August, 1974] BULLETIN OF THE CHEMICAL SOCIETY OF JAPAN, VOL. 47(8), 1833—1837 (1974) 1833

An Infrared Study of the Steric Effects of Alkyl Substituents on the N–H Stretching Absorptions of *sym*-Dialkylureas

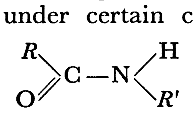
Yoshiyuki Mido

Department of Chemistry, Faculty of Science, Kobe University, Nada, Kobe 657

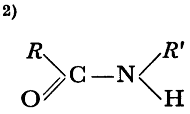
(Received October 6, 1973)

By examining their N–H stretching absorptions in the hydrogen-bonding system, the steric effects of the substituent on the C=O or N–H group have been studied for *sym*-disubstituted alkylureas of the *R*HNCONH*R'* type in carbon tetrachloride. By comparing the estimated percentage of the monomer, it is concluded that the steric effects are not large enough to convert the *trans* conformation into the *cis* conformation, though the branched alkyl groups may prevent another molecule from approaching more strongly than the normal alkyl groups. Correlations among some spectral parameters have been examined, such as the estimated percentage of the monomer, the frequency shift upon hydrogen-bond formation, the apparent integrated absorption intensity, and the half-intensity width of the associated band.

The peptide group in secondary amides has been shown to adopt possibly the *trans* and/or *cis* conformation under certain conditions:[1,2)]



trans

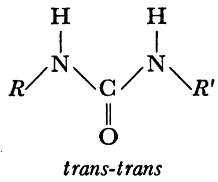


cis

The more favorable conformation and its percentage in solution are mainly decided by the steric factor between the substituents, *R* and *R'*, and the C=O group.[1–6)] The steric factor can affect the intensity of the associated band; that is, the larger the size of the *R* and *R'* groups, the weaker the intensity.[5,6)] The N–H stretching frequencies characteristic of their conformations have been established.[1–6)]

As *sym*-dialkylureas have the –CO–NH– structure, such as in secondary amides, it seemed that it would be interesting to examine the relationships between the size of *N*-alkyl substituents and the intensity of the associated N–H stretching band in solution, and to estimate the limit of the size which can convert the dominant *trans* conformation into the *cis* conformation, if the steric hindrance of a bulky group such as *tert*-butyl can convert in that manner.

We have studied various alkylureas by infrared spectrometry and have shown that *sym*-dialkylureas are dominantly in the *trans-trans* conformation in the solid[7,8)] and liquid states,[7)] and in solutions.[9,10)]



trans-trans

However, our conclusion regarding *sym*-di-*tert*-butylurea (*s*-D*t*BU) in solutions did not agree with that of Rao *et al.*,[11)] suggesting that, of the two closely-spaced monomeric N–H stretching bands, the stronger band, at 3437 cm^{-1}, arises from the *cis* rotamer.[12)] The other band, at 3469 cm^{-1} (indicated as a weak band by an arrow sign in Fig. 1) could be interpreted as being due to the *cis* conformation; we do not, however, have any conclusive evidence yet, though it is certain that the 3469 cm^{-1} band does not originate from the *trans* conformation.

The purposes of the present study are: (1) to examine whether or not the steric hindrance of a bulky group or groups such as *tert*-butyl is large enough to convert the *trans* conformation into the *cis* conformation, and (2) to establish possible correlations among the spectral parameters obtained from the N–H stretching absorptions for various *sym*-dialkylureas in a dilute carbon tetrachloride solution.

Experimental

All the dialkylureas used had already been identified in our previous studies.[7,8)] Carbon tetrachloride for spectroscopy was used. The spectra (3600—3200 cm^{-1}) were recorded with solvent compensation at a slow speed and using a five-fold-scale expansion in frequency. The measurements were made at 27°±2 °C with a Hitachi EPI-G2 Infrared Grating Spectrophotometer.

