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Nuclear Magnetic Resonance Studies of Keto–Enol Equilibria. V. Isomerization in Aliphatic Schiff Bases[1]

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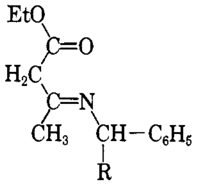
From the proton resonance spectra, structures are assigned to the isomers of ethyl β-benzylamino crotonate and of the condensation products of monoamines with hydroxymethylene ketones. In a variety of solvents, two isomers of each compound are noted; one isomer is a hydrogen-bonded ketamine in a chelated ring, and the second an extended structure with the chelated ring absent. Several of the compounds permit an evaluation of the *trans*-NH–CH spin–spin coupling constant. Molecular orbital calculations are used to gain further insight into the structures of the molecules.

Introduction

Previous investigations into the keto–enol tautomerization of Schiff bases prepared from monoamines and aliphatic dicarbonyl compounds have indicated that only one isomer—the keto-enamine—is present in solution.[2,3] Proton resonance spectroscopic studies on a wide variety of Schiff bases in several solvents have failed to uncover an observable amount of any of the other possible isomers. However, there are two systems described in the chemical literature for which isomeric Schiff bases have been isolated.[4–6]

Potapov, Trofimov, and Terent'ev have discussed tautomerization in the condensation product of (−)-α-phenylethylamine and acetoacetic ester. This compound exists in two interconvertible crystalline forms. One isomer, called here the *low-melting* isomer, possesses a melting point below room temperature, and the other, the *high-melting* isomer, melts in the 60–70° range. The lower melting isomer is apparently the more stable form.

The Russian workers, using optically active α-phenylethylamine, found that the liquid and a solution of the solid isomer possessed quite different optical rotations. Thus spectropolarimetry was a convenient analytical tool. From the analysis of the optical rotatory dispersion curves of the isomers, the Russians concluded that the high-melting compound may be a ketimine (**1**), and the more stable low-melting form, the enamine **2**.



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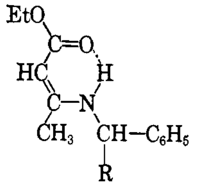
R=H, CH_3



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Earlier Schad[5] had assigned the enamine structure **2** (R = H) to both the high-melting and the low-melting varieties of Schiff bases derived from ethyl acetoacetate. He claimed, on the basis of solubility behavior, wet melting point depressions, ultraviolet, and infrared spectroscopy, that the difference between the two forms is an isomerization about the double bond. Thus, the low-melting species is the hydrogen bonded chelated form **2**, while the high-melting is an extended structure with intermolecular hydrogen bonds either to the solvent or to other Schiff base molecules (**4**).

Dabrowski[6,7] obtained two forms of the condensation products of amines with α-hydroxymethylene ketones by extracting with pentane at low temperatures. However, each isolated form rapidly reverted to the tautomeric mixture at room temperature. From detailed infrared studies[6,7] Dabrowski concluded that double bond isomerization in the vinylamine ketones is involved.

In all these cases, by utilizing a variety of solvents, the isomers present can be clearly deduced from the n.m.r. spectra of the compounds. The n.m.r. results clarify the ambiguous infrared studies and confirm the conclusions of Schad[5] and Dabrowski[6] that an isomerization about the double bond of the keto-amine form occurs.

Experimental

Spectra.—Spectra were obtained on a Varian A-60 spectrometer operating at 60.00 Mc. Line positions were determined by interpolating between side bands generated by an audiooscillator monitored by a frequency counter. The positions are accurate to 0.3 c.p.s. or 0.005 p.p.m. unless band width precluded such accuracy. The sample temperature was 31°.

Solutions.—Solutions for the n.m.r. spectra were prepared as previously described using tetramethylsilane as the internal zero of reference.[3] All chemical shifts are in p.p.m. downfield from this reference. Concentrations were approximately 1.0 *M* (10% w./v.) unless otherwise noted. The spectra in trifluoroacetic acid were taken immediately after making up the solutions and these solutions were not degassed.

Solvents.—Deuteriochloroform and pentadeuteriopyridine were supplied by Merck, Sharpe and Dohme of Canada. The other solvents were commercial reagent materials.

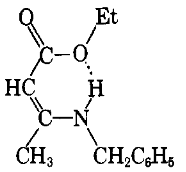
Compounds. Ethyl β-Benzylaminocrotonate.—Both the low- and the high-melting isomers were obtained by the procedure of Mohlau[8]; m.p. 23° and 65–70°, respectively (lit. 24° and 79°).

Schiff bases derived from hydroxymethylene ketones were prepared by the procedures of Benary[9,10] using only minor changes in conditions. Their properties agreed with those given by him. 4-Benzylamino-3-butene-2-one is a new compound, b.p. 116.5–117.0° (5 mm.), $n^{31}D$ 1.6048.

Anal. Calcd. for $C_{11}H_{13}NO$: C, 75.40; H, 7.48; N, 7.99. Found: C, 75.35; H, 7.63; N, 8.08.

