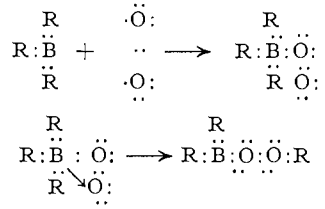
ion is the oxidizing agent.[11] Possibly the oxidation



of organoboranes can be considered to proceed as indicated.[21]

**Acknowledgment.**—The authors wish to thank Professor W. T. Simpson for many stimulating discussions, Professor B. S. Rabinovitch and his students for deuterium assays of vinylsodium, and Mr. Daniel B. Ritter for assistance with the figures.

(21) C. H. Bamford and D. M. Newitt, *J. Chem. Soc.*, 695 (1946).

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# The Infrared Spectra of Some Amino Acids

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The infrared spectra of some optically inactive amino acids including α- and β-alanine, α-, β- and γ-aminobutyric acids, and N-methylated glycines were obtained using the KBr technique in the region 5000-667 cm.$^{-1}$. The functional group frequencies have been correlated with the molecular structure of these compounds. The spectrum of betaine hydrate indicates that it is a dipolar ion in the form of a water complex.

## Introduction

The infrared spectra of solids can be conveniently obtained from KBr pellets in which finely ground samples have been dispersed.[2] Koegel, *et al.*,[3] using this technique, obtained the spectra of a large number of optically active amino acids. This paper presents some further work on optically inactive amino acids.

The object of this study was (1) to correlate the spectra of optically inactive amino acids including the N-methyl substituted glycines, (2) to see the effect on the spectra of amino acids when the position of the amino group is varied along the chain, and finally (3) to evaluate the structure of betaine hydrate.

## Experimental

The spectra were obtained from a Perkin–Elmer Model 112, single beam, double pass infrared spectrometer equipped with a sodium chloride prism. Pellets were prepared by first mixing the amino acid with KBr (J. T. Bakers Analytical Grade) in a Wig-L-Bug Amalgamator for 30 seconds. The resulting mixtures were used to make clear pellets 10 mm. in diameter and approximately 0.5 mm. thick. The procedure for pressing the pellets was essentially the same as described by Kirkland.[4] In this technique it was found that there was a finite concentration of an amino acid below which a clear pellet could be obtained. However above this concentration the pressed pellet became cloudy, as though excess amino acid had crystallized out. This may mean that the amino acid forms a solid solution in KBr.

The following substances were obtained from Nutritional Biochemical Co.: glycine, DL-α-amino-*n*-butyric acid, β-alanine, DL-norvaline, DL-norleucine, DL-valine, DL-isoleucine, DL-β-aminobutyric acid, γ-aminobutyric acid, sarcosine hydrochloride, N,N-dimethylglycine hydrochloride and betaine hydrochloride. The substances DL-alanine, α-amino-isobutyric acid and betaine hydrate were obtained from Eastman Kodak Company.

(1) National Institute of Health Fellow, 1955–1956.

(2) (a) U. Scheidt and H. Reinwein, *Z. Naturforsch.*, **76**, 270 (1950). (b) M. M. Stimson and M. J. O'Donnel, THIS JOURNAL, **74**, 1805 (1952).

(3) R. J. Koegel, J. P. Greenstein, M. Winitz, S. M. Birnbaum and R. A. McCallum, *ibid.*, **77**, 5708 (1955).

(4) J. J. Kirkland, *Anal. Chem.*, **27**, 1537 (1955).

## Results

The amino acids are divided into two groups: I—the straight and branched-chained amino acids and compounds in which the amino group is varied along the chain and II—glycine and N-methyl substituted glycines.

**The Region 3500-2000 Cm.$^{-1}$.**—Amino acids exhibit a great deal of hydrogen bonding as evidenced by the presence of many broad bands in their spectra, especially in the region 3000–2000 cm.$^{-1}$. This makes it difficult to differentiate between the C–H and N–H bands. Nevertheless there are a few generalizations which can be made in this region. α-Amino-*n*-butyric acid and α-alanine of group I both have broad bands at 2300 and 2262 cm.$^{-1}$, respectively, which do not appear in the β- and γ-acids. The same is true for the medium bands 3050 and 3042 cm.$^{-1}$ for the above two acids, respectively.

