Institutes of Health Predoctoral Fellow.
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metal ion catalyzed, nonenzymatic transamination reaction is an essential feature of the proposed reaction sequence leading to transamination.[10]

As part of our current investigations of the transamination and racemization reactions of the complexes **2**[11] and of stereoselective behavior manifested by the diastereoisomers of bis-chelate complexes similar to **1**,[1,12] we have become concerned with the stereochemistry of **1** and the reported extraordinarily facile racemization of several Cu(II) complexes of this type.[5] Racemization occurs at the α carbon and results in an optically inactive mixture of complexes prepared by a reaction involving an active amino acid ester and bis(salicylaldehydato)copper(II) under mild conditions. We have reinvestigated the racemization of **1** in order to ascertain the generality of the reaction with regard to the coordinated metal and structure of the complex, to determine the rate and mechanism of the reaction, and to identify the products. Particular attention has been paid to the possible intervention of the tautomeric bis(*o*-hydroxybenzyliminato) species in the racemization of **1**[5] and stereoselective effects which could result in a nonstatistical formation of diastereoisomers in the racemization process. In addition, a pmr investigation of the diastereoisomers of planar and tetrahedral salicylaldimine complexes carrying optically stable N substituents, the results of which are complementary to the studies of **1** and Ni(II) salicylaldimines,[1,12] has been carried out. The full results of this work are reported herein.

Experimental Section

Preparation of Compounds. (a) Amino Acid Esters. The ethyl esters of glycine, L-alanine, and L-phenylalanine were prepared as hydrochlorides by passing dry, gaseous hydrogen chloride through a stirred suspension of the amino acid in absolute ethanol. Volume reduction afforded white crystalline solids which were recrystallized from ethanol–ether: glycine ethyl ester hydrochloride, mp 145° (lit.[13] 142°); L-alanine ethyl ester hydrochloride, mp 75–77° (lit.[14] 76°); L-phenylalanine ethyl ester hydrochloride, mp 153–155° (lit.[15] 154–156°).

Chloroform or dichloromethane solutions of the free esters were obtained by bubbling dry ammonia through a suspension or solution of the hydrochloride (5 mmoles) in 30–40 ml of solvent. The precipitated ammonium chloride was removed by filtration. When solvent was removed under reduced pressure (0.05 mm), some loss of the glycine and L-alanine esters occurred. Therefore, these two free esters were not isolated but used in solution in the preparation of the salicylaldimine complexes (*vide infra*). The following rotations were observed: L-alanine ethyl ester, $[\alpha]^{25}D$ +5.0° (*c* 2.9, $CHCl_3$); L-phenylalanine ethyl ester, $[\alpha]^{25}D$ +23.8° (*c* 3.2, ethanol) [lit.[16] +22° (ethanol)].

(b) Amines. α-Phenethylamine was resolved into its (+) and (−) enantiomers using (−)-malic acid[17] and (+)-tartaric acid,[18] respectively; $[\alpha]^{25}D$ +40.1° (neat) (lit.[19] +39.9°), $[\alpha]^{25}D$ −40.3° (neat) (lit[18] −40.3°). (+)-Amphetamine was obtained from the Aldrich Chemical Co. and distilled from potassium hydroxide; $[\alpha]^{24}D$ +34.5° (neat) (lit.[19] $[\alpha]^{25}D$ +34.1°).

(c) N-(−)-α-Phenethylsalicylaldimine. This compound was prepared by refluxing a 10 mole % excess of (−)-α-phenethylamine with salicylaldehyde in ethanol. The solid isolated by volume reduction was twice recrystallized from absolute ethanol; mp 75°, $[\alpha]^{25}D$ +189° (*c* 1.06, methanol) (lit.[20] mp 76°, $[\alpha]^{20}D$ +202° (methanol)). ORD and CD spectra of the (−) isomer are given elsewhere.[19,21]

(d) Deuterated Compounds. Ethanol-1-*d* was prepared by a published procedure.[22] 2-Deuterioformylphenol was obtained by a Reimer–Tiemann reaction in D_2O according to Kemp's method.[23] No hydrogen-containing impurity could be detected in the pmr spectrum of either compound.

(e) Salicylaldehyde Complexes. The bis(salicylaldehydato) complexes, $M(sal)_2$, of Co(II), Pd(II), Cu(II), and Zn(II) were prepared according to standard procedures.[24] $Cu(sal)_2$ was purified by two recrystallizations from chloroform. All complexes were used in their anhydrous forms in the preparation of salicylaldimine complexes except for $Zn(sal)_2$, which could not be completely dehydrated by heating at 100° (0.05 mm) over phosphorus pentoxide for 72 hr or by refluxing in dimethoxypropane for 24 hr. It was used in the form of the hydrate isolated from the reaction solution. The bis(2-deuterioformylphenolato)copper(II) and -zinc(II) complexes, $M(d\text{-}sal)_2$, were obtained by the same procedures.

(f) Salicylaldimine Complexes. The bis-N-(alkoxycarbonylalkyl)salicylaldimine complexes (**1**) of Co(II), Pd(II), and Zn(II) were prepared by treating $M(sal)_2$ with the appropriate amino acid ester (2.1:1 mole ratio) in *freshly prepared* chloroform or dichloromethane solutions. After the reaction times specified below, the solutions were filtered, and the filtrates were reduced in volume until the products crystallized. The Cu(II) complexes were prepared similarly but using absolute ethanol as the solvent. Optimum yields were obtained using the following conditions: Zn(II), $CHCl_3$, 50°, 1 hr; Pd(II), CH_2Cl_2, 25°, 5 min; Co(II), $CHCl_3$, 50°, 30 min (all operations were carried out in a nitrogen atmosphere); Cu(II), ethanol, reflux, 30 sec. As previous observations[5] indicated, the corresponding Ni(II) complexes could not be prepared by reaction of $Ni(sal)_2$ with the ethyl esters of alanine and phenylalanine, although the glycine ethyl ester complex can be made in this way.[5] Bis[N-(1-ethoxycarbonylethyl)salicylaldimino]nickel(II) was prepared by means of a nonaqueous chelation reaction described previously.[25] The preparation and recrystallizations were performed in an atmosphere of dry nitrogen. The free Schiff base used in this reaction was obtained by condensation of the ester and salicylaldehyde in chloroform and was purified by vacuum distillation, which resulted in racemization.[26] The N-alkylsalicylaldimine complexes were prepared by reaction of $M(sal)_2$ and the amine in ethanol or chloroform. Solvents from which the complexes were recrystallized are given in footnotes to Table I, in which are listed characterization data for all complexes prepared in this work.

N-(Salicylidene)-(+)-alaninatocopper(II) and -zinc(II) and N-(salicylidene)-(−)-phenylalaninatocopper(II) (**2**, R′ = CH_3, CH_2Ph) were prepared by refluxing a 1.1:1:1 mole ratio of the amino acid, salicylaldehyde, and the appropriate metal acetate in water for 1 hr. The precipitated solids were recrystallized from methanol (Zn) or aqueous dioxane (Cu) and isolated as hydrates.

All bis-N-(alkoxycarbonylalkyl)salicylaldimine complexes prepared as described above gave no observable optical activity in their ORD spectra (250–650 mμ).[27] All N-alkyl and tridentate com-

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(27) The term "inactive" which is used subsequently refers to this behavior. Because none of the complexes 1 has been isolated in a nonracemized form, it is not possible to place an upper limit on the amount of each form which might actually be present but escape detection.