The 0.0025 M solutions in carbon tetrachloride were examined using a 2.0-cm NaCl cell. Some typical spectra are shown in Fig. 1. The apparent molar extinction coefficient, ε, for the monomeric N–H stretching band of each sample was determined by measuring its apparent optical density, O.D.$_{\text{mono}}$ of a 0.0005 M solution (using a 5.0-cm NaCl cell), in which the associated band no longer appears. The ε is defined as:

$$\varepsilon = \frac{1}{CL}\log_{10}\left(\frac{T_0}{T}\right)_{\nu_{\max}}$$

where C is the concentration of the solute in moles per liter, L is the cell length in cm, and T_0 and T are the apparent intensities of the incident and transmitted radiation at the maximum wave number respectively.

In order to obtain reliable data, three or more samples were independently prepared for each of the dialkylureas, and their spectra were recorded. The spectral parameters were independently estimated from three or four of their reproducible spectra. The average value of the estimations is listed in Table 1. As the monomeric and associated bands significantly overlap one another, and as the latter band is much broader, as is shown in Fig. 1, the average values are considered to have some certainty. Therefore, the O. D.$_{\text{mono}}$, the O. D.$_{\text{asso}}$, and the frequency shift, $\Delta\nu$, were obtained from the band-contours before the graphical separation by Jones' method,[6)] while the apparent integrated absorption intensity, B, and the half-intensity width, $\nu_{1/2}$, of the associated band were obtained from the band contours after the graphical separation. The estimated concentration percentage of the monomer, C_{mono}/C, was calculated from the O. D.$_{\text{mono}}$ and

TABLE 1. IR DATA FOR N-H STRETCHING BANDS OF DIALKYLUREAS (0.0025 mol/lit. in CCl_4)

Compound				Monomer band		Association band			
No.[a]	R'		ε[b]	O.D.	C_{mono}/C (%)	O.D.	B[c] ($\times 10^{-3}$)	$\nu_{1/2}$ (cm^{-1})	$\Delta\nu$[d] (cm^{-1})
	$CH_3NHCONHR'$								
1	Methyl	*s*-DMU	127	0.475	75	0.176	10	123	88
2	Ethyl	MUE	107.5	0.424	79	0.191	9.5	113	90
3	Propyl	MUP	110	0.417	76	0.184	9	110	87
4	Isopropyl	MU*i*P	90 (49)[e]	0.382 (0.229)	85 (93.5)	0.165	7.5	109	79[f]
5	Butyl	MUB	112.5	0.439	78	0.163	8	110	90
6	*s*-Butyl	MU*s*B	90.5 (46)[e]	0.371 (0.205)	82 (89)	0.165	7	108	81[f]
7	*t*-Butyl	MU*t*B	91.5 (41)[e]	0.419 (0.204)	91.5 (99.5)	0.082	3.5	90	65[f]
	$C_2H_5NHCONHR'$								
8	Ethyl	*s*-DEU	98.5	0.399	81	0.189	9	113	84
9	Propyl	EUP	97.5	0.403	82.5	0.152	6.5	108	80
10	Isopropyl	EU*i*P	79	0.369	93.5	0.125	4.5	99	76
11	Butyl	EUB	93.5	0.404	86.5	0.147	6	104	81
12	*s*-Butyl	EU*s*B	83	0.369	89	0.139	5.5	102	81
13	*t*-Butyl	EU*t*B	80	0.379	95	0.084	2.5	77	71
	n-$C_3H_7NHCONHR'$								
14	Propyl	*s*-DPU	93	0.381	82	0.161	7	103	82
15	Isopropyl	PU*i*P	74	0.334	90.5	0.127	5	97	75
16	Butyl	PUB	87	0.367	84.5	0.177	8	106	83
17	Isobutyl	PU*i*B	86	0.365	85	0.190	8.5	106	86
18	*s*-Butyl	PU*s*B	76.5	0.336	88	0.143	5.5	93	78
19	*t*-Butyl	PU*t*B	75	0.342	91	0.079	2	77	73
	n-$C_4H_9NHCONHR'$								
20	Isopropyl	BU*i*P	76	0.342	90	0.114	4	89	70
21	Butyl	*s*-DBU	91.5	0.376	82	0.150	6.5	107	79
22	*s*-Butyl	BU*s*B	77.5	0.343	88.5	0.133	5	96	74
23	*t*-Butyl	BU*t*B	71.5	0.339	95	0.077	2.5	80	75
	The other $R'NHCONHR'$								
24	Isobutyl	*s*-D*i*BU	96	0.369	77	0.221	9	100	88
25	*s*-Butyl	*s*-D*s*BU	83	0.386	93	0.117	4	86	67
26	*t*-Butyl	*s*-D*t*BU	77.5	0.362	93.5	—	(0.5)	—	(60)
27	*t*-Amyl	*s*-D*t*AU	80.5	0.376	93.5	—	(0.5)	—	(60)