Results

Ethyl β-Benzylaminocrotonate.—The proton resonance spectra of chloroform or carbon tetrachloride solutions of either isomer of ethyl β-benzylaminocrotonate are very similar to the spectrum of the neat liquid. Thus the same isomeric species predominates under these circumstances. The data for the spectra are listed in Table I. For purposes of comparison,[3] data for 4-benzylamino-3-penten-2-one are also given. From the n.m.r. results, it can be concluded that the low-melting isomer is the enamine **2** or **3**.



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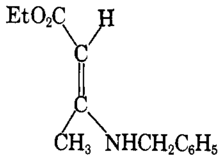

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(1) Part IV: *J. Am. Chem. Soc.*, **85**, 694 (1963).

(2) G. Dudek and R. H. Holm, *ibid.*, **83**, 2099 (1961).

(3) G. Dudek and R. H. Holm, *ibid.*, **84**, 2691 (1962).

(4) V. M. Potapov, F. A. Trofimov, and A. P. Terent'ev, *Zh. Obsch. Khim.*, **31**, No. 10, 3344 (1961).

(5) H. P. Schad, *Helv. Chim. Acta*, **38**, 1117 (1955).

(6) J. Dabrowski, *Spectrochim. Acta*, **19**, 475 (1963).

(7) J. Dabrowski and U. Dabrowska, *Roczniki Chem.*, **32**, 821 (1958).

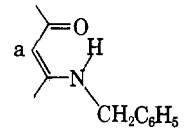
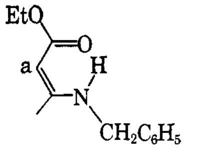
(8) R. Mohlau, *Ber.*, **27**, 3376 (1894).

(9) E. Benary, *ibid.*, **57**, 828 (1924); **59**, 108, 600 (1926); **63**, 1573 (1930).

(10) It should be noted that 4-amino-3-butene-2-one was always contaminated with a 3,4-disubstituted pyridine formed by self-condensation. It required several careful vacuum distillations to obtain a pure compound.

TABLE I

PROTON RESONANCE DATA IN P.P.M.

Compound	Solvent	Ethyl[a]		Methyls	Benzyl(*J*)[b]	H_a	NH
	Neat	. . .		1.70, 1.92	4.23 (6.3)[c]	4.99	11.3
	$CDCl_3$	. . .		1.89, 2.02	4.43 (6.7)	5.03	11.2
	Neat	1.11[d]	4.02	1.72	4.21 (6.4)	4.59	9.1[d]
	$CDCl_3$	1.23	4.05	1.88 (0.7)	4.47 (6.3)	4.48	8.9
	CCl_4	1.19	3.95	1.81	4.33 (6.5)	4.36 (0.7)	8.9
	C_6H_6	1.12	4.17	1.42 (0.7)	3.81 (6.5)	4.77 (0.7)	9.3
	$C_6H_5NO_2$	1.25	4.14	1.92	4.72 (6.5)	4.56	[f]
	CF_3COOH	1.18	4.35	2.71	5.01 (6.8)	4.0?	[f]
	C_6D_5N HMF[e]	1.17	4.15	2.62	4.30 (6.2)	4.95	[f]
	LMF	1.17	4.15	1.79 (0.6)	4.30 (6.2)	4.72	9.3

[a] *J* is 7.1 c.p.s. [b] In c.p.s. [c] Doublet. [d] Triplet. [e] Measured on the equilibrium mixture, using Fig. 3b for band identification (HMF, high-melting form; LMF, low-melting form). [f] Not located.

The hydrogen bonded NH signal for this isomer occurs at 8.9 p.p.m. The signal is clearly split into a triplet in the neat liquid (Fig. 1) and broadened in solution. The NH signal of 4-benzylamino-3-pentene-2-one is also a triplet in the neat liquid and unresolved in solution. The low field position of the acidic proton eliminates structure **4** for the low-melting isomer since the acidic proton of the nonchelated compound would appear at higher fields, even if it is intermolecularly hydrogen bonded, as in the dimedone Schiff bases[3] or the *trans* form of the amino vinyl ketones.

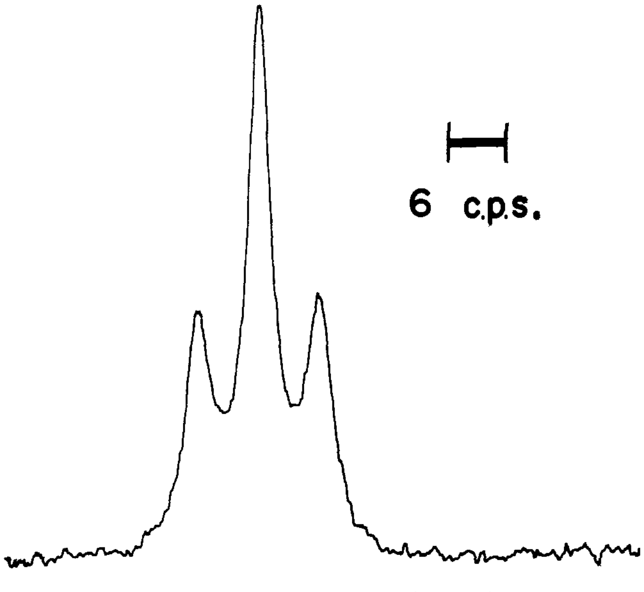


Fig. 1.—The amine hydrogen resonance of neat N-benzyl crotonate at 60.00 Mc.

