

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, BOSTON UNIVERSITY]

Crystalline Amido Acids: Correlation of Structure with Infrared Spectra<sup>1</sup>

By HAROLD H. FREEDMAN

RECEIVED NOVEMBER 29, 1954

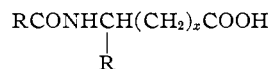
The band shifts encountered in the infrared absorption spectra of solid amido acids are discussed in terms of the intermolecular hydrogen-bonded structure. Evidence is presented for the existence of a strong hydrogen bond between the acid OH and the amide C=O in certain amido acids and miscellaneous bonding and resonance effects are discussed.

**Introduction.**—During recent years an active interest has been taken in the characterization of N-substituted amido acids by means of their infrared spectra.<sup>2</sup> In general when these compounds are examined in solution or in the liquid state the strong carbon-oxygen stretching bands corresponding to the carboxyl and amide carbonyl are found at or near the expected values for simple acids and amides, respectively. In the solid state, however, in a large number of amido acids the carbonyl bands are shifted greatly from the wave lengths expected for analogous simple solid acids and amides; the shifts being as much as 0.2  $\mu$  (50  $\text{cm.}^{-1}$ ) toward shorter wave lengths for the acid carbonyl and an equal amount in the opposite direction for the amide carbonyl.

Randall, *et al.*,<sup>3</sup> devote an entire section to the amido acids and present the spectra of over 40 of these compounds and their esters. Rasmussen<sup>4</sup> refers to anomalous band shifts when an amide and an acid group are in the same molecule and Fuson, Josien and Powell<sup>5</sup> in their study of mercapturic acids discuss this phenomenon in more detail. In every case it has been implied or stated that these shifts are due primarily to intermolecular forces

arising from the crystal lattice, and Thompson, *et al.*,<sup>6</sup> suggest that "the long wave shift (is) presumably due to hydrogen bonding of the COOH to the amide C=O." However there is missing from the literature a detailed explanation of the band shifts in terms of the probable intermolecular relationships of the crystalline amido acids and it is the purpose of this paper to answer this question.

**Compounds Studied.**—The data of ref. 3 proved to be invaluable as a source of spectral data concerning amides and amido acids; however, of the forty compounds presented, only four are not  $\alpha$ -amido acids, and these four are  $\omega$ , straight chain compounds. It seemed therefore of interest to examine a branched amido-acid of the type



Such compounds were prepared by the reaction of acrylonitrile and 12-hydroxystearic acid in one case and acrylonitrile and 10-undecenoic acid, in the other. This reaction between aliphatic nitriles and alkenes or alcohols was first investigated by Ritter<sup>7a-c</sup> and a number of amido-substituted stearic acids previously have been prepared by the

TABLE I  
NEW COMPOUNDS

Compound	Designation	M.p., °C.	Formula	C	Calcd. H	Analyses, %		Found H	N
						N	C		
Undecylenic acid plus acrylonitrile <sup>a</sup>									
11-Acrylamidoundecanoic acid	AUA	109.5-110	C <sub>14</sub> H <sub>25</sub> O <sub>3</sub> N	66.0	9.8	5.5	65.8	9.9	5.5
Methyl ester	AUA-Me ester	68-68.5	C <sub>15</sub> H <sub>27</sub> O <sub>3</sub> N	67.0	10.0	5.2	66.8	10.2	5.2
11-Propionamidoundecanoic acid	Dihydro AUA	84.5-85	C <sub>14</sub> H <sub>27</sub> O <sub>3</sub> N	65.3	10.5	5.5	65.5	10.5	5.4
12-Hydroxystearic acid plus acrylonitrile <sup>b</sup>									
Acrylamidostearic acid-I <sup>c</sup>	ASA-I	108-109	C <sub>21</sub> H <sub>39</sub> O <sub>3</sub> N	71.3	11.0	4.0	71.3	10.9	4.0
Acrylamidostearic acid-II <sup>c</sup>	ASA-II	89-89.5	C <sub>21</sub> H <sub>39</sub> O <sub>3</sub> N	71.3	11.0	4.0	71.2	10.9	4.0
Methyl ester	ASA-I-Me ester	87-89	C <sub>22</sub> H <sub>41</sub> O <sub>3</sub> N	71.9	11.1	3.8	71.8	11.2	4.0
Propionamidostearic acid-I <sup>d</sup>	Dihydro ASA-I	92-93	C <sub>21</sub> H <sub>41</sub> O <sub>3</sub> N	70.9	11.5	3.9	70.5	11.2	4.0

