and it is this carbinolamine which forms the weak $NiO_2A_2^{2-}$ species. Evidence for carbinolamine complex formation has previously been reported by Christensen and Riggs[15] in pyridoxal-sarcosine-metal ion systems. With the other amino acids β_{22} is roughly equal to β_{11}.[2] This is not observed for sarcosinate, which suggests that the lower complex, MOA, predominantly consists of independently bound pyruvate and sarcosinate.

The visible region absorption bands arising from the d-d transitions of these spin-free Ni(II) Schiff base complexes show the same interesting behavior noted previously for pyridoxal-glycinate-nickel(II)[15] and salicylaldehyde-glycinate-nickel(II).[16] In these imine complexes the absorbance of ν_1 (~10,000 cm^{-1}) is considerably enhanced relative to the absorbance of this band in other spin-free Ni(II) complexes. This effect is illustrated in Table III where the ratio $\epsilon_{\nu 1}/\epsilon_{\nu 3}$ ($\nu_3 \sim -15{,}000$ to $-16{,}000$ cm^{-1}) is given for various Ni(II) complexes. In addition, relatively high values of $\epsilon_{\nu 1}$ have also been observed in a series of octahedral salicylaldehyde-ethylenediamine-nickel(II) complexes.[17]

The β_{OA} values in Table I show significant interactions between pyruvate and all the amines studied here. The highest value of β_{OA} is found with isoleucinate which forms the weakest imine complex. It is very likely that uncoordinated pyruvylidene-isoleucinate is predominantly present in the *trans* configuration where steric hindrance is minimized. In the metal complex, the configuration must be *cis*. *cis-trans* isomerism as well as carbinolamine formation obscures attempts at a comparison between β_{OA} values and the complex stabilities. What is needed for comparison purposes are the constants for the reaction: $OA^{2-}_{cis} + M^{2+} \rightleftharpoons$ MOA.

Table III. Ratios of $\epsilon_{\nu 1}/\epsilon_{\nu 3}$ for Various Ni(II) Species

Complex	$\epsilon_{\nu 1}/\epsilon_{\nu}$
$Ni(H_2O)_6^{2+}$	~1.0
$Ni(gly)_3^-$	1.1
$Ni(en)_3^{2+}$	1.1
Ni(*o*-phen)$_3^{2+}$	0.6
NiP^{+} [a]	0.8
Ni(1,3-propanediamine)$_2^{2+}$	0.6[b]
$NiP_2(gly)_2^{2-}$ [a]	4.6
$NiP_2(\alpha\text{-ala})_2^{2-}$ [a]	4.1
NiP$_2$(*i*-leuc)$_2^{2-}$ [a]	3.4
$NiP_2(\beta\text{-ala})_2^{2-}$ [a]	2.1[c]
$Ni(sal)_2(gly)_2^{2-}$	1.9

[a] P^- = pyruvate. [b] With six-membered ring chelates $\epsilon_{\nu 3}$ tends to be greater than $\epsilon_{\nu 1}$: R. G. Wilkins, private communication. [c] The value of $\epsilon_{\nu 3}$ is somewhat high (see footnote *b*), but, nevertheless, ν_1 is somewhat less intense than is observed with the other pyruvylidenimines.

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Metal Ion Catalysis in Transamination. IV. Nickel(II)- and Zinc(II)-Glyoxalate-Amino Acid Complexes[1]

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Contribution from the Department of Chemistry, Ohio State University, Columbus, Ohio 43210. Received October 2, 1965

Abstract: Mixed Ni(II) and Zn(II) complexes involving glyoxalate and the amino acids glycine, α-alanine, and α-aminoisobutyric acid have been studied potentiometrically. Glyoxalate reacts rapidly and cleanly in these systems and offers a smaller steric requirement than pyruvate. Spectral data indicate a tendency to form carbinolamine complexes which decreases as the degree of substitution of the α carbon of the amino acid increases. With pyruvate, on the other hand, the imine form predominates. This behavior seems to have a stereochemical basis. The mixed complexes formed in nickel(II)-pyruvate-glycinate mixtures do not have structures identical with those formed with nickel(II)-glyoxalate-α-alanate. No changes in either case are observed for up to 24 hr showing that tautomerization in these species is slow under the reaction conditions employed.