Table I. Characterization of N-R-Salicylaldimine Metal(II) Complexes[a]

	R	M	Mp, °C	Calcd, % C	Calcd, % H	Calcd, % N	Found, % C	Found, % H	Found, % N
A. N-Alkoxycarbonylalkyl complexes (1)	$CH_3CHCOOEt$	Co[b]	145–147	57.72	5.65	5.61	57.30	5.53	5.74
	$CH_3CHCOOEt$	Ni[c,f]	90–95[k]	57.74	5.65	5.61	57.45	5.58	5.76
	$CH_3CHCOOEt$	Pd[c]	169–171	52.71	5.16	5.12	52.05	5.24	5.38
	$CH_3CHCOOEt$	Cu[d]	114–116[g]	57.19	5.60	5.56	57.07	5.60	5.67
	$CH_3CHCOOEt$	Zn[c]	145–146	56.98	5.58	5.54	56.78	5.51	5.49
	$PhCH_2CHCOOEt$	Co[b]	163–165	66.36	5.57	4.30	66.43	5.52	4.36
	$PhCH_2CHCOOEt$	Pd[e]	217–218	61.85	5.19	4.01	62.16	5.19	3.88
	$PhCH_2CHCOOEt$	Cu[d]	121–130[h]	65.89	5.53	4.27	65.88	5.52	4.40
	$PhCH_2CHCOOEt$	Zn[i]	151–154	64.82	6.01	3.98	65.18	6.07	4.06
	CH_2COOEt	Zn[e]	161–163	55.30	5.06	5.86	55.54	5.10	5.92
B. N-*sec*-Alkyl complexes	$PhCHCH_3$	Pd[e,f]	228–229	64.93	5.09	5.05	64.94	5.24	4.93
	$PhCHCH_3$ (+ or −)	Zn[c]	175–176	70.10	5.51	5.45	69.89	5.38	5.47
	$PhCH_2CHCH_3$	Pd[e,f]	215–217	65.92	5.53	4.81	66.33	5.55	4.65
	$PhCH_2CHCH_3$	Zn[c,f]	132–135[j]	70.91	5.95	5.17	70.97	5.87	5.22
	$CH_3OCH_2CHCH_3$	Zn[c,f]	105–108	58.74	6.27	6.23	59.13	6.37	6.14
C. Tridentate complexes (2)	$CH_3CHCOO(\cdot 3H_2O)$	Cu	231–232	38.90	4.90	4.54	38.59	4.66	4.26
	$PhCH_2CHCOO(\cdot H_2O)$	Cu	200–201	55.10	4.33	4.02	54.59	4.38	3.74
	$CH_3CHCOO(\cdot H_2O)$	Zn	>350	43.74	4.04	5.10	43.52	4.01	5.17

[a] All complexes prepared from optically active amines, amino acids, or amino acid esters unless otherwise specified. [b] Recrystallized from toluene–heptane. [c] Recrystallized from chloroform–heptane. [d] Not recrystallized because of decomposition during crystallization. [e] Recrystallized from chloroform–ether. [f] Prepared from racemic amine or N-(alkoxycarbonylalkyl)salicylaldimine. [g] Lit.[7] mp 97°. [h] Lit.[7] mp 129–130°. [i] Prepared in and recrystallized from ethanol: data for monoethanolate. [j] (+,+) isomer, mp 129–131°. [k] Softens but does not melt.

Table II. 60-Mc Proton Chemical Shifts of Ligands, Zn(II), Pd(II), and Ni(II) Complexes[a]

Compound	Solvent	Chemical shift, cps (group)[b]
Salicylaldehyde	CCl_4	652 (OH), 587 (CHO), 430 (ring)
Etala-sal-H	$CDCl_3$	499 (HC=N), 425 (ring), 250 (Et quartet), 246 (α-H quartet), 91 (α-Me doublet), 75 (Et triplet)
Zn(Etgly-sal)$_2$	$CDCl_3$	488 (HC=N), 415 (ring), 263 (α-H), 241 (Et quartet), 67 (Et triplet)
Zn(Etala-sal)$_2$	$CDCl_3$	487 (HC=N), 409 (ring), 243 (α-H quartet); 241, 237[c] (Et quartets); 97,[c] 94 (α-Me doublets); 67, 64[c] (Et triplets)
Zn(EtPhala-sal)$_2$[d]	$CDCl_3$	442 (HC=N), 410 (rings), 239, 236[c] (Et quartets); ~210[e] (CH_2Ph); 65, 61[c] (Et triplets)
Zn(PhEt-sal)$_2$	$CDCl_3$	487 (HC=N), 410 (rings), ~260[e] (α-H); 90 (active), 85 (*meso*) (α-Me doublets[g])
Zn(Amp-sal)$_2$	$CDCl_3$	463 (HC=N), 410 (rings), 214[e] (α-H), 176[e] (CH_2Ph), 71 (α-Me doublet)
Zn($MeOCH_2CHMe$-sal)$_2$	$CDCl_3$	491 (HC=N), 418 (ring), ~205[e] (α-H + CH_2), 192 (OMe), 73 (α-Me doublet)
Zn(ala-sal)·H_2O	CD_3OD	500 (HC=N), 427 (ring), 238 (α-H quartet), 88 (α-Me doublet)
Pd(Etala-sal)$_2$	$CDCl_3$	463 (HC=N), 415 (ring), 288 (α-H quartet), 252 (Et quartet), 102 (α-Me doublet), 76 (Et triplet)
Pd(EtPhala-sal)$_2$	$CDCl_3$	437[f] (HC=N), 405 (rings), 267 (α-H quartet), 251 (Et quartet), 214[e] (CH_2Ph), 74 (Et triplet)
Pd(PhEt-sal)$_2$	$CDCl_3$	448[f] (HC=N), 415 (rings), 359 (α-H quartet), 104 (α-Me doublet)
Pd(Amp-sal)$_2$	$CDCl_3$	446[f] (HC=N), 410 (rings), 305[e] (α-H), 175[e] (CH_2Ph), 81 (α-Me doublet)
Ni(Etala-sal)$_2$[h]	$CDCl_3$	+269, +337, (3-H); −1613, −1705 (4-H); −389 (5-H), −639, −655 (6-H); −34, −85 (Me)

[a] Data refer to diastereoisomeric mixture of complexes where appropriate. [b] Ring shifts refer to approximate center of gravity of multiple signal intensities; all $J_{HH} = 7 \pm 1$ cps; centers of multiplets given. [c] More intense component of the doubled signal. [d] α-H resonance obscured by overlapping signals. [e] Approximate center of unresolved multiplet. [f] Assignment uncertain due to overlap with ring proton signals. [g] Shifts at 111° (*cf.* Figure 5). [h] Paramagnetic; + and − signs refer to signals at higher and lower fields than that of TMS (unsigned shifts in this table refer as usual to shifts at lower field than TMS).

plexes were optically active and molar rotation data are given in the following section.

ORD Spectra. Measurements were made on a Cary Model 60 spectrometer using 0.1-dm cells at 25°. Spectra of the (+,+) and (−,−) isomers[28] of bis[N-(α-phenethyl)salicylaldimino]zinc(II) are shown in Figure 4. The corresponding Co(II), Ni(II), and Cu(II) complexes prepared from the active amine are also optically active and their partial or complete ORD spectra are given elsewhere.[1,29] In the data which follow [M] = [α](mol wt)/100.

Bis[N-(α-(−)-phenethyl)salicylaldimino]zinc(II) in Chloroform. (*c* 0.898): $[M]_{589}$ +958; (*c* 0.0121): $[M]_{450}$ +5090, $[M]_{400}$ +30,600, $[M]_{370}$ −47,600, $[M]_{355}$ −8500, $[M]_{290}$ −22,900.