<sup>a</sup> It was hoped to prepare the 10-acrylamidoundecanoic acid, but even though this was the major product it proved to be an uncrystallizable oil, only the  $\omega$  product being isolatable as a crystalline white solid. <sup>b</sup> Barring rearrangements due to migration up or down the carbon chain, the isomers should have the structure indicated. Probable structure where  $x + y = 3$ , R = CH<sub>2</sub>=CHCONH—, R' = CH<sub>3</sub>CH<sub>2</sub>CONH—. <sup>c</sup> CH<sub>3</sub>(CH<sub>2</sub>)<sub>4</sub>(CH<sub>2</sub>)<sub>x</sub>C(R)H(CH<sub>2</sub>)<sub>y</sub>(CH<sub>2</sub>)<sub>3</sub>COOH. <sup>d</sup> CH<sub>3</sub>(CH<sub>2</sub>)<sub>4</sub>(CH<sub>2</sub>)<sub>x</sub>C(R')H(CH<sub>2</sub>)<sub>y</sub>(CH<sub>2</sub>)<sub>3</sub>COOH.

(1) Presented in part before the Organic Division of the American Chemical Society, 126th Meeting, New York, N. Y., Sept. 17, 1954. Taken from work to be incorporated as part of a thesis to be submitted in partial fulfillment of the requirements for the Ph.D. degree, Chemistry Department, Boston University.

(2) H. W. Thompson, R. R. Brattain, H. M. Randall and R. S. Rasmussen, "The Chemistry of Penicillin," Princeton University Press, Princeton, N. J., 1949, Chapt. XIII.

(3) H. M. Randall, R. G. Fowler, N. Fuson and R. Dangel, "Infrared Determination of Organic Structures," D. Van Nostrand and Co., Inc., New York, N. Y., 1949, Chap. II.

(4) R. S. Rasmussen, "Fortschritte der chemie organischer Naturstoffe," Springer Verlag, Vienna, Vol. V, p. 372.

(5) N. Fuson, M. Josien and R. L. Powell, THIS JOURNAL, **74**, 1 (1952).

reaction of nitriles with oleic acid by Roe and Swern<sup>8</sup>; the present preparation follows a similar procedure. Acrylonitrile was chosen in order to study the effect of the double bond conjugation and to compare this to the simple propionamido substituted acid obtained upon reduction. The compounds prepared are summarized in Table I. Though the exact position of the amido group in

(6) See ref. 2, pp. 403-404.

(7) (a) J. J. Ritter and P. P. Minieri, THIS JOURNAL, **70**, 4045 (1948); (b) R. M. Luskin with J. J. Ritter, *ibid.*, **72**, 5577 (1950); (c) H. Plaut with J. J. Ritter, *ibid.*, **73**, 4076 (1951).

(8) E. T. Roe and D. Swern, *ibid.*, **75**, 5479 (1953).

the ASA compounds is not known, it may be assumed that ASA-I and II, the major products, are isomers in which the acrylamido group is attached to the 11-, 12- or 13-position.

The spectra of the compounds herein presented for the first time were obtained on a Perkin-Elmer model 12 instrument equipped with an automatic recorder, rock salt optics and a flushing system to minimize atmospheric absorptions. The calibration was checked against a pure polystyrene film and was found to be accurate to  $\pm 0.01 \mu$  in the 4-15  $\mu$  region. It is estimated that below 3  $\mu$  the accuracy does not warrant the presentation of any band in this region to more than one decimal place and therefore data for the N-H stretching band will be taken directly from Randall.<sup>3</sup> In other respects, duplicate spectra obtained in the present work agree closely with ref. 3, the majority of assigned bands checking within 0.01  $\mu$ .

### Discussion

Table II lists the characteristic absorptions in the 3-6  $\mu$  region of simple acids, esters and amides. These form the basis for evaluating abnormal band shifts and will be referred to as the need arises. Table III lists the bands in the 5-7  $\mu$  region for the AUA and ASA compounds. These were examined both as crystalline mulls in Nujol and as either crystalline, opaque (powdery) films or as amorphous, transparent films, obtained by evaporation from a suitable solvent. It was evident that the amorphous films were representative of the compound in its liquid state, the spectra in the 8-15  $\mu$  region showing a number of changes in both

band shape and wave length commonly encountered in going from a solid to a liquid fatty acid.<sup>9</sup>

**New Compounds.**—Reference to Table III indicates that the AUA compounds are entirely normal with regard to the acid, ester and amide carbonyl absorptions. The amide C=O long wave length shift in the double bond conjugated compounds is analogous to similar conjugated carbonyls such as  $\alpha,\beta$ -unsaturated ketones in which conjugation increases the wave length by *ca.* 0.1  $\mu$ .<sup>10</sup>

The band positions of the ASA compounds in the amorphous state and ASA-I ester are directly analogous to the corresponding AUA compounds except that the acid C=O is at 5.85 rather than 5.89  $\mu$ , the former being closer to the value found in liquid fatty acids.<sup>11</sup> In the crystalline state, however, the ASA compounds exhibit the C=O band shifts associated with certain amido acids, the acid C=O decreasing by *ca.* 0.1  $\mu$  and the amide C=O increasing by *ca.* 0.2  $\mu$ . When ASA-I was deposited from solution the film was partly powdery and partly amorphous, and as expected, the spectrum exhibited both normal and shifted carbonyl bands. The phenomenon associated with these abnormal C=O shifts will be referred to as "carboxy-amido" bonding.