There is a characteristic band at 2130 cm.$^{-1}$ which has been tentatively assigned to the N–H stretching in the group $NH_3^+$.[3,5] Table I also confirms that this band is related to the $NH_3^+$ group; however, a closer inspection of the data indicates that it may be related to an N–H bending mode rather than an N–H stretching mode. Evidence for this is that in the β-amino acids the absorption peaks are shifted to higher frequencies while the α-amino acids absorb at the normal frequency. This shift may be interpreted on the basis of hydrogen bonding which leads to ring formation. The α-, β- and γ-amino acids could form, respectively, 5-, 6- and 7-membered hydrogen bonded rings. The β-compound would be more stable since it could conceivably form a six-membered ring and as a result the N–H bending mode would have a higher absorption frequency in comparison to the other two types. If this were an N–H stretching mode the reverse would be true and the β-amino acid would absorb at a lower frequency in compari-

(5) L. A. Duncanson, *J. Chem. Soc.*, 1753 (1953).

TABLE I

ABSORPTION SPECTRA OF SOME AMINO ACIDS IN WAVE NUMBERS

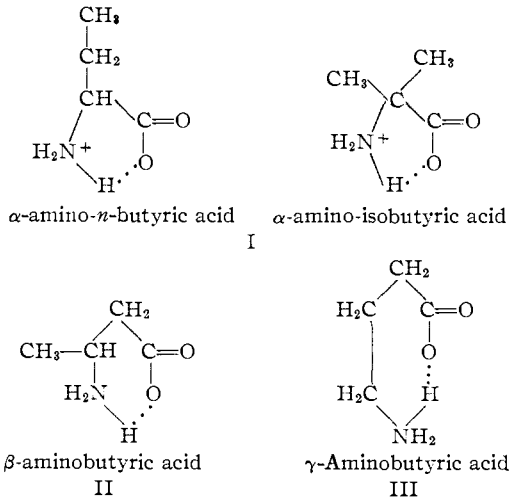
Very strong intensity (VS) 0%T; strong intensity (S) 0–10; medium strong intensity (MS) 10–20; medium intensity (M) 20–80; weak intensity (W) 80–96; very weak intensity (VW) 96–100; shoulder (sh); sharp (sp); broad (B).

| Compound Group I | Concn., mg./g. KBr | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DL-Alanine | 4.5 | | 3042M | | 2839MB | 2716M | | 2584M | 2500M(sh) | | 2262WB | | 2114M | |
| β-Alanine | 7.6 | | | | 2860MB | | | 2613M(sh) | | | | 2186MB | | |
| DL-α Amino-n-butyric acid | 6.2 | | 3050M | | 2860M | 2740M | | 2620M | 2543(sh) | | 2300WB | | 2132M | |
| α-Amino-isobutyric acid | 7.7 | | 3012SB | | 2839MSB | | 2677M | 2599M(sp) | 2459M(sh) | 2351M(sh) | | | 2090MB | |
| DL-β-Amino-butyric acid | 6.2 | | | 2955M(sh) | 2882MB | 2796MB | | 2599M | 2495M(sh) | | | 2177M | | |
| γ-Aminobutyric acid | 7.2 | | | | 2860MB | | 2686M(sh) | | 2537MB | | | | 2146MB | |
| DL-Norvaline | 4.7 | | | 2908SB | | | 2686(sh) | 3472(sh) | | | | | 2090MB | |
| DL-Valine | 7.6 | | | 2936MB | | | 2686MB | | 2543MB | | | | 2139MB | |
| DL-Norleucine | 3.9 | | | 2917SB | | | 2664(sh) | 2562(sh) | | | | | 2104WB | |
| DL-Isoleucine | 5.2 | | | 2955MB | | | 2686M | 2555M | 2506M(sh) | | | | 2129MB | |
| Group II | | | | | | | | | | | | | | |
| Glycine | 7.5 | 3158M | | | 2860MB | | | 2599M | 2513M | | | | 2129MB | |
| Sarcosine hydrochloride | 12.5 | | | 2955SB | | 2796M<br>2748M | 2657M(sh) | | 2495M | 2362M | | | | 1755S(sp) |
| N,N-Dimethylglycine hydrochloride | 7.0 | | | 2890MB | | 2796M<br>2716M(sh) | | 2628M(sh) | 2507M | 2414M(sh)<br>2351M(sh) | | | | 1734S(sp) |
| Betaine hydrochloride | 7.7 | | | 2936M<br>2993M(sh) | | 2812M | | 2628M | 2543M(sh)<br>2483M | 2425M(sh) | | | | 1739S(sp) |
| Betaine hydrate | 7.4 | 3376M | 3098MB | 2976M(sh) | | | | | | | | | | |