Glyoxalate undergoes rapid nonenzymatic transamination, usually in good yield, to give glycine and the corresponding oxo compound. Metzler, Olivard, and Snell[2] report that pyridoxamine and glyoxalate react rapidly at pH 5, 79°, in the presence of Al(III) to give about a 70% yield of pyridoxal. Amino acids also react facilely in a metal ion catalyzed reaction to give the keto acids.[2,3] Proton magnetic resonance[4] shows that the α-alanate-glyoxalate-zinc(II) system rapidly forms the Schiff base complex, N-glyoxylidene-α-alanatozinc(II), which slowly tautomerizes to give about a 50% equilibrium conversion to the N-pyruvylideneglycinatozinc(II) form after 1 hr. The tendency for the reverse reaction to give glyoxalate is slight[2] but, nevertheless, is detectable.[5] Previous papers[6,7]

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(1) Support by the National Science Foundation, GP 1627, is gratefully acknowledged.

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Table I. Log Formation Constants of Glyoxalate–Amino Acid Complexes at 25°, 0.50 *M* KCl

$$M^{2+} + iO^- + jA^- \rightleftharpoons MO_iA_j$$

$$\beta_{ij} = [MO_iA_j]/[M^{2+}][O^-]^i[A^-]^j$$

	Log β_{10}
Ni^{2+}	0.94
Zn^{2+}	0.64

$HA^{\pm}$		β_{11}	β_{12}	β_{22}	No. of points	Σ	β_{OA}
Glycine							
$pK_{1a} = 2.47$	Ni^{2+}	8.083 ± 0.014	12.915 ± 0.085	14.690 ± 0.011	51	0.0133	1.754
$pK_{2a} = 9.70$	Zn^{2+}	6.746 ± 0.013	10.695 ± 0.038	12.225 ± 0.030	48	0.0502	
α-Alanine							
$pK_{1a} = 2.44$	Ni^{2+}	7.555 ± 0.002	12.299 ± 0.006	13.728 ± 0.008	50	0.0027	1.273
$pK_{2a} = 9.83$	Zn^{2+}	6.320 ± 0.015	10.173 ± 0.050	12.029 ± 0.020	48	0.0379	
α-Aminoisobutyric acid[a]							
$pK_{1a} = 2.48$	Ni^{2+}	7.364 ± 0.016	12.350 ± 0.025	14.167 ± 0.012	34	0.0136	1.00
$pK_{2a} = 10.22$	Zn^{2+}	6.28	?	12.6 pptn	11	0.025	

[a]	β_{01}	β_{02}	β_{03}
Ni^{2+}	5.117	9.316	11.91
Zn^{2+}	3.850	8.88?	pptn

have described the characteristics of equilibrium systems involving pyruvate and different amino acids with several metal ions, particularly Ni(II) and Zn(II). The pyruvate methyl was found to interfere with alkyl substituents on the α carbon of the amino acid causing a lowering in the stability of the complex. The effect is larger with Ni(II) than with Zn(II).

Glyoxalate would appear to possess a steric advantage over pyruvate and, thus, should permit a more direct evaluation of substituent effects on metal–ligand bond strengths. Furthermore, since the pyruvate–glycinate system has been characterized,[6,7] it is of interest to study the properties of the complexes which, at least initially, would be found in the tautomeric form, *i.e.*, those involving α-alanate and glyoxalate.

This investigation was undertaken to characterize the properties of the mixed complexes between glyoxalate and glycinate, α-alanate, and α-aminoisobutyrate (AIB). This series of amino acids tests the effect of increasing methyl substitution on the α carbon of the amino acid.

Experimental Section

Sodium glyoxalate monohydrate, Sigma Chemical, was recrystallized from water as previously described.[2] Analysis of a weighed dissolved sample by exchange of the sodium ions using a strong acid ion-exchange column in the hydrogen ion form indicated a purity of 100.0 ± 0.1% calculated as $HCO_2Na{\cdot}H_2O$.

Glycine, DL-α-alanine, and α-aminoisobutyric acid (Calbiochem, A grade) were recrystallized from ethanol–water mixtures and were dried *in vacuo*.

Titrations followed the same general pattern previously used.[6,7] Solutions 0.50 *M* in KCl, about 0.050 *M* accurately known in either Ni^{2+} or Zn^{2+} and containing 0.050, 0.10, or 0.150 *M* total glyoxalate and having a total titratable hydrogen ion concentration of 0.050 *M* (by addition of a known volume of standard HCl), were titrated with standard solutions of sodium salts of the amino acids at 25°.