Table IV is a compilation of data taken directly from Randall.<sup>3</sup> In every case the C=O stretching bands and amide II wave lengths are those assigned by the authors, while the NH and OH stretching bands are those indicated but are not assigned as such. In the case of NH there can be little doubt that the assignments are correct while the OH band assignments are open to some question, in some cases being absent and presumably hidden by the strong Nujol bands at 3.4  $\mu$  and in other cases more than one band being present at or near the expected wave length.

In general the carboxyl and amide carbonyl values vary in what may at first seem to be an unpredictable manner, ranging from 5.71 to 5.93  $\mu$  for the acid and from 5.99 to 6.29  $\mu$  for the amide. To facilitate discussion the compounds in Tables III and IV have been divided into four groups, dependent upon the bonding, conjugation or resonance effect responsible for the C=O absorptions.

**Group I. Normally Bonded Compounds.**—The compounds in this group have their key stretching bands at or near the values for simple acids, esters or amides. It is evident from the band shifts of Table II that for the acids and monosubstituted amides the bands are greatly influenced by hydrogen bonding in the solid state, the strength of the hydrogen bond manifesting itself in a longer carbonyl wave length absorption. This is generally true of all hydrogen-bonded carbonyls, the stronger the bond the greater the shift of the stretching band to longer wave lengths.<sup>12</sup> These normally bonded compounds include numbers 1-4 of Table III, and dihydro AUA. In this group may also be included all esters with the exception of 16e and 5e-7e of Table IV, and the ASA and AUA methyl esters which will be discussed elsewhere. Randall, *et al.*,<sup>3</sup> have pointed out that amido-acids may be recognized by comparison of the spectra of the acid and ester. Inasmuch as the esters are not subject to "carboxy-amido" bonding they offer a basis for evaluating resonance and inductive effects unobscured by bonding effects.

Randall<sup>3</sup> also states that  $\alpha$ -amido acids may be recognized

TABLE II  
WAVE LENGTHS (IN  $\mu$ ) OF STRETCHING BANDS FOR SIMPLE ACIDS, ESTERS AND AMIDES

	C=O		O-H (or N-H)	
	Solid	Dilute soln.	Solid	Dilute soln.
RCOOH <sup>a,b</sup>	5.89	5.68 <sup>d</sup>	<i>ca.</i> 3.5	<i>ca.</i> 3.0
RCOOEt <sup>a,b</sup>	5.76	5.74	..	..
RCONH <sub>2</sub> <sup>c</sup>	6.04	5.81	2.98, 3.13	2.84, 2.94
RCONHR <sub>alk</sub> <sup>c</sup>	6.09	5.95	3.06	2.92
RCONHR <sub>ar</sub> <sup>c</sup>	5.96-6.02	..	..	..
RCONR <sub>1</sub> R <sub>2</sub> <sup>c</sup>	6.06	6.06	..	..

<sup>a</sup> R. G. Sinclair, A. F. McKay and R. Norman Jones, *THIS JOURNAL*, 74, 2570 (1952). <sup>b</sup> O. D. Shreve, *et al.*, *Anal. Chem.*, 22, 1498 (1950). <sup>c</sup> H. W. Thompson, D. Nicholson and L. Short, *Disc. Faraday Soc.*, 9, 229 (1950). <sup>d</sup> This band is due to the non-bonded, monomeric carboxyl carbonyl and is usually hidden by the strong absorption due to the bonded dimer.

TABLE III  
WAVE LENGTH (IN  $\mu$ ) OF AUA AND ASA COMPOUNDS

Compound	State <sup>a</sup>	C=O		Amide II <sup>c</sup>	
		(O)	C=C <sup>b</sup>	(N)	
AUA	xl	5.88	6.04	6.17	6.46
AUA-Me ester	xl	5.76	6.04	6.16	6.45
AUA-dihydro	xl	5.89	..	6.08	6.45
ASA-I	xl	5.79	6.06m	6.24	6.46
ASA-I	xl	5.79	6.05ms	6.23	6.45
	am	5.87	..	6.17	..
ASA-II	xl	5.78	6.06m	6.22	6.45
ASA-II	am	5.85	6.06	6.18	6.46
ASA-I, Me ester	xl	5.77	6.05	6.17	6.45
ASA-I, dihydro	xl	5.79	..	6.23	6.46

<sup>a</sup> xl = crystalline, am = amorphous. <sup>b</sup> All bands are of strong intensity except those marked: m = med., ms = med. str. <sup>c</sup> In thin films this band is resolved into a doublet: the above values represent the center of what ordinarily would be a single band.