| Compound Group I | Concn., mg./g. KBr | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DL-Alanine | 4.5 | 1625S(sh) | 1590VS | | 1522M | | 1454M(sp) | 1426M(sp) | | 1355S(sp) | 1306S(sp) | | 1238M | |
| β-Alanine | 7.6 | 1633MB | 1575MB | | 1507MB | | 1451M | 1414M(sh)<br>1405M | 1389M | | 1331M | 1293M | 1262MB | |
| DL-α-Amino-n-butyric acid | 6.2 | | 1600VSB | | 1525MS | 1476M | 1458M<br>1446M | 1418MS(sp) | 1379M(sh) | 1354S(sp) | 1314VSB | 1265M | | |
| α-Aminoisobutyric acid | 7.7 | 1639S | 1575S | | 1544VS | | 1443M | 1412S(sp) | | 1369S(sp) | | 1291M(sp)<br>1272S(sp) | | |
| DL-β-Aminobutyric acid | 6.2 | 1644S | 1585–<br>1540VSB | | 1514S | | 1441S(sp) | 1409VW | 1377M | 1354M | 1331M<br>1308M | 1287M(sp)<br>1267M(sp) | | |
| γ-Aminobutyric acid | 7.2 | 1639M | 1595MS | 1559MS | 1531MS | 1475M | 1456M(sp) | 1426M | 1390MS | 1352S(sp) | 1325VS(sp) | 1292M<br>1287M | 1232MS<br>1254M | |
| DL-Norvaline | 4.7 | 1653S(sh) | 1584VSB | | 1510S | | 1457M | 1421S(sp) | 1379M(sh) | 1358M(sp) | 1333MS<br>1327MS | 1270M(sp) | | |
| DL-Valine | 7.6 | | 1598SB | | 1502S | 1473M(sh) | | 1417M | 1393M | | | | | |
| DL-Norleucine | 3.9 | 1609S(sh) | 1581BS(sp) | | 1517M | | 1456M | 1418VS(sp) | | 1356MS(sp) | 1339S(sp) | 1286M | 1237M | |
| DL-Isoleucine | 5.2 | | 1595SB | | 1499VSB | | | 1416S(sp) | 1379M | 1363M | 1328M(sp)<br>1310M(sp) | | | |
| Group II | | | | | | | | | | | | | | |
| Glycine | 7.5 | | 1616SB | | 1506SB | | | 1414SB | | | 1331SB | | | |
| Sarcosine hydrochloride | 12.5 | | 1616WB | | | | 1451MS(sp) | 1412MS | 1398MS | | 1308VW | | | |
| N,N-Dimethylglycine hydrochloride | 7.0 | | | | | 1477M | 1451M | 1414MB<br>1433M | 1384M(sh)<br>1375M | | | 1285W | | 1221SB |
| Betaine hydrochloride | 7.7 | 1639M | | | | 1478M(sp) | 1460M | 1405M<br>1430M | | | 1338W(sh)<br>1327M | 1289W | 1246M | |
| Betaine hydrate | 7.4 | | 1633SB | | | 1489M(sh)<br>1478MS | 1450M(sh)<br>1440M | 1416M(sh) | 1395SB | | 1333SB | | 1240M(sp) | |

TABLE I (*continued*)

| Compound Group I | Concn., mg./g. KBr | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DL-Alanine | 4.5 | 1150M | 1114M | 1026MB | 1017M | | 917M | | 854M | 769MB | | |
| β-Alanine | 7.6 | 1151MB | | 1060M | 990M | | 943M | 885MB | 845M | | | |
| DL-α-Amino-*n*-butyric acid | 6.2 | 1152M | 1109M | 1062MB | 1040M(sh) | 1022M | 928MB | 868M | 809VS | 757MB | | |
| α-Amino-isobutyric acid | 7.7 | 1196S(sp) | | 1089M | | 1004W | 952M | 894MB | | 801M | | |
| | | | | | | | | | | 788S(sp) | | |
| DL-β-Aminobutyric acid | 6.2 | 1210MB | 1139M(sp) | 1119M(sp) | 1033MB | 1006MB | | 936M | | 758M | | |
| | | | | | | | | 914M | | | | |
| γ-Aminobutyric acid | 7.2 | | 1164MB | 1110MB | 1062WB | 1038WB | 1006W | 978M | 912MB | 866WB | 776MB | |
| | | | | | | | 990M | | | | | |
| DL-Norvaline | 4.7 | 1196M | 1156M | 1130M(sh) | 1118M | 1076MB | 1036MB | | 909M | 899M(sh) | 850M | 740MB |
| DL-Valine | 7.6 | 1180M | | 1133M | 1104M | 1066MB | 1034MB | 948M | 925WB | 892M | 820M | 777MB |
| DL-Norleucine | 3.9 | 1193M | 1157M | | 1119M | 1074MB | | 959WB | 924MB | 867M | | 722MB |
| DL-Isoleucine | 5.2 | 1182M | | 1132MB | 1102W | 1074WB | 1044WB | 994WB | 963M | 925W | 891W | 827W | 799M | |
| Group II | | | | | | | | | | | | | | |
| Glycine | 7.5 | | | 1133M | 1109M | | 1033MB | | | 911MB | 893MSB | | | |
| Sarcosine hydrochloride | 12.5 | 1205SB | 1161M(sp) | | | 1046M | | | 964M | 903MB | | 841VSB | 778MB | |
| N,N-Dimethylglycine hydrochloride | 7.0 | | 1163MB | | | 1055M | 1024M | 1002M | 965M(sp) | 900M(sp) | | 856M | 805M | |
| | | | 1152M | | | | | | | | | 848M | | |
| Betaine hydrochloride | 7.7 | 1189SB | | 1131MS | | 1070WB | | 992MS(sp) | 950M(sp) | 930M(sp) | 883S(sp) | 840M | 777M | |
| Betaine hydrate | 7.4 | | 1144W | 1130W | | | | 1006W | 953M | 931MS | 892SB | | | |
| | | | | | | | | 981M | | | | | | |