In some solvents, the spectrum of the low-melting isomer is complicated in the 4-p.p.m. region by overlapping bands; however, the small solvent shifts in chloroform solution (Fig. 2) as compared to either carbon tetrachloride solution or the neat liquid assist in the interpretation of these signals. For the chloroform solution, the singlet at 4.48 p.p.m. is the vinyl signal, the doublet at 4.36 p.p.m. is due to the benzyl group (*J* = 6.3 c.p.s.), and the quartet at 4.05 p.p.m. is the methylene of the ethyl group with *J* = 7.1 c.p.s. The position and spin-coupling of the benzyl hydrogens are in the expected range, while the vinyl signal is about 0.5 p.p.m. to higher field than that of 4-benzylamino-3-penten-2-one. Upon integration of the peak areas, the ratios found are in agreement with the above assignments. Furthermore, when the chloroform solution is shaken with D_2O, the benzyl doublet collapses to a single unsplit signal.

In concordance with the conclusions of Schad[5] and Potapov, *et al.*,[4] the low-melting species is tautomer **2** or **3** for the following reasons: 1. The presence of the low field NH signal split into a triplet (the weaker hydrogen bond may indicate that **3** is a contributor to the structure of this tautomer[11]). 2. The corollary to this, the benzyl signal being a doublet which collapses upon deuteriation. 3. The presence of the vinyl signal.

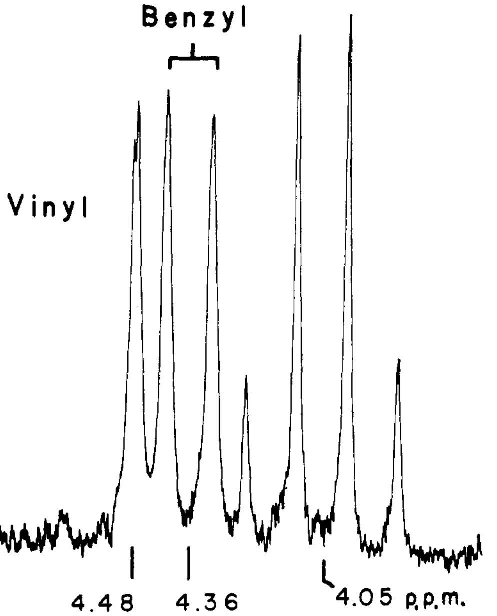


Fig. 2.—The vinyl region of N-benzyl crotonate nuclear magnetic resonance spectrum ($CDCl_3$ soln. at 60 Mc.)

The n.m.r. results bear out the observations of previous workers[4,5] that the rate and equilibrium of the tautomeric interconversion is markedly solvent dependent. In chloroform and carbon tetrachloride solutions the equilibrium heavily favors the low melting species and only traces of the other one can be detected in the proton resonance spectrum.[12] However, with pyridine as a solvent, the apparent rate of interconversion is much slower, and the final concentration of the high-melting moiety is somewhat larger than in the more inert sol-

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[11] A. R. H. Cole and G. T. A. Muller, *J. Chem. Soc.*, 1224 (1959).

[12] The solubility of the higher melting form may be the important factor here. With carbon tetrachloride and benzene as solvents, the solution process is slow (to 10% w./v.), while with pyridine the solution process is quite rapid.

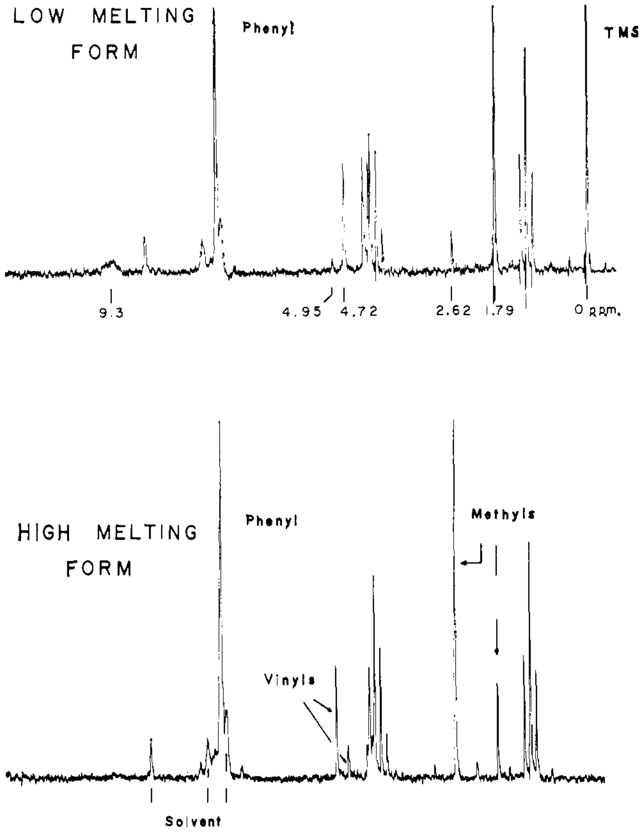


Fig. 3.—The proton spectrum of N-benzyl crotonate in deuteriopyridine. The upper spectrum is that of an equilibrium mixture, the lower one is that of the *high-melting* form 10 min. after it had dissolved.