a) Point number in figures. b) Apparent molar extinction coefficient ($mol^{-1}\cdot l\cdot cm^{-1}$). c) $B=\int\frac{1}{CL}\log_e\left(\frac{T_0}{T}\right)d\nu$ ($mol^{-1}\cdot l\cdot cm^{-2}$). d) $\Delta\nu=\nu_{mono}-\nu_{asso}$, see Ref. 9 for ν_{mono}. e) Side band (monomer), see Experimental. f) The average value, see Experimental.

ε values. The B is defined as:

$$B=\frac{1}{CL}\int\log_e\left(\frac{T_0}{T}\right)d\nu$$

where $d\nu$ is the differential of the wave number.

In a special case with such a band-splitting as is seen in MU*i*P, MU*s*B and MU*t*B, when the values of parameters are as plotted in Figs. 2—7, the average value of two for the splitting in a spectral parameter was used except in C_{mono}/C and the corresponding ε in Figs. 2 and 4 respectively, since, generally, the N–H vibrations, which derive from two components due to two N–H groups on dialkylurea, appear as only one band. The exceptional C_{mono}/C in Fig. 2 for the special three was estimated for only the higher component in splitting because the intensity of the lower component is considerably affected by the neighboring associated band.

The uncertainties of C_{mono}/C, B, $\nu_{1/2}$, and $\Delta\nu$ may be estimated to be about 4%, 0.5×10^3 $mol^{-1}\cdot cm^{-2}$, 7 cm^{-1}, and 5 cm^{-1} respectively.

Results and Discussion

It is expected that the bulkier the effective size of alkyl substituents on dialkylureas is, the larger the steric hindrance between the C=O and the substituents will be, and the harder the intermolecular association through hydrogen bond will be, thus weakening the intensities of associated bands. Figure 1 shows the expected spectral behavior of the broader associated N–H band in dialkylureas; in their associated band-intensities, *s*-DMU, with the smallest methyl groups, is the strongest, while *s*-D*t*BU, with the largest *tert*-butyl groups, is the weakest, the other two being in the middle.

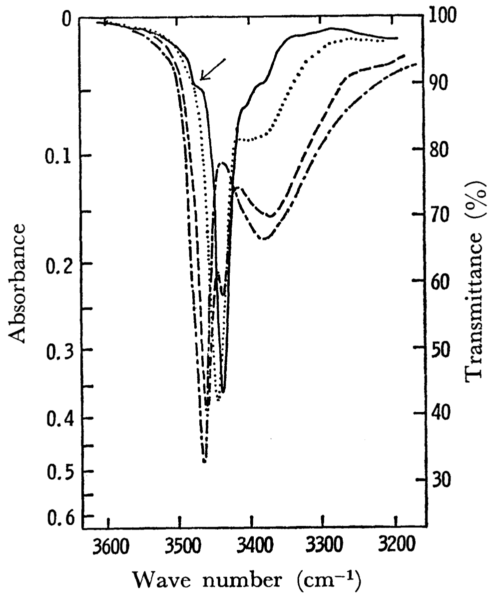


Fig. 1. Infrared spectra, N-H stretching region, of dialkylureas in CCl_4 (0.0025 M), ——————: *s*-DMU (1), ------: MU*i*P (4), ······: EU*t*B (13), ——: *s*-D*t*BU (26). An arrow sign indicates the questionable band, which was assigned to the *trans* ν(N-H) vibration by Rao *et al.*[1)]