N-(Salicylidene)-(+)-alaninatocopper(II) in Dioxane. (*c* 0.345): $[M]_{650}$ +104, $[M]_{610}$ +66, $[M]_{589}$ +90, $[M]_{510}$ +751; (*c* 0.0143): $[M]_{383}$ −4190, $[M]_{347}$ +5150, $[M]_{300}$ +1860.

N-(Salicylidene)-(−)-phenylalaninatocopper(II) in Dioxane. (*c* 0.245): $[M]_{650}$ −726, $[M]_{589}$ −1210, $[M]_{570}$ −1256, $[M]_{550}$ −1250; (*c* 0.0123): $[M]_{395}$ −18,200, $[M]_{335}$ +24,600, $[M]_{295}$ +14,900, $[M]_{265}$ +20,400.

N-(Salicylidene)-(+)-alaninatozinc(II) in Methanol. (*c* 0.248): $[M]_{589}$ −157; (*c* 0.014): $[M]_{450}$ −1110, $[M]_{385}$ −3510, $[M]_{335}$ +3420, $[M]_{308}$ +2680, $[M]_{300}$ +1080, $[M]_{280}$ −1010.

Molecular Weights. Measurements were made with a Mechrolab Model 302 osmometer at 37° using dry toluene as the solvent. The following results were obtained: bis[N-(α-(+)-phenethyl)salicylaldimino]zinc(II), 436 (12.99 m*m*), 450 (9.76 m*m*), 405 (2.61 m*m*) (calcd 513); bis[N-(1-ethoxycarbonylethyl)salicylaldimino]zinc(II), 498 (5.25 m*m*), 438 (2.30 m*m*), 457 (1.21 m*m*) (calcd 505); bis[N-(1-ethoxycarbonylethyl)salicylaldimino]nickel(II), 521 (1.54 m*m*) (calcd 499). The low results in the first two cases are apparently due to a small amount of decomposition despite the use of dried solvent.

Other Physical Measurements. Electronic spectra were obtained on a Cary Model 14 spectrometer. Optical rotations were measured with the Cary Model 60 ORD spectrometer or with a Perkin-Elmer Model 141 spectropolarimeter. Proton resonance spectra were recorded on a Varian A-60 or A-60A spectrometer using tetramethylsilane as an internal reference. Infrared spectra were measured with a Perkin-Elmer Model 337 grating instrument.

Deuterium Labeling and Exchange Studies. Relevant proton chemical shift data are given in Table II. Cu(*d*-sal)$_2$ (5 mmoles) was allowed to react with L-alanine or L-phenylalanine ethyl ester in

(28) The + and − designations refer to the sign of $[\alpha]_D$ for the free amine, amino acid, or amino acid ester from which the complex is derived and are used to indicate the same or opposite absolute configurations at the two asymmetric ligand centers in a given complex. This notation has been used previously.[1,12,25]

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30 ml of refluxing absolute ethanol for 30 sec. The resultant dark green solution was quickly filtered and the complex crystallized from the filtrate on cooling. Each was dried *in vacuo* and then decomposed with 25 ml of 5 *M* sulfuric acid to liberate salicylaldehyde. This solution was twice extracted with 25 ml of carbon tetrachloride; the extracts were combined, washed twice with 25 ml of water, dried over anhydrous sodium sulfate, and evaporated to ~1 ml. TMS was added and the pmr spectrum recorded. The ring proton signals centered at 430 cps were observed; completely absent was the formyl proton signal found at 587 cps (CCl_4) in undeuterated salicylaldehyde. In a related experiment, bis[N-(1-ethoxycarbonylethyl)salicylaldimino]copper(II) was prepared in ethanol-1-*d*. The ligand was freed from the isolated complex by treatment of a carbon tetrachloride solution of the complex with dry hydrogen sulfide gas. After removal of the precipitated cupric sulfide, the filtrate was evaporated and the pmr spectrum recorded: 499 (azomethine), 425 (center, ring protons), 250 (ethoxymethylene quartet, J = 7 cps), 91 (α-methyl singlet), 75 cps (ethoxymethyl triplet). Also observed at much reduced intensity was the α-methyl doublet centered at 91.5 cps (slightly shifted from the α-methyl singlet in the deuterated species) resulting from incomplete deuteration. Integration of α-methyl and azomethine signals indicated ~65 and ~0% deuteration at the α- and azomethine carbons, respectively.

Bis[N-(1-ethoxycarbonylethyl)salicylaldimino]zinc(II) was prepared as described above except that in one reaction Zn(*d*-sal)$_2$ was used and in the other 8 ml of ethanol-1-*d* was added to the reaction mixture containing 5 mmoles of Zn(sal)$_2$ in 15 ml of chloroform. In the first case the azomethine proton signal, which appears at 487 cps in the undeuterated complex, could not be detected in the pmr spectrum in $CDCl_3$. In the second case the azomethine proton signal appeared with undiminished intensity while the pair of α-methyl doublets centered at 97 and 94 cps due to the active and *meso* diastereoisomers (see text) partially collapsed to two singlets, indicating partial deuteration at the α-carbon. Integration revealed ~70–80% deuteration. The completely undeuterated complex (1 mmole) in 5 ml of chloroform was treated with 2 ml of ethanol-1-*d* and the solution gently heated for 1 hr. The pmr spectrum of the recovered complex showed no diminution of the azomethine proton signal intensity and the two α-methyl doublets again partially collapsed to two singlets as above. By integration ~60–70% deuteration was estimated. Signal assignments in this region were independently established by proton–proton spin decoupling experiments. The pmr spectra of complexes deuterated at the azomethine and α-carbon atoms are shown in Figures 1 and 2, respectively, and are discussed further in the text.

N-(Salicylidene)-(+)-alaninatozinc(II) was prepared in D_2O and its pmr spectrum recorded in methanol-d_4. The spectrum is identical in relative intensities with that of the complex prepared in H_2O (*cf.* Table II), indicating no observable deuteration at any position.

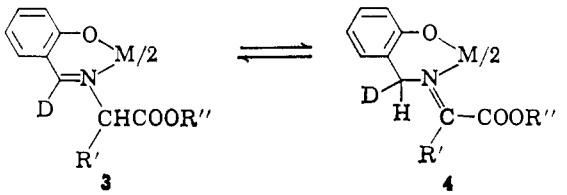
Results and Discussion

Bis(N-substituted salicylaldimino)metal(II) complexes such as **1** and the tridentate metal(II) complexes **2** are designated throughout as M(X-R-sal)$_2$ and M(X-R-sal), respectively, in which X is a benzene ring substituent (not explicitly specified when X = H) and R is the nitrogen substituent. For R the following abbreviations are used: CH_2COO, gly; CH_2COOEt, Etgly; CH_3CHCOO, ala; $CH_3CHCOOEt$, Etala; $PhCH_2CHCOO$, Phala; $PhCH_2CHCOOEt$, EtPhala; $PhCHCH_3$, PhEt; $PhCH_2CHCH_3$, Amp (from amphetamine).