vents. Figure 3a is the spectrum of the equilibrium mixture of both forms, while 3b is that of the solid species shortly after the isomer was dissolved in deuteriopyridine.[13]

In the spectrum of the high-melting isomer the vinyl and methyl resonances are shifted downfield, the methyl shift being particularly large (0.8 p.p.m.). The benzyl doublet (overlapping the methylene quartet) is present, but the NH band at 9.3 p.p.m. cannot be located. These observations are consistent with Schad's conclusions that the high-melting form is the *trans*, extended structure **4**, and the tautomerization of ethyl benzylaminocrotonate involves an isomerization about the double bond.

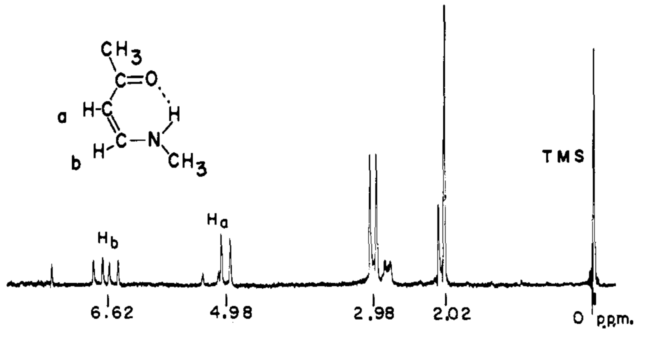
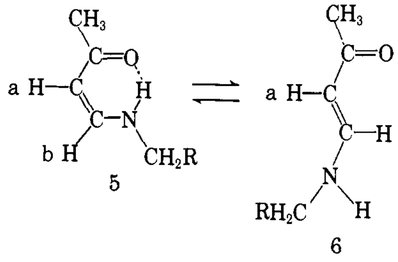


Fig. 4.—The n.m.r. spectrum of N-methyl-3-butene-2-one in $CDCl_3$ at 60.00 Mc.

4-Alkylamino-3-butene-2-ones.—The spectra of 4-methylamino-3-butene-2-one (**5**, R = H) are typical of the series and illustrate the behavior and analysis of the other members (the data are in Table II). For the chloroform solution (Fig. 4), the methyl singlet is at 2.02 p.p.m., the N-methyl doublet at 2.98 p.p.m. (J = 5.1 c.p.s.), and a doublet at 4.98 p.p.m. is from H_a (J = 7.4 c.p.s.). The quartet at 6.62 p.p.m. is due to the terminal vinyl (H_b) proton with a *cis*-double bond hydrogen spin–spin coupling of 7.4 c.p.s. and a *trans*-NH–CH spin–spin coupling of 12.8 c.p.s. The NH signal appears at 9.6 p.p.m.



There is an additional group of signals of smaller intensity which can be attributed to structure **6**. In this group, H_a appears at 5.18 p.p.m. with J = 13.3 c.p.s., suggestive of a *trans* coupling; the broadened N-methyl doublet is at 2.78 p.p.m. with J reduced to 4.2 c.p.s. The broadening of the doublet and the smaller spin coupling indicates that in the open structure proton exchange on the nitrogen is more facile.

When the concentration of 4-methylamino-3-butene-2-one in chloroform is 1.0 M, the ratio of the two isomers ($^6/_5$) is about 0.34; when the concentration is increased to 1.4 M, the methyl doublet of the *trans* form becomes a broad, unresolved singlet, while the ratio of the isomers increases to 0.39; at 1.9 M the ratio of isomers is 0.56. For the limiting case—the neat liquid—with no solvent present, the compound appears to be largely structure **6**. The low field NH signal of the neat liquid is not observed and may be hidden under one of the other bands at higher fields, while the vinyl hydrogen doublet (H_a) is broadened but with a J = 13.3 c.p.s. The high value of J_{H_a} and the large diamagnetic shift of the NH signal are the basis for the assignment of **6** as the structure of the prevailing form in the neat liquid.

The diamagnetic solvent shifts of benzene previously observed with Schiff bases are similar to the ones noted here.[2] The acetomethyl resonance is unaffected by the aromatic solvent, also the vinyl hydrogen (H_a). The N-methyl and the terminal vinyl (H_b) experience a diamagnetic shift of ~0.75 p.p.m. This effect is believed to arise from a weak hydrogen bond between the benzene and the carbonyl.[14] The interpretation is strengthened by the large negative charge on the oxygen according to the MO calculations (*vide infra*).