(9) For example: the series of sharp bands at 8-8.5  $\mu$  in crystalline ASA-II, is replaced by a single broad band at 8.05  $\mu$  in amorphous ASA-II. This change is noted by R. N. Jones, A. F. McKay and R. G. Sinclair, *THIS JOURNAL*, 74, 2575 (1952), in their study of fatty acids.

(10) R. S. Rasmussen, D. D. Tunnicliff and R. R. Brattain, *ibid.*, 71, 1068 (1949).

(11) See ref. 3 under Table I.

(12) L. N. Ferguson, "Electron Structures of Organic Molecules," Prentice-Hall Inc., New York, N. Y., 1952, pp. 251-268.

TABLE IV  
 COMPOUNDS FROM REFERENCE 3, 2-6  $\mu$  STRETCHING BANDS<sup>a</sup>

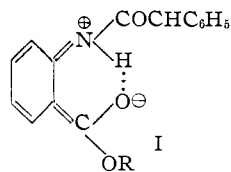
No.	Ref. 3, page	Acid and ester	Structure	State <sup>b</sup>	N-H	O-H <sup>c</sup>	C=O- (O)	C=O- (N) <sup>d</sup>	Amide II
1	131	$\epsilon$ -Phenacetamido- <i>n</i> -caproic	PhCH <sub>2</sub> CONH(CH <sub>2</sub> ) <sub>5</sub> COOH	S	3.00	ca. 3.5	5.90	6.11	6.53
2	132	$\delta$ -Phenacetamido- <i>n</i> -valeric	PhCH <sub>2</sub> CONH(CH <sub>2</sub> ) <sub>4</sub> COOH	S	3.00	ca. 3.5	5.90	6.11	6.46
2e	132	Me ester		S	3.03	..	5.76	6.12	6.41
3	133	<i>N</i> -Phenacetyl- $\beta$ -alanine	PhCH <sub>2</sub> CONH(CH <sub>2</sub> ) <sub>2</sub> COOH	S	3.03	ca. 3.5	5.93	6.10	6.48
3e	133	Me ester		S	3.00	..	5.76	6.05	6.48
3s	116	Na salt		S	3.00	..	6.38	6.09	6.46
4	135	$\epsilon$ -Benzamidocaproic	PhCONH(CH <sub>2</sub> ) <sub>5</sub> COOH	S	3.06	3.79	5.89	6.14	6.52
4e	137	Me ester		S	2.99	..	5.75	6.07	6.49
4s	115	Na salt		S	3.00	..	6.38	6.09	6.46
5	127	$\alpha$ -Acetamido- $\beta,\beta$ -dimethyl- acrylic	CH <sub>3</sub> CONH(COOH)C=C(CH <sub>3</sub> ) <sub>2</sub>	S	3.04	3.90	5.89	6.12	6.50
5e	128	Me ester		S	3.05	..	5.80	6.08	6.52
6	129	<i>N</i> -Phenacetylthranilic	O-HOOC-C <sub>6</sub> H <sub>4</sub> -NHCOCH <sub>3</sub>	S	3.03	ca. 3.5	5.93	5.99	6.53
6e	129	Me ester		L	3.04	..	5.93	6.31	6.58
7	138	$\alpha$ -Benzamido- $\beta,\beta$ -dimethyl- acrylic	PhCH <sub>2</sub> CONHC(COOH)=C(CH <sub>3</sub> ) <sub>2</sub>	S	3.07	3.79	5.90	6.09	6.63
7e	138	Me ester		F	3.01	..	5.81	6.10	6.60
8	156	<i>N</i> -Phenacetylsarcosine	PhCH <sub>2</sub> CON(CH <sub>3</sub> )CH <sub>2</sub> COOH	S	..	3.92	5.85	6.24	..
						4.11			
8e	156	Me ester		L	..	..	5.71	6.04	..
8s	117	Na salt		S	..	..	6.32	6.13	..
9	135	Phenaceturic	PhCH <sub>2</sub> CONHCH <sub>2</sub> COOH	S	2.97	3.99	5.80	6.22	6.54
9e	136	Me ester		S	3.10	..	5.73	6.10	6.43
9s	117	Na salt		S	3.01	..	6.35	6.10	6.50
10	134	$\alpha$ -Phenacetamido- <i>n</i> -valeric	PhCH <sub>2</sub> CONHC(COOH)HCH <sub>2</sub> C <sub>2</sub> H <sub>5</sub>	S	2.98	4.03	5.82	6.25	6.46
10e	134	Me ester		S	3.08	..	5.78	6.10	6.43
11	138	$\alpha$ -Phenacetamido- <i>n</i> -caproic	PhCH <sub>2</sub> CONHC(COOH)H(CH <sub>2</sub> ) <sub>3</sub> CH <sub>3</sub>	S	2.97	4.11	5.82	6.25	6.52
11e	139	Me ester		L	3.00	..	5.72	6.09	6.50
12	139	$\alpha$ -Phenacetamidoisobutyric	PhCH <sub>2</sub> CONHC(COOH)(CH <sub>3</sub> ) <sub>2</sub>	S	2.95	..	5.81	6.20	6.51
12e	140	Me ester		S	3.10	..	5.75	6.09	6.46
13	140	$\alpha$ -Phenacetamido- $\alpha$ -methyl- <i>n</i> -butyric	PhCH <sub>2</sub> CONHC(COOH)(CH <sub>3</sub> )C <sub>2</sub> H <sub>5</sub>	S	2.97	3.99	5.86	6.22	6.55
13e	141	Me ester		S	3.08	..	5.76	6.10	6.43
14	153	<i>N</i> -Phenacetylproline	$\begin{array}{c} \text{HOOCHC}-\text{N}-\text{COCH}_2\text{Ph} \\ \diagup \quad \diagdown \\ \text{H}_2\text{C}-\text{CH}_2-\text{CH}_2 \end{array}$	S	..	3.90	5.83	6.29	..
						4.05			
14e	157	Me ester		L	..	..	5.74	6.08	..
15	154	<i>N</i> -Acetylthiazolidine-4- carboxylic	$\begin{array}{c} \text{CH}_2-\text{CHCOOH} \\ \diagup \quad \diagdown \\ \text{S}-\text{CH}_2-\text{NCOCH}_3 \end{array}$	S	..	4.01	5.83	6.29	..
16	135	Hippuric	PhCONHCH <sub>2</sub> COOH	S	2.97	4.01	5.72	6.26	6.43
16e	135	Et ester		S	3.01	..	5.70	6.09	6.54
17	154	<i>N</i> -Phenacetyl- <i>N</i> -methyl- anthranilic	O-HOOC-C <sub>6</sub> H <sub>4</sub> -N(CH <sub>3</sub> )COCH <sub>2</sub> Ph	S	..	?	5.83	6.15	..
18	155	<i>N</i> -Phenacetyl- <i>N</i> -phenyl- glycine	PhCH <sub>2</sub> CON(Ph)CH <sub>2</sub> COOH	S	..	?	5.71	6.11	..
18e	155	Me ester		L	..	..	5.71	6.00	..