son to the α- and γ-amino acids. This same type of reasoning has been used to explain the abnormal acidity of *n*-butyric acid in the series formic, acetic, propionic and butyric acid.[6]

It should be noted that amino acids form intermolecular hydrogen bonds in the crystalline state whereas there is no direct experimental proof of intramolecular hydrogen bonding.[7] However the above data cannot be explained on the basis of intermolecular hydrogen bonding. There are three reasons for conceivably anticipating the presence of intramolecular hydrogen bonds together with the intermolecular type: (1) the concentrate of amino acid used was dilute—0.05 *m* (2) the amino acid was ground thoroughly in a grinder with KBr and therefore there is a tendency to break up some of the intermolecular hydrogen bonds and allow for the formation of intramolecular bonds and finally (3) the pellet technique may involve the formation of solid solutions as mentioned in the Experimental section.

**The Region 2000-1300 Cm.$^{-1}$.**—In this region there is a great deal of similarity in the spectra of the amino acids and as a result a large number of correlations have been made.[3,8-14] There is an absorption band at 1640–1610 cm.$^{-1}$ which has been assigned to the $NH_3^+$ deformation.[14] Bellamy[8] states that there is a great deal of confusion with respect to the assignment of this band. Inspection of Table I shows that DL-valine, DL-isoleucine and DL-α-amino-*n*-butyric acid do not absorb in this region. Furthermore betaine hydrochloride shows an absorption peak at 1639 cm.$^{-1}$; however, this compound is N-trimethylated. More-

(6) J. F. Dippy, *J. Chem. Revs.*, **25**, 189 (1939).

(7) J. M. Robertson, "Organic Crystals and Molecules," Cornell University Press, Ithaca, N. Y., 1953, p. 242.

(8) T. J. Bellamy, "The Infrared Spectra of Complex Molecules," Chapter 13, John Wiley and Sons, Inc., New York, N. Y., 1954.

(9) N. Fuson, M. Josien and R. L. Powell, THIS JOURNAL, **74**, (1952).

(10) H. W. Thompson, D. L. Nicholson and L. N. Short, *Disc. Faraday Soc.*, **9**, 222 (1950).

(11) I. M. Klotz and D. M. Gruen, *J. Phys. Colloid Chem.*, **52**, 961 (1948).

(12) H. Lenormant, *J. chim. phys.*, **43**, 327 (1946).

(13) H. Lenormant, *Compt. rend. acad. sci. Paris*, **222**, 1432 (1946).

(14) H. M. Randall, R. G. Fowler, N. Fuson and J. R. Dangl, "Infrared Determinations of Organic Structures," D. Van Nostrand Co., Inc., New York, N. Y., 1949, p. 16.

over, it does not contain the ionic carboxyl absorption peak to complicate the spectrum. These facts all indicate that the above assignment is doubtful.

The absorption band from 1550–1485 cm.$^{-1}$ has been assigned to the $NH_3^+$ acids and the hydrochlorides.[9,11,14] From Table I it is seen that all the compounds in group I together with glycine show this peak. The other four compounds in group II do not exhibit absorption here. This is to be expected since they all have methylated amino groups. Furthermore, all the bands are not broad except for glycine, $\beta$-alanine and DL-isoleucine indicating that the effect of hydrogen bonding on this deformation frequency is small. The maximum spread between peaks is 32 cm.$^{-1}$ (from DL-isoleucine to $\gamma$-aminobutyric acid, exclusive of $\alpha$-amino-isobutyric acid) so that the effect of the ionic carboxyl group, as explained for the $NH_3^+$ deformation at 2130 cm.$^{-1}$, cannot be detected. This is due to the experimental error in measuring the peak frequencies.