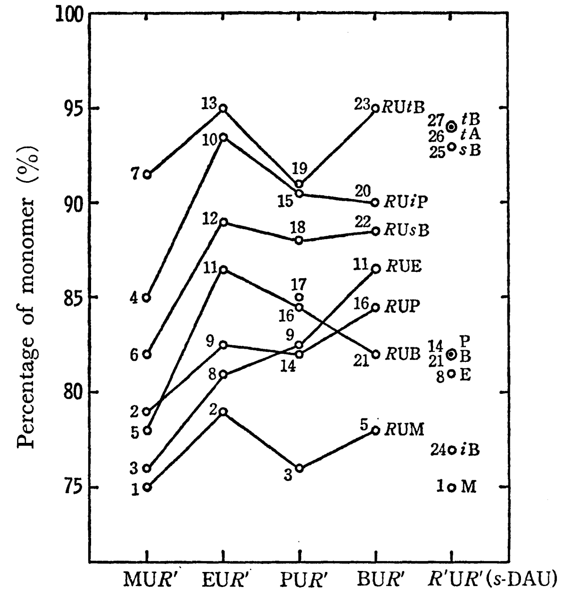


Fig. 2. The estimated percentage of monomer of dialkylureas in CCl_4 (0.0025 M). The points are numbered as in Table 1, column 1 (as in Figs. 3—7). The observed data for dialkylureas with the same *R'* group are connected by a line.

The band-splitting of the monomeric absorption in MU*i*P (as well as in MU*s*B and MU*t*B) results from two different types of N-H groups, the higher component resulting from the methyl group, and the lower component, from the branched alkyl group, but not from rotational isomerism.[9,10)] As the above monomeric band has been already assigned to the *trans* conformation except for the 3469 cm^{-1} band in *s*-D*t*BU,[9,10)] it is also reasonable to similarly assign the associated band to the *trans* conformation.[13)] Several spectral data obtained quantitatively are summarized in Table 1.

The estimated percentage of the monomer is plotted in Fig. 2 for four series of *R*HNCONH*R'* (*R*U*R'*) according to the *R* group and a series with the same substituents (*s*-DAU). As may be seen in Fig. 2, the percentages are sensitive to the alkyl substituent and may be classified into three groups; the derivatives with a methyl group (*R*UM) have the lowest value, those with another primary alkyl group have a middle value, while those with such a branched alkyl group as isopropyl, *sec*- and *tert*-butyl have the highest value. The values for *s*-DAU are more sensitive to the alkyl substituents.

This suggests that the percentage roughly differentiates the alkyl substituent on dialkylurea. Also, the monomeric N-H stretching frequency of dialkylurea has been found to differentiate the alkyl substituent.[9,10)] Therefore, we examined the correlation between the frequency and the percentage (Fig. 3). Figure 3 shows that the larger the percentage, the lower the frequency. It is interesting to note that the hydrogen-bonding formation ability of dialkylurea may, qualitatively but directly, be deduced from its monomeric N-H stretching frequency itself, though it can also, of course, be deduced from the well-established correlations of the frequency shift, $\Delta\nu$, with the physical properties.[14)]