<sup>a</sup> The 5-6 $\mu$  bands are the assignments of ref. 3. <sup>b</sup> S = solid, L = liquid, F = film. <sup>c</sup> See comments given elsewhere in this paper. <sup>d</sup> This is referred to as the "Amide-I" band by Randall.<sup>3</sup>

by the fact that in every case the amide C=O band lies on the long wave length side of 6.18  $\mu$  and the acid band lies on the short wave length side of 5.90  $\mu$ . This statement is applicable to the compounds studied by them, but unfortunately these compounds are limited to  $\alpha$ - and  $\omega$ -amido acids and it is a conclusion of the present research that branched as well as  $\alpha$ -amido acids will exhibit the band shifts associated with "carboxy-amido" bonding, and only the straight chain ( $\omega$ ) amido-acids will not. This is demonstrated by the fact that the ASA compounds, which are branched but are not  $\alpha$ -amido-acids, exhibit the band shifts while the straight chain AUA compounds do not. The reason for this phenomenon is not known, but crystallographic comparison of the branched, the straight chain and the simple  $\alpha$ -substituted amido-acids could supply an answer.

**Group II. Normally Bonded Compounds Complicated by Resonance Effects.**—This group includes numbers 5-7 and 5e-7e of Table IV, AUA, AUA-Me ester, amorphous ASA-

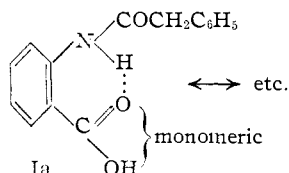
I and -II, and ASA-I methyl ester. The influence of the double bond conjugation on the amide C=O of the AUA and ASA compounds has been mentioned earlier. This same shift to longer wave lengths is noted for the double bond conjugated esters 5e and 7e which now absorb at 5.80 and 5.81  $\mu$ , respectively, a value in good agreement with that found by Rasmussen and Brattain<sup>13</sup> for this type of com-



(13) R. S. Rasmussen and R. R. Brattain, THIS JOURNAL, 71, 1073 (1949).