Precipitation interfered in the AIB experiments preventing a complete characterization of this system.

Experiments were also performed using Cu(II). While the glyoxalate complexes appeared to be stable under acid conditions, drifting pH readings were obtained in this same region when the mixed species were formed. On standing overnight metallic Cu was deposited from the solutions. No further investigation of the Cu(II) systems was made.

Spectra were obtained using a Cary 14 spectrophotometer.

Results and Discussion

In striking contrast to pyruvate, the glyoxalate systems were found to equilibrate relatively rapidly. Even in the least favorable case studied, nickel(II)–AIB–glyoxalate, equilibration times were no more than 10 min. With zinc(II)-glycinate–glyoxalate, equilibraion appeared to occur within the time of mixing. Most points were monitored with a recorder for up to 30 min without observing any tendency to change from the initial steady-state value. In separate experiments certain points were monitored for 6 hr without noting a change in pH. No differences were observed between the systems containing glycinate, where the free energy of tautomerization is zero; alanate, where the free energy of the reaction is probably negative;[2] and AIB, where tautomerization is not possible. It would appear from these results that under the titration conditions, which primarily are more acidic than those used in the pmr study,[4] either tautomerization or exchange between complexed and uncomplexed ligands is very slow. It is expected that in the alanate system discernible pH changes would be observed as the glycinate concentration in the system builds up.

For the most part the experimental points could be fit to theoretical titration curves within the precision of the pH measurements (0.01–0.02 pH unit) by adjusting only the parameters representing the mixed complex constants, β_{11}, β_{12}, and β_{22}, in the set of equilibrium equations applying to the systems.[6,8] Glyoxalate not only reacts more rapidly than pyruvate but also seems to be free of interfering side reactions, such as dimerization. The constants which best fit the data in the least-squares sense are presented in Table I.

The results show, first, that the simple glyoxalate complexes are less stable than those of pyruvate.[7] At first glance this seems anomalous since the proton affinities of the ligands are in the opposite order: the pK_a values are 2.98 and 2.35 for glyoxylic acid and pyruvic acid, respectively. However, in aqueous solutions the relative degrees of hydration of glyoxalate

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(8) D. L. Leussing, *Talanta*, **11**, 189 (1964).

and pyruvate differ. Kuta and Valenta[9] report the ratio of free to hydrate is 6×10^{-4} for glyoxylic acid and 0.016 for the glyoxalate ion. Thus, the measured value of pK_a for glyoxalic acid is essentially that for the hydrated species. The corresponding pK_a for hydrated pyruvic acid–pyruvate is about 3.6.[4,10,11] Log β_{10} for the reaction $Zn^{2+} + P^{-}_{hyd} \rightleftharpoons ZnP^{+}_{hyd}$ is 2.5.[4] Comparing this *consistent* set of values, the proton and zinc(II) affinities are then placed in the same order, and the difference between the two ligands is therefore attributable to the inductive effect of a methyl group relative to a hydrogen atom.

The stepwise glyoxalate addition constants, $K_{01}{}^{11}$, are given in Table II. As with pyruvate, the high affinity of glyoxalate for the amino acid complexes relative to the aquo ions shows that large interligand interactions exist in the mixed species. There is a slight tendency for the Ni(II) $K_{01}{}^{11}$ values to decrease with the substitution of an alkyl group on the amino acid, but the effect is much smaller than observed with pyruvate.[7] Further evidence that little or no steric hindrance exists in these compounds is the general adherence of $K_{01}{}^{11}$ to the normal order Ni(II) > Zn(II). With pyruvate this order is generally inverted.