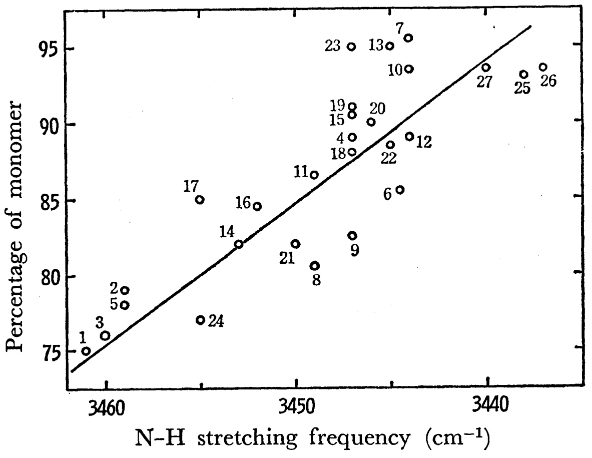


Fig. 3. The correlation between the monomeric N-H stretching frequency and the percentage of monomer.

Among the percentages of dialkylureas with a branched alkyl group or groups, there is no drastic difference, though there is a slightly increasing inclination in the percentage order: *R*U*s*B<*R*U*i*P<*R*U*t*B. This indicates that the steric hindrance between C=O and a *tert*-butyl group or groups is not large enough to drastically convert the *trans* conformation into the *cis* conformation. The indication adds support to our conclusions[9,10)] that the dialkylureas examined exist dominantly in the *trans-trans* conformation in solution and that the stronger band at 3437 cm^{-1} of the two monomeric N-H stretching bands of *s*-D*t*BU arises from the *trans* conformation, contrary to the assignment by Rao *et al.*[11)]

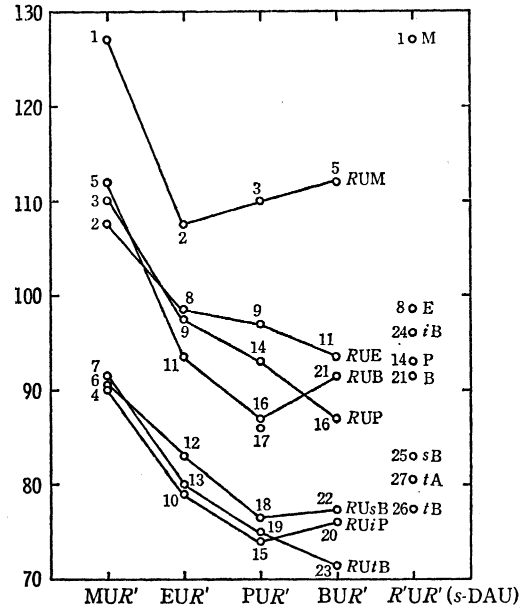


Fig. 4. The apparent molar extinction coefficient ε of dialkylureas in CCl_4 (0.0005 M, 5 cm).

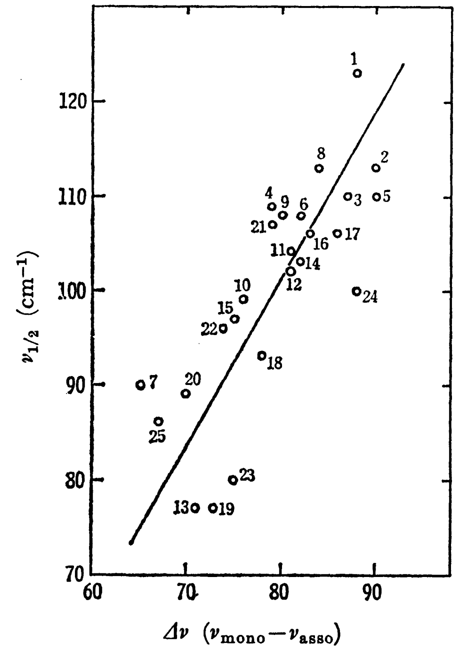


Fig. 5. The correlation between the frequency shift $\Delta\nu$ and the half-intensity width $\nu_{1/2}$.