When the substituent on the nitrogen is altered from a methyl to a benzyl group, the stability of the chelated structure is increased. In chloroform solution, for example, the *trans* isomer of the benzyl derivative cannot be detected, while in the neat liquid the low field NH (at 9.9 p.p.m.) is not only present but is split into a readily observable quintet of J = 5.9 and 12.8 c.p.s. A small amount of the extended structure **6** was observed in neat 4-benzylamino-3-butene-2-one since the resonance at 4.98 p.p.m. (H_a) possessed a broadened companion doublet with J = 11.8 c.p.s. The amount of the *trans* species was found to be only about 10% of the *cis* by integration of the peak areas.

Phenyl (β-methylamino)-vinyl ketone displays the same high stability of the *cis* isomer since in chloroform solution only this isomer is observed.

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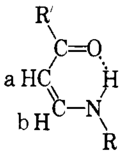
(13) Figure 3b was taken about 10 min. after dissolving the compound in the solvent. The spectrum after about 2 min. shows no trace of the lower melting form, but the 10-min. spectrum is illustrated for a better visual comparison.

(14) R. B. Moriarity, *J. Org. Chem.*, **28**, 1296 (1963).

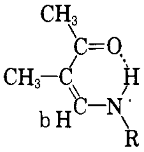
TABLE II

PROTON RESONANCE DATA FOR COMPOUNDS OF THE TYPE



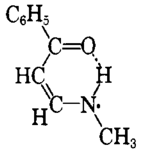
IN P.P.M. RELATIVE TO TETRAMETHYLSILANE

Compd., R =	Solvent	Methyl	R(*J*)[a]	H_a(*J*)[a]	H_b(*J*)[a]	NH
			R' = CH_3			
CH_3	Neat	T[b] 2.04	2.74	5.13(13.3)[c]	7.67 (13.2)	[e]
	$CDCl_3$ 1.9 *M*	C 2.02	2.98(5.2)	4.99(7.3)	6.64 $\begin{Bmatrix}7.3\\12.9\end{Bmatrix}^d$	9.7
		T 2.09	2.77	5.16(13.1)		
	$CDCl_3$ 1.0 *M*	C 2.02	2.98(5.1)	4.98(7.4)	6.62 $\begin{Bmatrix}7.3\\12.8\end{Bmatrix}$	9.6
		T 2.10	2.78(4.2)	5.19(13.3)		
	CCl_4	C 1.92	2.99(4.9)	4.85(7.3)	6.52 $\begin{Bmatrix}7.3\\12.7\end{Bmatrix}$	9.6
		T 1.98	2.75(2.9)	4.98(15.8)		
	C_6H_6	C 1.97	2.18(5.1)	4.87(7.3)	6.07 $\begin{Bmatrix}7.4\\13.7\end{Bmatrix}$	9.7
		T 2.03	2.32(4.7)	5.18(13.1)		
$CH_2C_6H_5$	Neat	C 1.88	4.11(5.8)	4.97(7.4)	6.67 $\begin{Bmatrix}7.5\\12.7\end{Bmatrix}$	9.93 $\begin{Bmatrix}5.9\\12.8\end{Bmatrix}$
		T . .	. . .	5.28(11.8)		
	$CDCl_3$	C 2.04	4.33(6.0)	5.03(7.5)	6.67 $\begin{Bmatrix}7.5\\12.8\end{Bmatrix}$	9.9
	CCl_4	C 1.93	4.27(6.1)	4.90(7.4)	6.54 $\begin{Bmatrix}7.4\\12.6\end{Bmatrix}$	10.0
	Neat	C 1.99	6.7	5.03(7.5)	7.1[h]	9.1
		T 2.05		5.42(12.8)	7.1[h]	6.7[g]
	$CDCl_3$ 2.0 *M*	C 2.04	6.7[g]	5.05(7.9)	6.78[h]	9.7
		T		5.39(13.2)		
	$CDCl_3$ 1.2 *M*	C 2.05	6.7[g]	5.05(7.9)	6.77[h]	9.0
	CCl_4	C 2.05	6.5[g]	4.92(8.4)	6.71[h]	9.0
		T 2.07		5.24(13.1)		
			R' = C_6H_5			
CH_3	$CDCl_3$		3.04(5.0)	5.68(7.4)	6.88 $\begin{Bmatrix}7.4\\12.7\end{Bmatrix}$	10.2
CH_2CH_2	$CDCl_3$	. . .	3.37(6.3)	5.69(7.6)	6.81 $\begin{Bmatrix}7.5\\12.5\end{Bmatrix}$	10.3



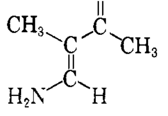
Compd., R =	Solvent	Acetomethyl	3-Methyl	R	H_b	NH
H	$CDCl_3$	C 2.18	1.82	. . .	6.7	. .
		T 2.11	1.67(0.8)	4.8	7.42(10.0)	4.8[f]
CH_3	CCl_4	C 1.97	1.77	2.95(4.9)	7.18(13.0)	10.3
		T 2.05	1.55	3.00(4.6)	6.42(12.0)	5.5
	$CDCl_3$ 0.9 *M*	C 2.07	1.81	2.95(4.9)	6.54(12.7)	9.4
		T 2.17	1.65	3.03(5.0)	7.23(13.0)	4.8
	$CDCl_3$ 1.6 *M*	C 2.07	1.80	2.95(5.1)	6.56(12.2)	9.6
		T 2.17	1.65	3.03(5.8)	7.26(13.5)	5.1

[a] Coupling in c.p.s. [b] C, *cis;* T, *trans* form. [c] Doublet. [d] Quartet. [e] Not located. [f] Intensity 2 protons. [g] Location somewhat uncertain. [h] Complex signal.