Racemization of N-Alkoxycarbonylalkyl Groups. Pfeiffer, *et al.*,[5] observed that when Cu(sal)$_2$ and *optically active* hydrochlorides of several amino acid esters were allowed to react with heating in the presence of sodium acetate in ethanol, well defined bis-chelate complexes of type **1** could be isolated which were *optically inactive* in ethanol solution at a series of wavelengths. Although these results have been frequently quoted, the mechanism of the racemization process has not been investigated despite the fact that it is at least superficially similar to the racemization reactions of the tridentate complexes **2**, which are presumably implicated in transamination.[10] We have confirmed the results of Pfeiffer, *et al.*,[5] for Cu(II) complexes and have further observed that racemization also occurs for Zn(II), Pd(II), and Co(II) complexes, M(Etala-sal)$_2$ and M(EtPhala-sal)$_2$. In all cases the loss of optical activity is essentially complete within the reaction times which, however, had to be varied from 30 sec to 1 hr (*cf.* Experimental Section) in order to obtain pure products in reasonable yield. If these complexes are nonplanar in the sense that both chelate rings are planar and define a nonzero dihedral angle, they are enantiomorphous at the metal in addition to possessing two asymmetric ligand centers (*vide infra*). Nearly equimolar mixtures of complexes with opposite absolute configurations at the metal are anticipated and, as the results described here show, racemization results from a loss of optical activity at the α-carbon atom. In contrast to the complexes, the Schiff bases obtained by reaction of salicylaldehyde and the active amino acid ester[2,6] or salicylaldehyde, the active ester hydrochloride, and sodium acetate[5] have been found to be optically active immediately after formation in ethanol and to racemize relatively slowly.[5] Racemization of N-(ethoxycarbonylbenzyl)salicylaldimine is virtually complete only after 160 hr.[5]

The implication of these results is that coordination by the metal ion, specifically Cu(II), enhances the racemization rate. This could occur by virtue of an intrinsic lability conferred upon the α-H protons in **1** which provides a pathway for facile racemization, or by the formation of an intermediate in the synthetic reaction which is capable of rapid racemization. A series of investigations has been carried out in order to investigate these possibilities using the representative complexes M(Etala-sal)$_2$ and M(EtPhala-sal)$_2$.

Several pathways of racemization of the complexes themselves must be considered. Pfeiffer, *et al.*,[5] proposed that racemization resulted from an equilibrium between **1** and the corresponding N-substituted bis(*o*-hydroxybenzyliminato)metal(II) tautomer, which presumably would be present in very low concentration. This proposal is subject to an unequivocal check by labeling the azomethine carbon with deuterium. The dynamic equilibrium **3** ⇌ **4** must result in a scrambling



3 **4**

of the deuterium label at the azomethine and α-carbon atoms regardless of the nature of the transition state. Previously Dwyer[30] and ourselves[4] have pointed out the gross resemblance between the tautomeric pathway and the general methylene–azomethine rearrangement[31] $R_1R_2CHN{=}CR_3R_4 \rightleftharpoons R_1R_2C{=}NCHR_3R_4$, which, however, requires strong base. A reexamination of this reaction has revealed the probable intermediacy of a

(30) F. P. Dwyer, "Chelating Agents and Metal Chelates," F. P. Dwyer and D. P. Mellor, Ed., Academic Press Inc., New York, N. Y., 1964, Chapter 8.

(31) D. J. Cram and R. D. Guthrie, *J. Am. Chem. Soc.*, **87**, 397 (1965); **88**, 5760 (1966), and references therein.

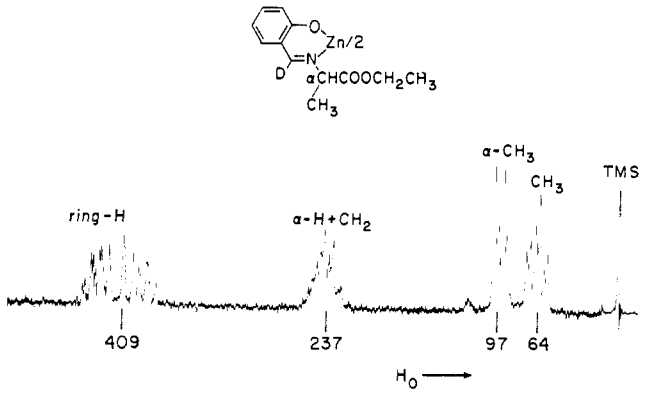


Figure 1. The 60-Mc pmr spectrum of Zn(Etala-*d*-sal)$_2$ in $CDCl_3$ solution demonstrating the lack of hydrogen incorporation at the azomethine position (*cf.* Figure 2) when the complex is prepared from Zn(*d*-sal)$_2$.

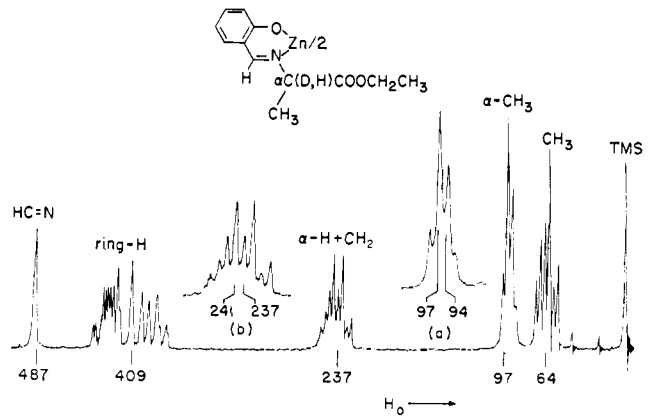
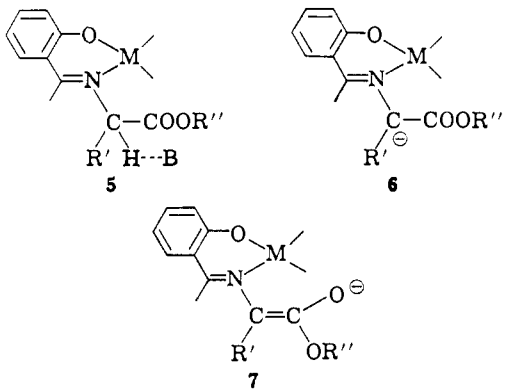


Figure 2. The 60-Mc pmr spectrum of Zn(Et(*d*)ala-sal)$_2$ in $CDCl_3$ solution demonstrating partial deuteration at the α-carbon (*cf.* Figure 1) when the complex is prepared in the presence of ethanol-1-*d*. Inserts: (a) expansion of α-CH_3 region; (b) expansion of α-H and CH_2 region.

carbanion rather than the bimolecular transition state required by a one-stage, concerted mechanism.[31] A second pathway involves removal of the proton *at the α-carbon only via* the agency of base (**5**, B = acetate[5] or ethanol) or by its dissociation to form a carbanion (**6**) stabilized by enolate resonance (**6** ↔ **7**).



Attempted Arrest of the Racemization Reaction. Because one of our initial objectives of this work was measurement of racemization rates and comparison with rates of intramolecular deuterium rearrangement or external deuterium incorporation, considerable effort was expended to prepare complexes with net optical activity by arresting racemization at an intermediate stage. In the preparation of the Cu(II) complexes, which required the shortest effective reaction times, a wide variety of conditions was employed which differed from the original synthetic conditions.[5] These included variation of reaction times, the use of a nonbasic medium (chloroform, dichloromethane) together with the free amino acid ester rather than its hydrochloride and sodium acetate, and the removal of water formed in the reaction by absorbents. However, *in every case an inactive product resulted*, precluding any measurement of the rate of optical activity loss.

Racemization Pathways. These have been investigated by deuterium labeling or exchange experiments which have been followed by proton resonance. Details are given in the Experimental Section, and relevant pmr data are listed in Table II. The bis[N-(ethoxycarbonylalkyl)salicylaldimino]zinc(II) complexes are especially convenient for this purpose because the results of any H–D exchange are directly observable in the pmr spectrum of the complex itself.