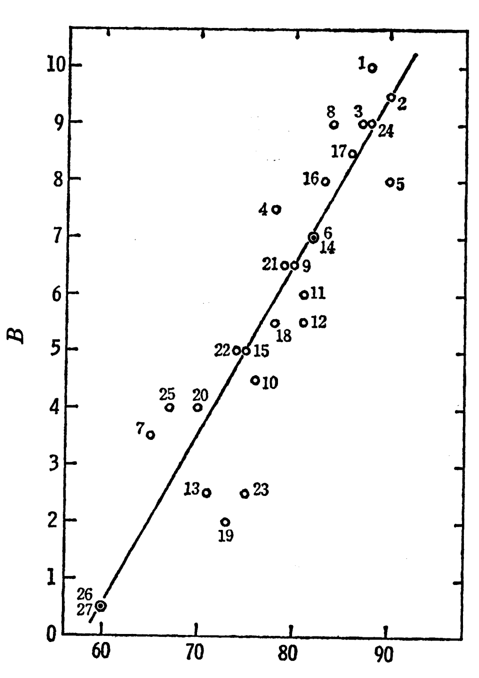


Fig. 6. The correlation between the frequency shift $\Delta\nu$ and the apparent integrated absorption intensity *B*.

The zig-zag-like line-plots in Fig. 2 seem to stem from the steric effect characteristic of the substituent on the hydrogen bond. The fact that no line-plots of the apparent molar extinction coefficients, ε, shown in Fig. 4 are zig-zag suggests that the steric effect affects the hydrogen-bonding formation and that the effect of the ethyl group is quite effective. Similar studies of *N*-alkylamides *R*CONH*R'* have shown that, of the *n*-alkyl groups, the ethyl group most greatly hinders the hydrogen-bonding formation, and that the effects of the longer-chain alkyl group are constant.[5,6)]

The plots for ε may also be classified into three groups according to the *R'* group in *R*U*R'*. As there are large differences in ε among the three groups, it must be emphasized that when a hydrogen-bonding system is quantitatively studied, an examination should be made not only of the intensity of the associated band, but also of that of the monomeric band.

The amount of the X–H stretching frequency shift, $\Delta\nu$, upon a hydrogen-bonding system (X–H···Y) has generally been accepted as a measure of the strength of the hydrogen bond, and it has been directly related to the half-intensity width, $\nu_{1/2}$, and the intensity, *B*, of the associated band, the enthalpy of the hydrogen-bonding formation, and the X–H distance, but inversely related to the X···Y distance and the Hammett sigma function.[14,15)]

In the present study, some correlations among spectral parameters have been examined for the hydrogen-bonding system of dialkylureas in a 0.0025 M carbon tetrachloride solution. It is quite evident from Table 1 and Fig. 1 that the bulkier the *R* and *R'* groups in *R*U*R'*, the smaller the $\Delta\nu$, $\nu_{1/2}$, or *B* value. The correlations between $\Delta\nu$ and $\nu_{1/2}$ or *B* were found to be linear (Figs. 5 and 6). A similar correlation was established between *B* and the estimated percentage of the associated species, C_{asso}/C (Fig. 7). The remarkable deviation of Points 26 (for *s*-D*t*BU) and 27 (*s*-D*t*AU) in Fig. 7 is considered to arise because their percentages of associated species were overestimated, since the questionable band at 3469 cm^{-1} in *s*-D*t*BU and the corresponding band in *s*-D*t*AU, which are also monomeric bands, as described, were not estimated to be added to their percentages of the monomer.

It is natural that the bulkier the alkyl substituents of dialkylureas are, the smaller the values of the $\Delta\nu$, $\nu_{1/2}$, *B* and C_{asso}/C become and, accordingly, the more closely the points approach to the original in Figs. 5—7.