Dabrowski separated the two isomers of 4-amino-3-butene-2-one[6,7] and the infrared spectrum of each was thoroughly examined. His conclusion that the *cis* tautomer is the predominant isomer in dilute chloroform solution is consistent with our observation that the spin coupling constant for the vinyl hydrogen (H_b) is 7.5 c.p.s. The *trans* isomer is present to the extent of 10% of the *cis* isomer (at 2.0 *M*). The coupling constants involving H_b in 4-amino-3-butene-2-one cannot be readily evaluated since an ABXY system is involved.

A methyl group in the 3-position of the vinylamine alters the *cis–trans* equilibria to favor the *trans* form in solution. The proton resonance spectrum of the 3-methyl Schiff base contains an acetomethyl signal at 2.11 p.p.m. and a vinylmethyl peak at 1.67 p.p.m. The vinyl hydrogen signal is a triplet located at 7.42 p.p.m. with J = 10.0 c.p.s. and to lower fields than the vinyl resonances in the other vinylamines studied. The NH proton gives rise to a broad signal at 4.8 p.p.m. with an intensity of about 2 protons. These facts are all indica-



tive of the *trans* isomer. The *cis* tautomer, on the other hand, displays an acetomethyl resonance at 2.18 p.p.m., a vinyl methyl resonance at 1.81 p.p.m., and a vinyl hydrogen signal at 6.7 p.p.m. The *trans*/*cis* ratio is about 3. The triplet for the vinyl signal in the *trans* species indicates that the two amine hydrogens are equivalent. In the *cis* structures, the hydrogen bond to the carbonyl fixes the geometry of the nitrogen so that usually two NH spin couplings and two NH absorptions are observed.

In the N-methyl Schiff bases with a 3-methyl substituent, the N-methyl group apparently increased the stability of the *cis* form since, in chloroform solution, the ratio of the two isomers is nearer to unity (*cis*/*trans* = $^3/_4$).

Discussion

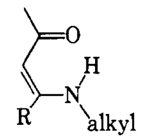
In order to gain further insight into the β-amino-α,β-unsaturated ketone system, simple molecular orbital calculations of the Hückel type were undertaken.[15] Selecting the parameters for the hetero atoms is always difficult as there is little agreement in the literature on suitable values for the coulomb integrals (α) and for the resonance integrals (β) of oxygen and nitrogen.[16] In general, small variations in any one of the parameters appear to have little effect upon the calculated properties of the system.

The simplest method for the introduction of a methyl group into MO calculations is the "inductive model" of Pauling and Wheland; however, the "hetero atom approach" was used here as its success in many calculations is encouraging.[17] The calculations did not account specifically for the substituent on the nitrogen but a large range for the Coulomb integral was used. This simplification is justified since experimentally the substituent on nitrogen appears to have little influence on the basicity of the nitrogen, and the calculations are too inexact to allow for such a small effect. The MO calculations were further simplified by ignoring the hydrogen bond since the absence of the bond in the dimedone derivatives did not markedly affect the properties of the system.

One of the original purposes of the molecular orbital calculations was to estimate the differences in stability between the ketoamine and the enolimine forms of the Schiff bases. Unfortunately, simple MO calculations do not distinguish unambiguously between the two tautomeric forms. In these molecules there are two different hetero atoms; one atom supplies one electron and the other supplies two electrons to the π-system. If a calculation yields an electron density of oxygen = 1.86 and nitrogen = 1.24, it is still uncertain whether this is O = −0.86, N = +0.76 or O = +0.14, N = −0.24; *i.e.*, the proton on nitrogen in the former and on oxygen in the latter case.[18] The ambiguity in assigning coulomb values to the two types of oxygen and nitrogen is an additional complication. The ranges given for each parameter are large with overlap occurring between them. In the aliphatic system where the chemical evidence strongly favors one form, this ambiguity is of no great concern; however, for the aromatic Schiff bases it is a significant problem since the energy barrier between forms is much smaller.[1]

TABLE III

SUMMARY OF MOLECULAR ORBITAL CALCULATIONS

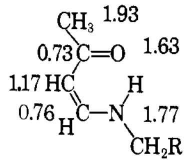


Compd., R =	α_N	α_O	$\beta_{C=O}$	Charge density N	Charge density O	Charge density C_3	Carbonyl bond order	$\Sigma\beta$
H	0.2	2.0	1.0	1.24	1.86	1.19	0.40	13.36
	0.5	2.0	1.0	1.41	1.83	1.19	.43	13.76
	0.5	1.0	1.0	1.47	1.68	1.23	.60	12.00
	1.5	1.0	1.0	1.77	1.63	1.17	.67	13.62
	2.0	1.2	1.0	1.84	1.67	1.14	.64	14.86
	2.0	1.0	1.0	1.84	1.61	1.14	.69	14.54
	2.5	2.0	1.0	1.87	1.81	1.12	.51	17.18
	3.0	2.0	1.0	1.90	1.81	1.10	.51	18.12
CH_3	0.5	0.8	1.0	1.53	1.64	1.27	.64	15.82
	0.2	0.8	1.0	1.40	1.67	1.30	.61	15.72
	2.0	2.0	1.0	1.84	1.83	1.18	.48	20.44
	3.0	2.0	1.0	1.81	1.82	1.14	.49	22.38