Table II. Stepwise Glyoxalate Addition Constants

$$MA^{+} + O^{-} \overset{K_{01}{}^{11}}{\rightleftharpoons} MOA$$

$$\log K_{01}{}^{11} = \log \beta_{11} - \log \beta_{01}$$

A^{-}	Log $K_{01}{}^{11}$ Ni^{2+}	Log $K_{01}{}^{11}$ Zn^{2+}
Glycinate	2.43	1.87
α-Alanate	2.25	1.76
α-Aminoisobutyrate	2.24	2.43
H_2O	0.94	0.64

The Ni(II)-mixed glyoxalate complexes show an interesting variation in spectral properties. The positions of the absorption maxima and their extinction coefficients for the $NiO_2A_2{}^{2-}$ d–d transitions are given in Table III. The ratios $\epsilon_{\nu_1}/\epsilon_{\nu_3}$ are seen to increase progressively with increasing methyl substitution from 2.1 with glycinate to 4.7 with AIB. This last value is about the same as that found for N-pyruvylideneglycinatonickel(II).[7]

Table III. Ni(II) d–d Transitions for $Ni(glyoxalate)_2A_2{}^{2-}$

A	ν_1, cm^{-1} [a]	ν_3, cm^{-1} [a]
Glycinate	10,025 (10.8)	17,090 (5.2)
α-Alanate	10,150 (19.9)	16,740 (6.6)
α-Aminoisobutyrate	10,420 (33.3)	16,390 (7.1)

[a] The figures in parentheses are the extinction coefficients.

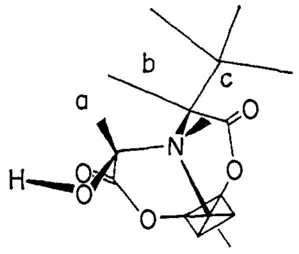
The spectrum of this last species differs from that of the tautomeric glyoxalate–alanate complex not only in the $\epsilon_{\nu_1}/\epsilon_{\nu_3}$ ratios but also with regard to the positions of the absorption maxima. For N-pyruvylideneglycinate, ν_1 and ν_3 lie at 10,260 and 16,300 cm^{-1} compared to 10,150 and 16,740 cm^{-1} for the tautomer. Quite clearly the same complex is not formed in the two cases. The spectra for the tautomeric complexes are both stable (at least on standing overnight) indicating a very slow rate of tautomerization.

The low $\epsilon_{\nu_1}/\epsilon_{\nu_3}$ ratio for glycinate–glyoxalate–Ni(II) suggests the presence of an appreciable proportion of saturated nitrogen, *i.e.*, the carbinolamine. Consistent with this interpretation are the positions of the spectral band maxima. Coordination of Ni(II) to imine nitrogen tends to cause high values of ν_1 and low values of ν_3 relative to coordination involving ligands donating saturated nitrogen, which is less polarizable.[6] The positions of ν_1 and ν_3 for AIB are actually seen in Table III to lie inside the bounds set by these bands in the glycinate complex, suggesting a greater imine content in the former.

Additional evidence for differences in the degree of imine content with varying methyl substitution is obtained from the ultraviolet spectra of the zinc complexes. Glyoxalate ion shows an absorbance maximum at 352 mμ with an extinction coefficient of 0.86. In the glycinate and α-alanate–mixed glyoxalate–zinc(II) complexes this band appears as a shoulder at 275 mμ. However, the extinction coefficient of this band for glycinate (700 l. $mole^{-1}$ cm) is about one-half the value observed for alanate (1300 l. $mole^{-1}$ cm). Also the nmr spectra of the zinc(II)- and calcium–pyruvate–glycinate complexes exhibited bands which were interpreted as arising from a small amount of the carbinolamine.[4]

Taking 1.1[7] and 4.7 as normal values of the $\epsilon_{\nu_1}/\epsilon_{\nu_3}$ ratio for saturated and imine nitrogen, respectively, it is calculated that 72% of the glyoxalate–glycinate–nickel(II) complex exists as the carbinolamine, while with alanate–glyoxalate–nickel(II) the hydrated form corresponds to 47%.

It is possible to explain most of the observations in the glyoxalate series as well as the differences between glyoxalate and pyruvate on the basis of stereochemistry. The results of the preceding work[7] indicated that the five-membered imine chelate ring systems are strained. Through hydration the constraints imposed by the imine bonds are removed and the carboxylate oxygen atoms can then coordinate to *cis* octahedral positions in a less strained configuration. For α-alanate–glyoxalate–nickel(II) the most stable configuration of the carbinolamine is



If the OH group and hydrogen atom a were to be interchanged, rotational interference between the OH and hydrogen b would occur. Glycinate is no different from α-alanate in this respect. Interchanging hydrogen b and the methyl group c produces interference between hydrogen a and this methyl group. This last

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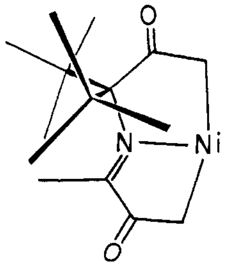
effect imposes more constraints on the α-alanate system than glycinate, thereby, if for no other reason, statistically reducing the stability of the complex. Since AIB possesses two C-methyl groups, considerable hindrance would occur in the carbinolamine form. Because of this the imine form predominates.