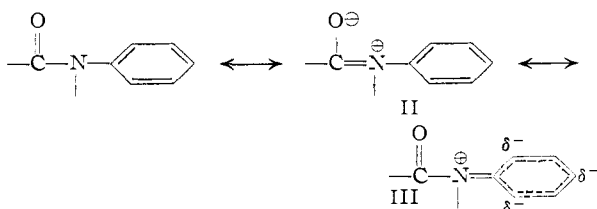
pound. Number 6e shows the effect of carbonyl-phenyl conjugation greatly enhanced by the additional resonance form I due to the electron-supplying *o*-nitrogen and stabilized by chelation. This effect is identical with that observed for methyl anthranilate which absorbs at  $5.92 \mu$ .<sup>14</sup>

The effect of conjugation and resonance on the acid C=O band is not as clear as with the ester. Thus in numbers 5 and 7 we find the acid C=O band at very near the same wave length as for non-conjugated acids, even though Freeman<sup>15</sup> has shown that carboxyl conjugated with C=C absorbs at *ca.*  $0.05 \mu$  higher. The acid C=O of no. 6 is found at  $5.93 \mu$ , a wave length characteristic of phenyl-conjugated acids such as benzoic acid which absorbs at  $5.94 \mu$ .<sup>16</sup> However, the additional resonance due to the *ortho* substituent is entirely absent in the acid; were it present we would expect the acid C=O band near  $6.00 \mu$  as it is in the case of anthranilic acid.<sup>17</sup> It is probable that here the usual dimeric carboxyl ring has been somehow disrupted due to chelation, as shown in Ia. The corresponding N-disubstituted compound (see



no. 17), in which chelation is not possible, does not afford any additional information since it falls into the category of "carboxy-amido" bonded compounds. It is hoped that the structure of these *o*-N-acylanthranilic acids will be elucidated further by an investigation of the *meta* and *para* isomers.

Introduction of a double bond on the amide N seems to have little or no effect on the amide C=O absorption (see no. 5 and 7). This is in direct contrast to N-substitution of phenyl and it will be shown that the converse is true when C=C and phenyl are on the C=O rather than on the N. Richards and Thompson<sup>18</sup> have shown that when a phenyl group is attached to the amide N, then the C=O wave length is lowered by an average of  $0.1 \mu$  for monosubstituted amides (see Table I). This is attributed to inhibition of the usual amide resonance II, by contribution of form III.

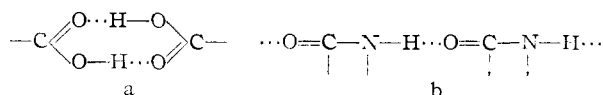


This accounts for the abnormally low amide C=O wave length in no. 6 but raises a question concerning the  $6.31 \mu$  band in the corresponding ester (no. 6e). This band has been assigned by Randall<sup>3</sup> to both the amide C=O and conjugated phenyl. Inasmuch as amide resonance will be inhibited further in the ester by forms such as I as well as III, it is believed that the amide band has been lowered to the point where it is superimposed upon the ester C=O band at  $5.93 \mu$ , the enhanced  $6.31 \mu$  band being due only to conjugated phenyl.

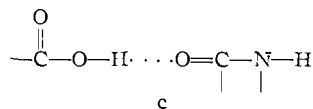
**Group III. "Carboxy-Amido"-Bonded Compounds.**—This group includes no. 8–15 of Table IV and dihydro ASA. The important stretching bands and the wave length shifts observed on comparing these compounds to simple amides and acids, is given in Table V.

It has been shown that in the solid state simple carboxylic acids and monosubstituted amides exist in the completely bonded form, the acids existing

as dimers and the amides as linear chains.<sup>18</sup> This bonding is illustrated in a and b.



In the "carboxy-amido" bonded compounds however, bonding as in a and b is replaced by c in



which a strong intermolecular bond is formed between the hydroxyl and the amide carbonyl with neither the acid carbonyl nor the NH of the (monosubstituted) amide involved in a bond of any appreciable strength. This is in agreement with the X-ray work of Carpenter and Donohue<sup>19</sup> who examined crystals of N-acetylglycine, a compound which would be expected to fall into the category of "carboxy-amido" bonded compounds. Moreover, the NH and OH bands of N-acetylglycine have been investigated by others<sup>20,21</sup> who have concluded that the N-H . . . O bond is very weak while the O-H . . . O bond is exceptionally strong.

Bonding as in c satisfactorily accounts for the previously unexplained band shifts encountered in certain amido-acids. The short wave length shift of the NH and acid C=O bands and the long wave length shift of the OH and amide C=O bands indicate that the former are no longer involved in a strong bond, while for the latter the bonding is now stronger than usual. The relation between bonding and resonance in its effect upon the individual band shifts will now be discussed.