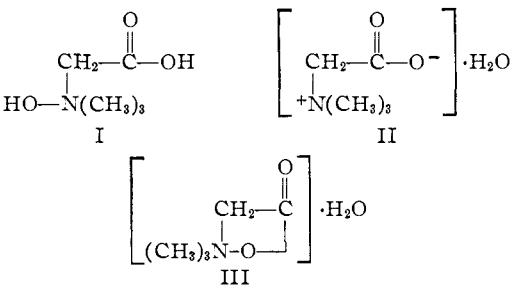
All the compounds of group I have a strong band near 1600 cm.$^{-1}$ indicating the existence of the asymmetric ionic carboxyl mode of vibration. The hydrochlorides in group II, on the other hand, do not have this group. Sarcosine hydrochloride shows a weak band at 1616 cm.$^{-1}$ which could be inherent in the hydrochloride, but it might be due to the presence of a small amount of sarcosine which shows strong absorption at 1616 cm.$^{-1}$.[14]

The second absorption at 1410 cm.$^{-1}$ arising from the symmetric mode of vibration of the ionic carboxyl group is less easy to identify in the infrared spectrum although it appears clearly in many Raman spectra of $\alpha$-amino acids.[8,15] All the compounds in Table I show absorption here. This result can be interpreted in two different ways. The presence of the 1410 cm.$^{-1}$ band in the hydrochlorides may be inherent in hydrochlorides of amino acids with strongly basic methylamino groups. The absorption band for all the other compounds would then be due to the ionic carboxyl group. However if the 1410 cm.$^{-1}$ band is not inherent in the hydrochlorides then the above assignment is not valid, for the hydrochlorides do not contain ionic carboxyl groups.

All hydrochlorides of group II show strong absorption from 1754–1724 cm.$^{-1}$ and do not show absorption at 1610 cm.$^{-1}$. Hence this mode is assigned to the normal carboxyl group. Sarcosine hydrochloride, however, exhibits weak absorption at 1616 cm.$^{-1}$ and, as stated previously, could be due to a small amount of sarcosine present or, more likely, it could be a band inherent in sarcosine hydrochloride.

All the compounds in Table I except glycine and isoleucine show absorption from 1438 to 1460 cm.$^{-1}$ which is due either to the asymmetric C–H deformation of the C–$CH_3$ group (1450 ± 20 cm.$^{-1}$)[8] or to the –$CH_2$ deformation (1465 ± 20 cm.$^{-1}$).[8] The absence of this band in glycine and isoleucine probably is due to the fact that there are strong broad absorption bands located at 1414 and 1499 cm.$^{-1}$, respectively, and consequently have washed out the weaker band.

**The Structure of Betaine Hydrate.**—Table I shows that betaine hydrate has an absorption band at 3376 cm.$^{-1}$ which is due to the bonded OH in water. There is also a strong absorption peak at 1633 cm.$^{-1}$ which is due to an ionic carboxyl group. The possible structures for the hydrate are illustrated below. There is some confusion as to what the structure is. For example Harrow and Mazur[16] indicate that it is either structure I or III. Fruton and Simmons,[17] on the other hand, indicate that the structure is II. Structure I can be eliminated since it should have a normal acid carboxyl frequency near 1725 cm.$^{-1}$ and no ionic carboxyl mode. Structure III would be analogous to a lactone and would have a carbonyl frequency near 1800 cm.$^{-1}$. Hence this structure can be eliminated. Structure II is the only structure which is consistent with the spectrum. It has an ionic carboxyl group which would give rise to the $COO^-$ mode near 1600 cm.$^{-1}$. The bonded OH frequency would be due to the associated water. The spectrum does not give any information as to where the water is located. As a result the compound is probably a water complex, the nature of which is not entirely known.



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(15) J. T. Edsall, J. W. Otvos and A. Rich, THIS JOURNAL, **72**, 474 (1950).

(16) B. Harrow and A. Mazur, "Textbook of Biochemistry," W. B. Saunders Co., Philadelphia, Pa., 1954, p. 54.

(17) J. A. Fruton and S. Simmons, "General Biochemistry," John Wiley and Sons, Inc., New York, N. Y., 1953, p. 55.