With pyruvate, hydrogen a is replaced by either the methyl group or the hydroxyl. In either case strong interference between this group and hydrogen b occurs in the carbinolamine. Thus, pyruvate complexes favor the imine. Zinc(II)-pyruvate-glycinate apparently can exist to an appreciable extent (30%) as the carbinolamine[4] owing to the more flexible coordination permitted by this metal ion. The interfering group can swing away from hydrogen b if a distortion from planar coordination is permitted.

The reduction in the intensity of ν_1 for nickel(II)-pyruvate-β-alanate reported in the preceding paper[7] suggests some carbinolamine formation. This result is consistent with the present conclusions since the more flexible six-membered ring permits hydrogen b to swing away from the interfering group even if planar coordination with the carboxylate oxygens occupying *trans* positions is required.

The imine of glyoxalate-AIB-nickel(II) has the structure



where substituent interference is minimized, but where ring strain nevertheless exists.

Reactivity of Hydrogen Atoms toward Some Cobalt(III) Complexes in Aqueous Solutions[1]

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Contribution from the Department of Chemistry, University of Chicago, Chicago, Illinois 60637. *Received October 8, 1965*

Abstract: Kinetic studies on the reduction of various cobalt(III) complexes by hydrogen atoms are described. The hydrogen atoms were generated by Co^{60} γ irradiation of the solutions and the rates of reaction with the cobalt(III) complexes determined by competition with the reaction with ethanol. Rate constants ranging from 3.3×10^{10} to 2.0×10^{7} M^{-1} sec^{-1} (at 26°) were determined for the reactions of H atoms with $Co(NH_3)_5I^{2+}$, $Co(NH_3)_5Br^{2+}$, $Co(NH_3)_5NCS^{2+}$, $Co(NH_3)_5(H\text{-fumarate})^{2+}$, $Co(NH_3)_5Cl^{2+}$, $Co(NH_3)_5N_3^{2+}$, $Co(NH_3)_3(NO_2)_3$, $Co(NH_3)_5NO_2^{2+}$, $Co(NH_3)_5CN^{2+}$, and $Co(CN)_6^{3-}$, along with upper limits for reactions with a number of other cobalt(III) complexes. In a number of cases the rates of reactions with the corresponding free ligands also were determined. The mechanisms of these reactions and the relation of the observed reactivity patterns for H atoms to those for other reductants are considered.

Recent studies[3-5] on the kinetics and mechanisms of inorganic electron-transfer reactions have included a number of systematic investigations on the reduction of cobalt(III) complexes (notably of the pentaamminecobalt(III) family) by various reducing agents including Cr^{2+}(aq), V^{2+}(aq), Eu^{2+}(aq), $Cr(dipyridyl)_3^{2+}$, $Ru(NH_3)_6^{2+}$, and $Co(CN)_5^{3-}$. Among the objectives of these investigations have been the determination of whether electron transfer occurs by an inner- or outer-sphere mechanism and the elucidation and interpretation of the reactivity patterns, *e.g.*, that of a given reductant toward a series of different pentaamminecobalt(III) complexes. Similarities as well as differences among the reactivity patterns of the various reductants were found, some of which apparently are related to whether the electron-transfer reactions are of the inner- or outer-sphere type. The significance of these reactivity patterns, particularly for inner-sphere reactions, is, however, far from completely understood and their elucidation calls for further work.

In this context it appeared of interest to examine the kinetics of the reduction of a variety of pentaammine and related cobalt(III) complexes by still another reducing agent of somewhat different, but not unrelated, properties, namely, atomic hydrogen. At the time that this investigation was undertaken only a few such measurements had been reported,[6] based on a very indirect method which yielded only relative rate constants. While this work was in progress, two other papers[7,8] appeared reporting further kinetic measurements on such reactions. In view of the incomplete scope of

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(1) Support of this research through a grant from the National Science Foundation and through a grant to the University of Chicago from the Advanced Research Projects Agency is gratefully acknowledged.

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