It is generally accepted that resonance of type II makes a greater contribution in the amides than in the acids, while the converse is true of hydrogen bonding. The resonance effects may be evaluated by comparing the C=O wave length of the unbonded amide to the unbonded acid. Since the former absorbs at a substantially longer wave length we may conclude that the amide C=O group has more single bond character than the carboxyl C=O and that therefore resonance is more important in the amide. The bonding effect may be evaluated by comparing the increase in wave length observed in going from the non-bonded to the bonded form. Since in the acid this amounts to  $0.21 \mu$  while in the amide (monosubstituted) the increase is  $0.14 \mu$ , we may conclude that bonding is more important in the acid. It is obvious that both of these effects may have been predicted on the basis of the relative electronegativities of oxygen and nitrogen.

Application of the above permits a reasonable explanation of the OH and amide C=O band shifts. The hydrogen bond linking the acid OH to the amide C=O is especially strong<sup>22</sup> by virtue of the combination of both the large resonance contribution of the amide and the bonding contribution of the acid. The increased electron density at the amide C=O oxygen due to the amide resonance enables the O-H to form a stronger bond than in the normal acid dimer, and this is manifested in a longer absorption wave length. Similarly the amide C=O wave length is lengthened as a result of its being bonded to the oxygen of the acid O-H, rather than to the less electronegative nitrogen, as in simple amides and straight chain amido acids. This type of intermolecular bond may be contrasted to that involving a hydrogen bond between the amide N-H and the acid C=O.

(19) G. B. Carpenter and J. Donohue, *THIS JOURNAL*, **72**, 2315 (1950).

(20) R. Newman and R. M. Badger, *J. Chem. Phys.*, **19**, 1147 (1951).

(21) R. C. Lord and R. E. Merrifield, *ibid.*, **21**, 166 (1953).

(22) The value  $2.56 \text{ \AA}$ . for the O-H . . . O bond in acetylglycine (ref. 19, p. 2326) may be compared to the value of  $2.67 \text{ \AA}$ . as found for the O-H . . . O bond in formic acid dimer (ref. 25, p. 306).

(14) Reference 3, p. 107.

(15) N. K. Freeman, *THIS JOURNAL*, **75**, 1859 (1953).

(16) Reference 3, p. 104.

(17) Reference 3, p. 121.

(18) R. E. Richards and H. W. Thompson, *J. Chem. Soc.*, 1248 (1947).

In this case the donor atom is the less electronegative nitrogen and the acceptor is the oxygen bearing a smaller resonance-induced electron density. It is therefore not surprising to find that the  $\text{O}=\text{CNH}\cdots\text{O}=\text{C}-\text{OH}$  bond plays an insignificant role in the amido acids,<sup>23</sup> and accounts for the shortened N-H and acid C=O wavelengths. This is confirmed by the disubstituted amido acids 14 and 15 in which the usual band shifts are observed despite the complete lack of bonding involving N-H.

The acid C=O band shifts allow further speculation. Since it has been postulated that this C=O is no longer involved in a strong hydrogen bond, we might expect to find the C=O band at or near 5.68  $\mu$ , the value typical of a monomeric carboxyl C=O. However, this band is actually found at significantly longer wave lengths and from this may be deduced information regarding the effect of bonding on resonance. Pauling<sup>24</sup> and others<sup>10,25</sup> have pointed out that in the case of the carboxylic acid dimer the ionic forms due to resonance will tend to make the hydrogen bond between the electropositive proton and the electronegative C=O oxygen even stronger. However, "carboxy-amido" bonding demonstrates that the converse of this is also true; that strong bonding of the OH proton will stabilize any

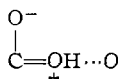
TABLE V

WAVE LENGTH<sup>a</sup> (IN  $\mu$ ) OF STRETCHING BANDS FOR SOLID "CARBOXY-AMIDO" BONDED COMPOUNDS

	C=O	$\Delta^b$	N-H	$\Delta^b$	O-H	$\Delta^b$
-COOH	5.83 <sup>c</sup>	-0.06	..	....	4.0-4.1	+ ca. 0.6
-CONHR	6.23	+ .14	2.97	-0.09	.....	.....
-CONRR'	6.27	+ .19	..	.....	.....	.....

<sup>a</sup> Unless otherwise indicated, the wave lengths are  $\pm 0.02 \mu$ . <sup>b</sup> This represents the difference between the bands in this table as compared to the corresponding bands for simple compounds as given in Table I. <sup>c</sup> This band is found at 5.79  $\mu$  in the ASA compounds.

ionic contribution involving the carboxyl C=O. The comparatively long wave length of the non-bonded acid C=O in these compounds can be due only to the strong  $-\text{OH}\cdots\text{O}=\text{CN}-$  bond which in making available electrons at the hydroxyl oxygen increases the contribution from the resonance form