α_{CH_3} = 2.0, β_{CH_3} = 0.7 $\beta_{2,3} = 0.95\beta_c$ $\beta_{4,N} = 1.0\beta_c$

Aux. ind. parm. = 0.1 $\beta_{3,4} = 1.0\beta_c$

The MO results confirm the fact that there is a large charge separation in the molecule **7**, with the oxygen probably being at the negative end and nitrogen at the positive end of the dipole (expected from electronegativity considerations). The large charge separation is consistent with strong hydrogen bonds observed in this system and the negative oxygen for the strong complex to benzene mentioned previously. It is interesting that a large negative charge is centered on oxygen, but the positive charge is more uniformly distributed over the molecule.



7

M.O. change densities

With any reasonable combination of parameters for the hetero-atoms, the net delocalization energy of the system is not large, indicating that the dipolar nature of the molecule is responsible for its chemical properties.[19]

It was disappointing to note the small difference between the presence or absence of a methyl on position 4 of the chain. The $\Sigma\beta$'s differ between compounds, but this is due to the 4β used in the "hetero-atom" treatment of the methyl group. The results do indicate a stronger hydrogen bond when the 4-methyl is present since a larger positive charge on the nitrogen is calculated.

Space filling models of the Stuart–Leybold type suggest that the difference in properties between the acetylacetone and the hydroxymethylene ketone Schiff bases can be attributed to steric factors. Hammond, Bordouin, and Guter[20] also noted important steric effects in the enolization of the β-diketones which are the parent compounds of the Schiff bases discussed here. For example, in a model of the *cis* configuration of 3-methyl

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(15) The general reference extensively used is: A. Streitwieser, Jr., "Molecular Orbital Theory for Organic Chemists," John Wiley and Sons, Inc., New York, N. Y., 1961.

(16) Reference 15, Chapt. 5.

(17) A detailed explanation of these methods is not given as they are well described in ref. 15.

(18) The low bond order (0.4) for the carbonyl group could be cited as determining the site of the proton. However, the point at which the bond order is high enough to indicate a carbonyl is still unknown especially since the infrared spectra favor very low bond orders for the carbonyl groups; G. Dudek and G. Volpp, to be published.

(19) If the parameters of 7 are chosen, and the molecule is reconstructed from acetaldehyde ($\Sigma\beta$ = 7.56) and aminoethylene ($\Sigma\beta$ = 5.50), then the delocalization energy amounts to 0.56β. If the coulombic energies of the electrons are substracted from $\Sigma\beta$ of 7, the delocalization energy amounts to 5.42β, or 1.08β larger than the two isolated Kekulé structures (C=O and C=C).

(20) G. S. Hammond, W. G. Bordouin, and G. A. Guter, *J. Am. Chem. Soc.*, **81**, 4682 (1959).

Schiff bases, the 3-methyl and the acetomethyl groups interact quite strongly, whereas in the *trans* form no large steric interactions are observable and a planar configuration of maximum orbital overlap may easily be maintained. When the methyl group is placed in the 4-position, as in acetylacetone Schiff bases, the reverse situation occurs. In a planar *cis* configuration, no important steric interactions are noted; however, in the *trans* arrangement, the 4-methyl and the carbonyl groups interact to such a degree that it is difficult to obtain a planar backbone for maximum overlap.

The variation in the *cis–trans* equilibrium as the group on the nitrogen is changed from a methyl to a benzyl or a hydrogen may also be attributed to steric factors. Either the ability of the solvent to solvate the nitrogen or the ease of forming dimers and *n*-mers between the *trans* forms of the molecule may be involved.

The NH–CH spin–spin coupling of 13 c.p.s. in these systems of fixed *trans* geometry is larger than the value of 6 c.p.s. for the coupling between an amino hydrogen and a freely rotating alkyl group, similar to the constants for hydrocarbon systems. Of course the coupling constants involving amine hydrogens are in error to the extent that proton exchange on the nitrogen is significant. Since the observed couplings vary only a small amount between compounds and between solvents, exchange probably is not a serious problem.

The paramagnetic shift of the vinyl hydrogens between the *cis* and *trans* forms can be attributed to the carbonyl group which is closer to these protons in the extended form than in the chelated form. The large amount of negative charge calculated for the 3-carbon is reflected in the relatively diamagnetic location of the vinyl proton H_a in these compounds.

The increase in the amount of the *trans* species with increasing concentrations of the compounds in solution is indicative of a weak intermolecular association through the NH and C=O groups. Apparently, the entropy of intramolecular hydrogen bonding is counterbalanced by dipole repulsions and a larger *trans* conjugation energy.[20] Thus solvent and substituent effects[21] can readily swing the *cis–trans* equilibrium in one direction or the other.