(a) Tautomeric Exchange. The exchange scheme **3** ⇌ **4** can be unequivocally eliminated. Reaction of Zn(*d*-sal)$_2$ and L-alanine ethyl ester yielded an inactive product whose pmr spectrum, given in Figure 1, is clearly that of Zn(Etala-*d*-sal)$_2$ (*vide infra*). The azomethine proton signal at 487 cps (compare with Figure 2) is completely absent. Further, *all* signals in Figure 1 can be assigned satisfactorily to the complex with the aldimine structure (*vide infra*). In an equivalent experiment the reaction products from Cu(*d*-sal)$_2$ and this ester and L-phenylalanine ethyl ester were acid hydrolyzed to yield salicylaldehyde; no hydrogen incorporation was detectable in its pmr spectrum. Either the tautomer **4** is completely absent, as seems especially likely,[32] or it is present in only very small concentration and interconverts slowly compared to the over-all racemization rate, and cannot be the intermediate through which any significant amount of racemization occurs.

(b) α-H Exchange. Before turning to the results of deuterium exchange reactions, the spectrum of undeuterated, inactive Zn(Etala-sal)$_2$ is considered. The feature of particular significance is the occurrence of certain signals as chemically shifted pairs of unequal intensity. This behavior is readily observed for the ethoxymethyl and α-methyl resonances (*cf.* Figure 1 and Table II). It has been established that none of these signals is due to free Schiff base or to Zn(ala-sal) and ethanol which could conceivably arise from the hydrolysis[7] of Zn(Etala-sal)$_2$. These observations are entirely similar to the doubling of signals found in the spectra of Ni(X-R-sal)$_2$ complexes in which R carries an asymmetric center[1,12] and are concluded to be due to the formation of a diastereoisomeric mixture in the

(32) No examples of tautomeric bis-chelate complexes such as 4 have been isolated nor is there any evidence that such species are produced in any detectable amount by the condensation of an amine with metal–salicylaldehyde complexes. Recognized examples of tautomeric Schiff base complexes are at present confined to tridentate species. Cu(II) complexes of 5-chloro-N-(2-hydroxybenzyl)salicylaldimine and N-(2-hydroxy-4-chlorobenzyl)salicylaldimine have been prepared.[33] More recently, isolation of Cu(ala-sal)·H_2O and its tautomer, 2-(*o*-hydroxybenzylideneimino)propionatocopper(II) monohydrate, has been claimed.[34] In these cases the tautomeric complexes were prepared from the pair of tautomeric Schiff bases; no information concerning their relative stabilities is available.

(33) Y. Inagaki, O. Ohashi, M. Kishita, and M. Kubo, *Bull. Chem. Soc. Japan*, **38**, 1197 (1965).

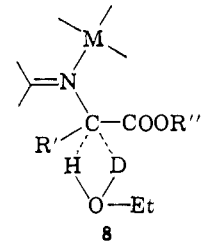
(34) Y. Nakao, S. Sasaki, K. Sakurai, and A. Nakahara, *ibid.*, **40**, 241 (1967).

racemization proeess. One set of signals arises from the racemic pair (+,+) and (−,−) while the other is due to the *meso* isomer, (+,−). Because neither the active nor the *meso* form can be deliberately prepared in an enriched mixture, no specific assignment of the doubled signals to one or the other form is possible. However, the signals of the two forms are not equally intense as would be the case for a statistical distribution (25% (+,+), 25% (−,−), 50% (+,−)), thereby indicating a small stereoselective effect in the racemization process. Similar observations were made in the spectrum of Zn(EtPhala-sal)$_2$.

The results of deuterium exchange experiments are entirely consistent with a racemization pathway involving proton exchange *at the α-carbon only*. Preparation of Zn(Etala-sal)$_2$ in a chloroform–ethanol-*d* medium yielded a product with the pmr spectrum displayed in Figure 2. In agreement with experiments described above, the azomethine proton signal occurs with no detectable diminution in relative intensity. However, the complex multiplet containing the α-H and ethoxymethylene quartets is reduced in relative intensity, and the two methyl singlets of the diastereoisomers are clearly evident. Under the conditions employed deuteration is estimated to be ~70–80% complete.

In an additional, independent experiment demonstrating that racemization of **1** occurs at the α-carbon, the *active* complexes Cu((+)-ala-sal)·3H$_2$O and Cu((−)-Phala-sal)·H$_2$O were prepared and their ORD spectra obtained. These complexes almost certainly have the roughly planar structure of Cu(gly-sal)[35] and owe their activity to one asymmetric ligand center. Cu(EtPhala-sal)$_2$ was hydrolyzed under the conditions of Houghton and Pointer[7] to yield totally *inactive* Cu(Phala-sal)·H$_2$O. In this case a comparison of the ORD spectra of active and inactive complexes was possible,[27] leading to a firm estimate of at least 90% racemization in the preparation of Cu(EtPhala-sal)$_2$. Hydrolysis of Cu(Etgly-sal)$_2$ yields Cu(gly-sal), and Auld and Davison[8] have shown that the former compound undergoes H–D exchange exclusively at the α carbon.

Evidence that the complexes racemize *after* their formation was obtained by the observation that preformed Zn(Etala-sal)$_2$ exchanges readily (60–70%) in a chloroform–ethanol-*d* medium and is recoverable in an otherwise unchanged condition. The same observation has been recorded for Cu(Etgly-sal)$_2$,[8] which, however, contains no asymmetric ligand centers. These results do not exclude the possibility raised above that some racemization under preparative conditions can occur in an unspecified intermediate, but do strongly support the proposition that significant racemization occurs in structure **1** itself. The anionic intermediate **6** ↔ **7** is considered to be the most likely. Under preparative conditions inactive products are obtained in the absence of added base in decidedly nonbasic media (chloroform, dichloromethane). In the presence of a large excess of ethanol-*d* a synchronous exchange, such as is represented in **8**, would be expected to lead to essentially equal extents of deuteration and racemization, contrary to the collective evidence presented here. The low dielectric media employed probably favor the formation of an "incipient" carbanion whose rate of



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collapse with its own proton and, hence, the rate of racemization, exceeds the rate of H–D exchange. Although the details of the intermediate structure cannot be established with certainty, it is clear that the α-H is activated by the electronic withdrawing groups HC=N—M and COOR'' which flank it. The complexes M(PhEt-sal)$_2$, M(Amp-sal)$_2$, M(*s*Bu-sal)$_2$[1,12,29] (M = Co, Ni, Cu), and M(*l*-menthyl-gly-sal)$_2$[5] (M = Ni, Cu), in which the asymmetric center is not subject to the effects of both of these groups, are optically stable. Experiments are currently underway to determine which of these groups, if either, is the more significant in labilizing α-H and to establish the cause of the relatively large optical stability of **2** compared to **1**.[36]

Stereochemistry of Complexes. Racemization under preparative conditions has been observed for M(Etala-sal)$_2$ and M(EtPhala-sal)$_2$ complexes regardless of the nature of the divalent metal ion and the stereochemistry. The infrared data summarized in Table III reveal a characteristic decrease of the imine stretching frequency due to complexation.[37] The Pd(II) complex is anomalous in this respect and the origin of the 1653-cm^{-1} band is unclear. The presence of an uncoordinated azomethine group is not indicated by the pmr spectrum, which is consistent with the planar *trans*-**1** structure found in crystalline Pd(3Et-*i*Pr-sal)$_2$.[38] With two possible exceptions the ester carbonyl stretching frequencies do not indicate significantly strong interaction of the carbonyl group with the metal. Frequencies of the Pd(II), Co(II), and Zn(II) complexes differ from the free ligand by no more than 15 cm^{-1}; chelated amino acid esters generally show *ca.* 30–100-cm^{-1} decreases.[39] The carbonyl frequencies of these complexes more closely resemble those cases in which only the amino group of the ester is coordinated.[39a,40] Ligand field spectra of several M(Etala-sal)$_2$ complexes

Table III. Ester Carbonyl and Imine Stretching Frequencies of M(Etala-sal)$_2$ Complexes in Chloroform[a]

M	ν, cm^{-1} C=O	ν, cm^{-1} C=N
H	1737	1636
Cu	1734, 1710	1623
Co	1722	1611
Ni	1695	1629
Pd	1728	1653, 1627[b]
Zn	1739	1620

[a] ~0.01 *M* solutions. [b] Additional strong band observed at 1603 cm^{-1} which may be a phenyl deformation.