It follows that any weakening of the  $-\text{OH}\cdots\text{O}=\text{C}-$  bond would decrease the ionic carboxyl resonance and should result in a shorter acid C=O absorption. Confirmation was found in compound 18. Here, as explained above, the phenyl group decreases amide resonance (as manifested in the low wave length shift of the amide C=O from ca. 6.29 to 6.11  $\mu$ ). This inhibition of amide resonance decreases the electron density at the amide oxygen, effectively lowers the strength of the  $-\text{NC}=\text{O}\cdots\text{HOC}=\text{O}$  bond and decreases the resonance contribution of this hydrogen bond to the carboxyl C=O. As a result this band absorption is now found at 5.71  $\mu$ , a value very near that for a monomeric acid C=O. Further confirmation is found with no. 17 which displays a similar effect, but in this case the acid C=O is at 5.83  $\mu$  due to the phenyl conjugation. If we

(23) Again in the case of N-acetylglycine, the value of 3.03  $\text{\AA}$ . for the N-H $\cdots$ O bond may be contrasted to the usual value of 2.8  $\text{\AA}$ . as found in amino acids (ref. 19, p. 2327).

(24) L. Pauling, "The Nature of the Chemical Bond," Cornell University Press, Ithaca, N. Y., 1948, p. 307.

(25) Y. K. Syrkin and M. E. Dyatkina, "Structure of Molecules and the Chemical Bond." Interscience Publishers, Inc., New York, N. Y., 1950, p. 274.

compare this to no. 6 we see that the acid C=O of no. 17 has indeed been lowered by 0.1  $\mu$ .

**Group IV. "Carboxy-Amido" Bonded Compounds Complicated by Resonance and Inductive Effects.**—In this group we find (the previously discussed) 16-18 of Table IV, and crystalline ASA-I and -II. Conjugation of amide C=O with C=C as in ASA-I and -II, seems to have no effect on the C=O band since the latter remains at substantially the same wave length as in the non-conjugated dihydro ASA-I. The absence of effective resonance is emphasized further by the observation that the 6.06 band assigned to C=C decreases to a medium intensity in crystalline ASA-I and -II, while it remains strong in the non-"carboxy-amido" bonded compounds shown in Table III. This phenomenon is as unexplained as the observation that phenyl conjugated with the C=O of simple amides does not increase the C=O wave length,<sup>18</sup> as it does with esters, acids and ketones.

In hippuric acid (no. 16) we find the amide C=O at approximately the wave length expected for a non-conjugated "carboxy-amido" bonded compound, indicating that again the phenyl conjugation has little effect. Further, were the phenyl conjugation enhancing the ionic contribution to the usual amide resonance we would expect a stronger bond between the amide and acid and this would be expected to lengthen the acid C=O wave length. Instead we find this C=O band at 5.72  $\mu$ , a value comparable to that of 18 in which the phenyl is on the nitrogen of the amide, rather than the carbonyl. It can only be suggested that in this case it is an inductive effect which is responsible; the fact that the amide C=O of the ethyl ester of hippuric acid (no. 16e) is also much lower than usual, though the ester is not subject to anomalous bonding, would seem to bear this out.

Finally, it is noted that approximately six amido acids whose spectra are given by Randall<sup>3</sup> are not included in this present study. For the most part these exhibit features common to both simple and "carboxy-amido" bonded compounds and, for the present at least, no conclusions regarding their structure can be made.

**The Amide-II Band.**—This band, found near 6.5  $\mu$  in monosubstituted amides, has been investigated intensively.<sup>26,27</sup> Though its assignment as an NH bending band is currently favored, there is recent evidence which points to its being a C-N stretching band.<sup>28</sup> An observation in favor of the latter assignment is presented here. It was noted, and is pointed out in Table II, that the strong amide-II band at 6.45  $\mu$  was resolved into a sharp doublet when thin films were examined. This doublet absorbed at 6.41 and 6.50  $\mu$  in all the amido acids shown in Table II, though in some cases the former band was more intense while in others the opposite was true.<sup>29</sup> Were the amide-II band due to N-H bend we would expect absorption at a longer wave length in the weakly N-H bonded "carboxy-amido" (group III and IV) compounds, as compared to the stronger N-H bonded normal (group I and II) compounds. Since in fact this does not occur, assignment of the amide-II band to C-N stretching is indicated.

**Acknowledgments.**—The author is indebted to Dr. A. I. Medalia, Profs. W. J. Gensler and J. P. Mason for their encouragement and advice, and to Prof. R. C. Lord and Mrs. Erika Smakula for their suggestions and critical reading of the manuscript.

BOSTON 15, MASS.

(26) Reference 3, pp. 10-13.

(27) Reference 1, pp. 389 ff.

(28) H. Letaw, Jr., and A. H. Gropp, *J. Chem. Phys.*, **21**, 1621 (1953).

(29) It is not known whether this feature was observed by Randall,<sup>3</sup> but it could account for the amide-II band wave length variations as given in Table IV.