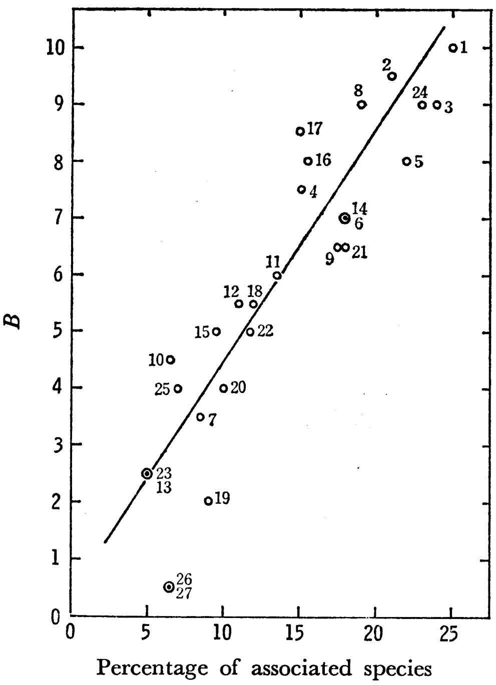


Fig. 7. The correlation between the estimated percentage of associated species C_{asso}/C and the apparent integrated absorption intensity B.

A comparison of the spectra of dialkylureas and *N*-alkylamides[6] shows clear differences in their spectral properties: (1) The $\Delta\nu$ values of the latter (*N*-alkylamides), when estimated from the spectra with N–H stretching band-intensities similar to those of the former, are approximately one and a half times as large as those of the former. (2) The former can form hydrogen bonds in a solution at a lower concentration than the latter. Probably, those spectral differences originate mainly from the differences in the electronic structure and the number of N–H groups per molecule. This consideration is supported by the facts that the C=O stretching frequencies of the former are generally higher than those of the latter, indicating the stronger tendency in the former to impart a double-bond character to the C=O bond, and that trialkylureas with only one N–H group give spectra with band-intensities similar to the latter at the same concentration.[16]

The author wishes to express his deep gratitude to Dr. Hiroatsu Matsuura of the Institute for Protein Research of Osaka University for his kind advice and to Prof. Hiromu Murata of Hiroshima University for his encouragement.

References

1) L. J. Bellamy, "The Infrared Spectra of Complex Molecules," 2nd ed., Methuen, London (1958), Chap. 12.

2) H. E. Hallam and C. M. Jones, *J. Mol. Struct.*, **5**, 1 (1970).

3) R. A. Russell and H. W. Thompson, *Spectrochim. Acta*, **8**, 138 (1956).

4) I. Suzuki, M. Tsuboi, T. Shimanouchi, and S. Mizushima, *ibid.*, **16**, 471 (1960).

5) R. L. Jones, *ibid.*, **23A**, 1745 (1967).

6) R. L. Jones, *ibid.*, **22**, 1555 (1966).

7) Y. Mido and H. Murata, This Bulletin, **42**, 3372 (1969).

8) Y. Mido, *Spectrochim. Acta*, **28A**, 1503 (1972).

9) Y. Mido, *ibid.*, **29A**, 1 (1973).

10) Y. Mido, *ibid.*, **29A**, 431 (1973).

11) C. N. R. Rao, G. C. Chaturvedi, and R. K. Gosavi, *J. Mol. Spectry*, **28**, 526 (1968).

12) For dialkylureas, Rao *et al.* did not define the term "*cis* rotamer" with regard to the two C–N rotational axes. Three forms could be considered: the *trans-trans*, the *trans-cis*, and the *cis-cis* forms, but the *cis-cis* form is unlikely on steric grounds.[9] It is possible that there is no difference in the N–H frequency for the *trans* conformation between the *trans-trans* and the *trans-cis* forms. We propose that the *cis* conformation represents only a *cis* relation between an N–H group and a C=O group about the C–N rotational axis.

13) If the associated band of the *cis* conformation is considered in relation to the case of secondary amides, it must appear 100—150 cm^{-1} lower than that of the *trans* conformation.[1,4,5]

14) G. C. Pimentel and A. L. McClellan, "The Hydrogen Bond", W. H. Freeman and company, San Fracisco and London (1960), Chap. 3.

15) Chap. 23 in Ref. 1.

16) Y. Mido, to be published.