(35) T. Ueki, T. Ashida, and M. Kakudo, *Acta Cryst.*, 22, 870 (1967).

(36) M. J. O'Connor and R. H. Holm, to be published.

(37) J. E. Kovacic, *Spectrochim. Acta*, 23A, 183 (1967).

(38) R. L. Braun and E. C. Lingafelter, *Acta Cryst.*, 22, 787 (1967).

(39) (a) M. P. Springer and C. Curran, *Inorg. Chem.*, 2, 1270 (1963); (b) E.-G. Jäger, *Z. Anorg. Allgem. Chem.*, 349, 139 (1967); R. W. Hay and L. G. Porter, *Australian J. Chem.*, 20, 675 (1967).

(40) M. D. Alexander and D. H. Busch, *Inorg. Chem.*, 5, 602 (1966).

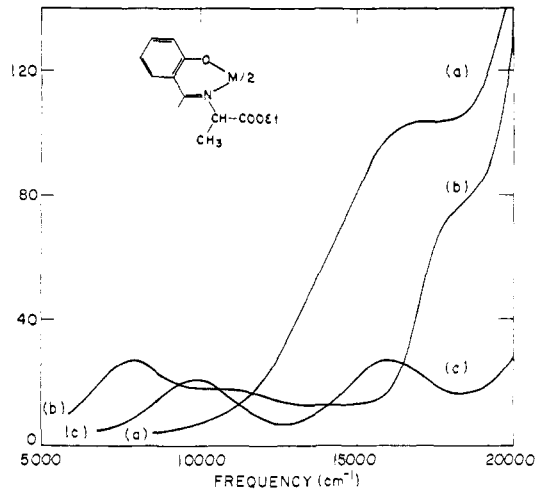
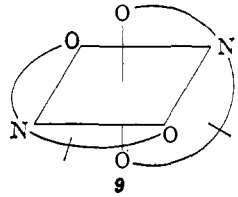


Figure 3. Ligand field spectra of M(Etala-sal)$_2$ complexes in chloroform solution: (a) Cu, (b) Co, (c) Ni.

are presented in Figure 3; spectra of the corresponding M(EtPhala-sal)$_2$ complexes are practically identical. The band positions and, to a lesser extent, band intensities indicate tetrahedral and essentially planar structures for the Co(II) and Cu(II) complexes, respectively, on the basis of comparison with the spectra of M(R-sal)$_2$, R = alkyl.[41] The existence of a five-coordinate Cu(II) species, suggested by the infrared data, cannot be decided from the electronic spectrum. Ni(Etala-sal)$_2$ is chiefly of interest because a prior attempt to prepare it without any stated exclusion of air and water led only to Ni(H-sal)$_2$,[5] possibly as a result of oxidative deamination. We have prepared this complex in low yield under nonaqueous conditions and in the absence of air. Its infrared, pmr, and ligand field spectra leave little doubt that it is pseudo-octahedral, resembling Ni(MeOCH$_2$CHMe-sal)$_2$, which has structure **9**.[42]



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The signs and magnitudes of the contact shifts of Ni(Etala-sal)$_2$ are consistent with those of Ni(MeOCH$_2$-CHMe-sal)$_2$[42] and other monomeric, octahedral Ni(II) salicylaldimine complexes of closely related structure.[43] The complex was prepared from the racemic Schiff base, and its active and *meso* forms are readily detected by the doubled resonances of the contact-shifted aromatic protons.

Diastereoisomeric Zn(II) Complexes. Nonplanar bis-chelate complexes containing two identical, unsymmetrical chelate rings are enantiomorphous at the metal atom, giving rise to the absolute configurations Δ and Λ.[44] If in addition each chelate ring bears an asymmetric center, the possible diastereoisomeric complexes and their enantiomers are the following.

$$\Delta(-,-) \equiv \Lambda(+,+)$$
$$\Delta(+,+) \equiv \Lambda(-,-)$$
$$\Delta(+,-) \equiv \Lambda(-,+)$$

In a total mixture there are in principle three nmr-detectable forms of a complex such as M(PhEt-sal)$_2$ present. However, the two active forms differ only if the lifetime of the configuration at the metal is sufficiently long to be detectable on the nmr time scale. Previous studies of nickel complexes,[1,12] *e.g.*, Ni(5Me-(−)-PhEt-sal)$_2$ and the β-ketoamine species Ni((−)-PhEt-PhHMe)$_2$ and Ni((+)-PhEt-PhHH)$_2$, have never resulted in the detection of *two* active species despite the fact that observations were made down to −50° and that these complexes exhibit large contact shifts which are often capable of revealing subtle structural differences. In these cases it is concluded that the frequencies of planar–tetrahedral interconversion are sufficiently rapid to average out chemical shift differences due to the Δ and Λ configurations. Furthermore, the (−,−) and (+,+) nickel complexes have always given identical spectra.

In past work the only bis-chelate complexes in which active and *meso* forms have been detectable by nmr are those of Ni(II)[1,12] which exist at least partially in the paramagnetic, pseudo-tetrahedral configuration. Their large contact shifts amplify the intrinsic chemical shift difference between the two forms with the result that separate signals of each are readily resolved. Hence, the observation of both forms of Zn(Etala-sal)$_2$ and Zn(EtPhala-sal)$_2$ was not anticipated. We have prepared diastereoisomeric mixtures of both planar (Pd) and tetrahedral (Zn) M(R-sal)$_2$ complexes in which R is an optically stable group (PhEt, Amp, MeOCH$_2$-CHMe). Active and *meso* Pd(II) complexes are in no case distinguishable by pmr. Because these complexes undoubtedly have the *trans*-planar structure, the mutual interaction of R groups, which is the sole source of chemical shift difference between them, must be very slight. This same interaction is certainly larger in a tetrahedral complex, but separate signals of active and *meso* forms at 60 or 100 Mcps have been observed in only one case, Zn(PhEt-sal)$_2$. Chemical shift data for all Pd(II) and Zn(II) complexes are given in Table II.

Conformations and Configurations of Active and *meso* Zn(PhEt-sal)$_2$. Preparation of this complex from optically pure α-phenethylamine results in the formation of strictly enantiomorphous active forms, as shown by their ORD spectra in Figure 4. The pmr spectra of the (+,+) and (−,−) forms are identical and contain as the feature of principal interest one α-methyl doublet at 90 cps whose position and multiplicity are independent of temperature in the range −50 to 111°. The *meso* form could not be prepared and isolated separately but was obtained by the following ligand exchange reaction in deuteriochloroform solution.

$$\text{Zn((+)-PhEt-sal)}_2 + \text{Zn((−)-PhEt-sal)}_2 = 2\text{Zn((+)-PhEt-sal)((−)-PhEt-sal)}$$

Spectra of the equilibrium mixture at various temperatures are presented in Figure 5. Formation of the

(41) (a) Co(II): L. Sacconi, M. Ciampolini, F. Maggio, and F. P. Cavasino, *J. Am. Chem. Soc.*, **84**, 3246 (1962); H. Nishikawa and S. Yamada, *Bull. Chem. Soc. Japan*, **37**, 1154 (1964); (b) Cu(II): L. Sacconi, M. Ciampolini, F. Maggio, and F. P. Cavasino, *J. Inorg. Nucl. Chem.*, **19**, 73 (1961); L. Sacconi and M. Ciampolini, *J. Chem. Soc.*, 276 (1964).