Acknowledgment.—We wish to thank Robert Freund for his assistance in programming and operating the IBM 1620 computer.

[21] R. W. Taft, Jr., "Steric Effects in Organic Chemistry," M. Newman, Ed., John Wiley and Sons, Inc., New York, N. Y., 1956, p. 619.

[CONTRIBUTION FROM THE CHEMISTRY DIVISION, OAK RIDGE NATIONAL LABORATORY, OAK RIDGE, TENN.]

Nuclear Magnetic Resonance Studies of BF_3 Addition Compounds. I. The Exchange of BF_3 between $(CH_3)_2O\cdot BF_3$ and $(C_2H_5)_2O\cdot BF_3$[1]

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Kinetic data for the exchange of BF_3 between $(C_2H_5)_2O\cdot BF_3$ and $(CH_3)_2O\cdot BF_3$ were obtained from the ^{19}F n.m.r. spectra of eight mixtures of $(C_2H_5)_2O$, $(CH_3)_2O$, and BF_3. The rate of exchange decreased as a larger portion of the ether was complexed, and the activation energies rose from 11 kcal. for mixtures having >20% free ether to 16 kcal. for the mixture having no free ether. Two exchange mechanisms are indicated. The equilibrium constant for the reaction $(C_2H_5)_2O\cdot BF_3 + (CH_3)_2O = (CH_3)_2O\cdot BF_3 + (C_2H_5)_2O$ was $\backsim$2.5 at 26°.

Introduction

Boron trifluoride forms stable 1:1 molecular addition compounds with methyl and ethyl ethers. In systems containing BF_3 and mixtures of these ethers, exchange of BF_3 occurs between the ether species. Although this exchange is too rapid to be observed by conventional techniques, it may be measured conveniently with a nuclear magnetic resonance spectrometer. This paper reports the results of kinetic studies made in this manner on the $(CH_3)_2O$–$(C_2H_5)_2O$–BF_3 system. Eight compositions containing varying BF_3/ether and methyl/ethyl ether ratios were examined over a temperature range of approximately 100° using the ^{19}F resonance. In addition, the equilibrium constant for the reaction

$$(C_2H_5)_2O\cdot BF_3 + (CH_3)_2O = (CH_3)_2O\cdot BF_3 + (C_2H_5)_2O$$

was measured at several temperatures for six of these mixtures.

The ^{19}F resonance for BF_3 addition compounds offers the combination of a strong signal, which is fairly narrow in the absence of chemical exchange, plus large chemical shifts between different BF_3 addition compounds. It is, therefore, suitable for quantitative kinetic studies. The spectra for two ether·BF_3 complexes are very simple, consisting at low temperatures of a pair of peaks which, as the temperature is raised, broaden, merge, and fuse to a single peak. The ^{19}F resonance for BF_3 complexed with $(CH_3)_2O$ appears at a field strength 5.3 p.p.m. above the corresponding $(C_2H_5)_2O\cdot BF_3$ complex. This large chemical shift permits very rapid exchanges to be observed; under the most favorable conditions, mean lifetimes (τ) as short as 1.5×10^{-5} sec. were measured. However, at low temperatures, mean lifetimes longer than 10^{-2} sec. were generally inaccurate. The observable range of τ varied from sample to sample. The temperature range for which accurate τ values could be measured also varied considerably. The usable temperature range for the sample containing the least BF_3 was −12 to −59°, while the range covered in the completely complexed system was +1 to +67°.

Experimental

The samples used in these experiments consisted of eight mixtures of BF_3, $(CH_3)_2O$, and $(C_2H_5)_2O$. The amount of uncomplexed $(CH_3)_2O$ was limited to allow the samples to be heated without subjecting the glass sample tubes to high pressures.

The BF_3 and $(CH_3)_2O$ used for these experiments were Matheson reagent grade chemicals; the $(C_2H_5)_2O$ was Mallinckrodt anhydrous analytical grade material. High vacuum techniques were used for all preparations. The BF_3 was freed from noncondensable gas by a series of condensations and expansions at reduced temperature. The ethers were vacuum distilled, the middle portion being used to prepare the BF_3 complex. Great care was used to eliminate water from the system. Even traces of water cause the BF_3–ether complexes to decompose.

The procedure for preparing a given mixture of $(C_2H_5)_2O$, $(CH_3)_2O$, and BF_3 was as follows. After the all-glass vacuum apparatus was assembled, it was pretreated with BF_3 to remove traces of water. Approximately 5 ml. of $(C_2H_5)_2O$ and $(CH_3)_2O$ were separately distilled into calibrated receiving vessels, then were transferred to the reaction flask. The ethers were frozen and a measured quantity of purified BF_3 was added. After the mixture was warmed and thoroughly mixed, 0.5 ml. was sealed in an n.m.r. sample tube which had previously been fused to the reaction vessel.

[1] This paper is based on work performed for the U. S. Atomic Energy Commission by Union Carbide Nuclear Co.