(42) A. Chakravorty, J. P. Fennessey, and R. H. Holm, *Inorg. Chem.*, **4**, 26 (1965).

(43) J. D. Thwaites and L. Sacconi, *ibid.*, **5**, 1029 (1966).

(44) These absolute configurations have been defined previously:[1] Δ, right-handed, Λ, left-handed helicity of chelate rings along the C_2 axis.

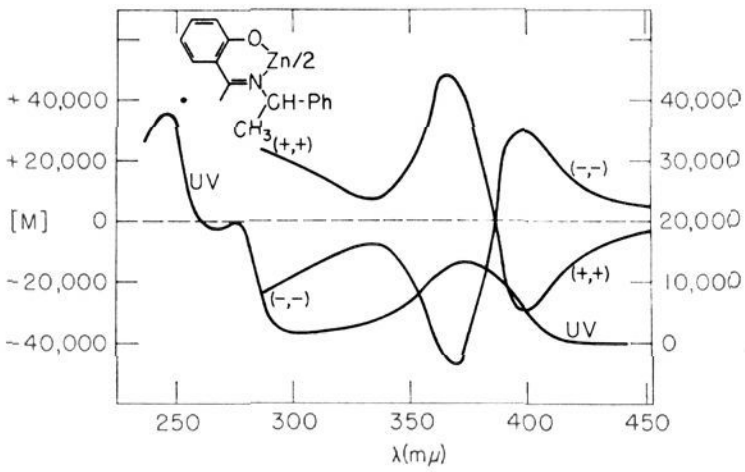


Figure 4. Ultraviolet absorption spectrum (UV) and ORD spectra of the (+,+) and (−,−) isomers of Zn(PhEt-sal)$_2$ in chloroform solution.

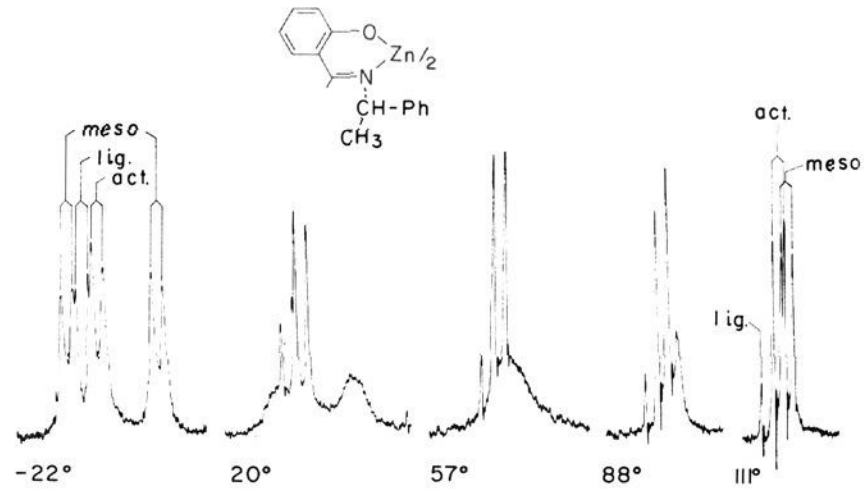
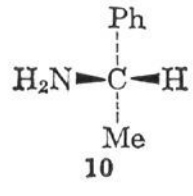


Figure 5. Pmr spectra of the methyl region of a mixture of active and *meso* Zn(PhEt-sal)$_2$ in $CDCl_3$ at various temperatures; lig. is free ligand produced in the exchange reaction.

meso isomer is indicated by the two methyl doublets at 53 and 108 cps (−22°), which broaden as the temperature is increased, coalesce at ~57°, and eventually sharpen to a single, well-defined doublet at 111° centered at 85 cps. These signals are clearly resolved from the methyl doublet of the active form which is centered at 90 cps.

In a series of measurements at or below room temperature in which the concentrations of the two active isomers were varied, it was definitely established that $K_{eq} > 4$, the statistical value.[45] This result together with observations on the tetrahedral complexes Ni(5Me-PhEt-sal)$_2$ and bis(3-α-phenethylamino-1-phenyl-2-propen-1-ono)nickel(II), Ni(PhEt-PhHH)$_2$,[1] for which $F_{act} - F_{meso} \sim +80$ cal/mole at 323°K, indicates that preferential stability of the *meso* form is generally found in salicylaldimine and β-ketoamine complexes with R = PhEt. Nonpolar solvent effects on the equilibrium position have not yet been determined but will be of restricted scope because of solubility limitations.

To investigate the detailed stereochemistry of the tetrahedral active and *meso* forms and their relative stabilities apart from solvent effects, the interactions between α-phenethyl groups of the same and opposite absolute configurations in both of the possible configurations about the metal (Δ,Λ) must be considered. All complexes were prepared from α-phenethylamine, whose (−) isomer has been related to L-alanine[46] and thus possesses the *S*-(−) configuration **10**. The



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interactions of the PhEt groups in both the active and *meso* complexes are best considered by viewing the complex down the true (active) or pseudo (*meso*) twofold axis, which bisects the N–N and O–O edges of the idealized O_2N_2 tetrahedron. Generalizing the PhEt groups as $CR_1R_2R_3$, the two C–R_1 bonds, say, may be considered to be in a common plane normal to C_2. Relative to this axis the R_1 groups are pseudo-equatorial whereas one pair of the remaining groups is pseudo-axial and the other pair *trans* but neither axial nor equatorial.

(45) The mutual overlap of signals in the methyl region from the active and *meso* forms and the free Schiff base produced in the exchange reaction precludes quantitative determination of K_{eq} by signal integration.

(46) W. Leithe, *Ber.*, **64**, 2827 (1931).

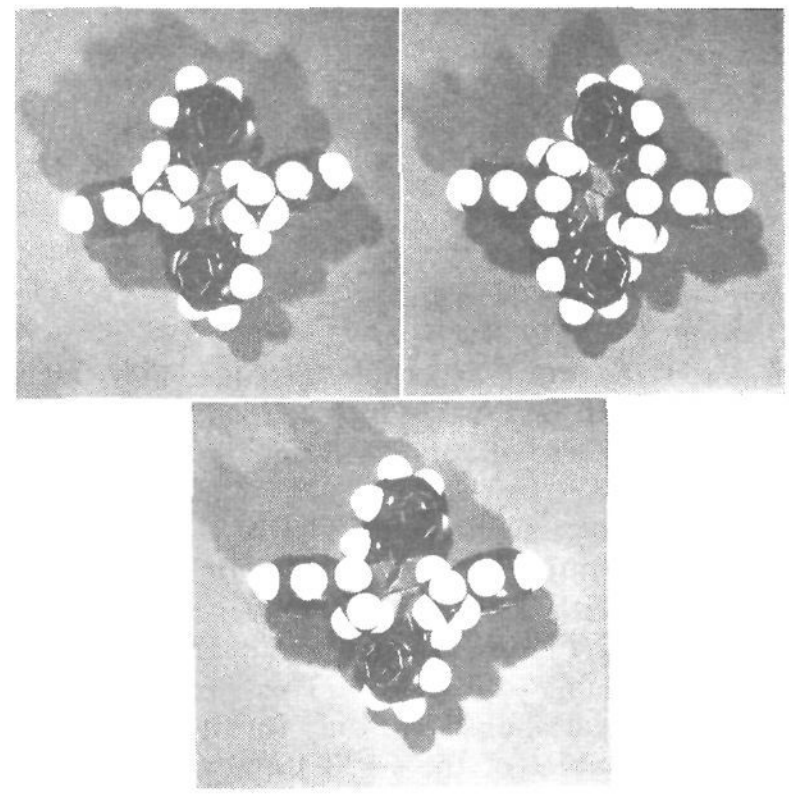
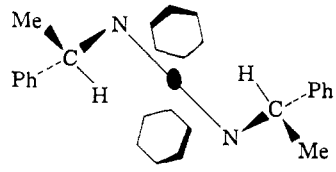


Figure 6. Space-filling metal chelate models (Stuart–Breigleb) illustrating conformations of the PhEt groups in active and *meso* stereoisomers of Zn(PhEt-sal)$_2$: upper left, Δ(−,−) (**11**) in which both methyl groups are axial; upper right, Λ(−,−) (**12**) in which both methyl groups are equatorial; bottom, Δ(+,−) (**13**) in which the methyl group of (+)-PhEt is equatorial and the methyl group of (−)-PhEt is axial.

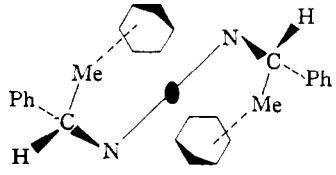
Conformations of the two $CR_1R_2R_3$ groups together which are assumed to possess energy minima are those whose substituents can be designated axial or equatorial in this sense. For each of the active isomers (*e.g.*, Δ(−,−), Λ(−,−)) there are six possible, stable conformations and for the *meso* isomers nine such distinct conformations.

Of the potentially stable forms of the *meso* and two active isomers, there is, uniquely one conformation of each in which the two phenyl groups are sterically remote (*trans*) from each other and are not considered to interact with substituents on the other asymmetric carbon. When viewed down the N–N edge these conformations may be represented as **11**, **12**, and **13**, in which the hexagons represent the benzene rings of the salicylaldimine groups; they are also depicted in Figure 6 by means of space-filling metal chelate scale models (Stuart–Breigleb) which reveal more clearly the steric effects involved. The most significant steric interactions will involve equatorial groups and the axial substituents projecting upward from the N–N edge. Pro-

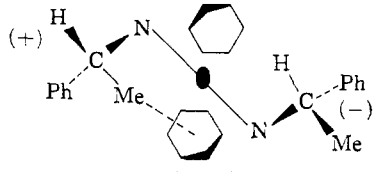
vided steric interactions completely determine the relative energies of the conformations, **11**, **12**, and **13** are



11 Δ(−, −)



12 Δ(−, −)



13 Δ(+, −)

considered the most favorable because they include no direct Ph–Ph or Ph–Me interactions and appear to cause the least loss of rotational entropy of the phenyl ring.[47]

Population of a single conformer of the *meso* isomer at low temperatures (presumably conformation **13**) is consistent with the temperature dependence of the pmr spectrum (Figure 5), which is characteristic of a two-site exchange process. This temperature-dependent behavior is observed only for the *meso* isomer; the methyl doublet of the (+,+) and (−,−) isomers is unchanged over the temperature interval. An intramolecular origin of the two low-temperature *meso* doublets is suggested by the equal intensity of the signals and is specified as (i) hindered rotation of the (+)- and (−)-PhEt groups about their N–C bonds, and/or (ii) freezing of the interconversion $\Delta(+,-) \rightleftarrows \Lambda(+,-)$.[49] The assignment of the low-temperature methyl features is based on the assumed population of conformation **13**. It can be seen in Figure 6 that in this conformation the equatorial methyl group is situated above the benzene and chelate rings of the opposite salicylaldimine group and is thus in the shielding region of the ring current. The axial methyl group does not experience this effect. In the spectrum of the frozen-in conformer, the more upfield doublet is assigned to the equatorial methyl.

The foregoing considerations lead to a deduction of the more stable absolute configurations of the active isomers. Examination of Figure 6 (**11** and **12**) shows that in Δ(−,−) both methyl groups are axial, whereas in Λ(−,−) both are equatorial. Referring to the low-temperature spectra, it is observed that the methyl group of the active species is in a magnetic environment similar to that of the axial methyl group of the *meso* form. The chemical shift difference between them at −22° is only 18 cps, while it is 37 cps for the *meso* equatorial methyl. On this basis it is concluded that the stable configuration of the active isomer is Δ(−,−) (equivalently, Λ(+,+)), in which both methyl groups are axial. Further, the observation of a single methyl doublet of the active species regardless of temperature requires that either Δ(−,−) is the only active isomer detectable or that there is an equilibrium $\Delta(-,-) \rightleftarrows \Lambda(-,-)$ which is fast relative to the nmr time scale and lies toward the left.

In **11**, **12**, and **13** axial–axial, axial–equatorial, and equatorial–equatorial steric interactions involve *H* and Me only. The axial–equatorial interaction in the two active isomers is H–Me. Because Δ(−,−) appears to be the more stable and a Me–Me interaction is more repulsive than H–H, it follows that the equatorial interaction is more sterically destabilizing than axial–axial. In the *meso* form these two interactions are of the H–Me type, and the apparently greater stability of *meso* over active (solvent effects excluded) derives from crossed steric interactions which are generally less destabilizing than the sum of interactions between groups of like size.[50]

The degree of stereospecificity achieved in the synthesis of tetrahedral salicylaldimine or β-ketoamine complexes with R = (−)- or (+)-PhEt is under active investigation.

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(47) There is no direct proof that these conformations are the most stable. The crystal structure of one active form of Cu(PhEt-sal)$_2$ has been determined.[48] The complex is slightly distorted toward the tetrahedral form in the manner of Cu(Et-sal)$_2$ (E. N. Baker, G. R. Clark, D. Hall, and T. N. Waters, *J. Chem. Soc., Sect. A*, 251 (1967)) and Cu(*i*Pr-sal)$_2$ (P. L. Orioli and L. Sacconi, *J. Am. Chem. Soc.*, **88**, 277 (1966)), but with a much smaller dihedral angle formed by the chelate ring planes. The phenyl groups appear to be roughly axial, but this configuration is not necessarily likely to be the most stable one when the dihedral angle is increased to ~90°, the likely value in the Zn(II) complexes, and when the complex is in solution and free from lattice effects.

(48) Z. A. Starikova, M. A. Porai-Koshits, and P. M. Zorkii, *Dokl. Akad. Nauk SSSR*, 171, 155 (1966). Other X-ray data of a preliminary nature on M(PhEt-sal)$_2$ complexes (M = Cu, Ni) have been given by Z. A. Starikova, M. A. Porai-Koshits, P. M. Zorkii, and T. S. Khodashova, *Zh. Strukt. Khim.*, 6, 315 (1965).

(49) If the rotational motion remains frozen, the Δ–Λ interconversion exchanges the methyl groups between axial and equatorial environments; the rotational motion alone cannot lead to an axial–equatorial methyl exchange without involving conformations with Ph–Me and Ph–Ph interactions. If the Δ–Λ interconversion, rather than hindered rotation, is indeed the mechanism causing the observed temperature-dependent behavior of the spectrum, the data can then be treated as a two-site exchange problem by the method of H. S. Gutowsky and C. H. Holm, *J. Chem. Phys.*, 25, 1228 (1956). Treatment of the data by this method gives the following Arrhenius rate law parameters: E_a = 1.2 ± 0.4 kcal and log k_0 = 2.9 ± 0.4. The error estimates arise from uncertainty in the limiting separation of the two doublets (taken to be 62 cps).

(50) E. L. Eliel, "Stereochemistry of Carbon Compounds," McGraw-Hill Book Co., Inc., New York, N. Y., 1962, Chapter 6.