Estimation of Charge Density on Nitrogen in Amides by Measurement of One-Bond Carbon-Hydrogen Nuclear Coupling Constants in $N-CH_3$ Group*,**

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One-bond, $^{13}C-^{1}H$ coupling constants, $J_1(C-H)$, in amines, ammonium ions, and carboxylic amides correlate with structure and support the concept that the value of $J_1(C-H)$ is related to the charge density on the nitrogen atom; for example, amine oxides have nearly the same charge density at nitrogen as does the tetramethylammonium ion. The $J_1(C-H)$ values for methyls bonded to nitrogen in various amides then give an experimental estimate of the charge density at the nitrogen atom that enables an estimate of the bond order in the C–N amide-bond; the data suggest that carboxylic amides have a C–N bond order of about 1.35, that sulfonamides have an S–N bond order of about 1.45, and that phosphinamides, $R_2P(O)N(CH_3)_2$, have a P–N bond order of about 1.3. In contrast, aminephosphines have a P–N single bond. The value for carboxylic amides is in reasonable agreement with bond distances in amides.

Key words: Amides; Amine oxides; Charge density at nitrogen; Sulfonamides; Phosphinamides.

Introduction

Our research with carbon-hydrogen coupling constants through one bond, $J_1(C-H)$ [1], is based upon the pioneering work by Lauterbur [2], Muller and Pritchard [3, 4] and Shoolery [5]. In particular, Muller and Pritchard noted interesting effects on the magnitude of these couplings for methyl groups bonded to various heteroatoms [3, 4], dominance of the Fermi contact term in $J_1(C-H)$, and experimental data in support of a direct relationship between $J_1(C-H)$ and percent s-character in the carbon atomic orbital [3–6]. Although there have been some doubts expressed about this simple view of C–H couplings [7, 8] the pattern that has emerged [9] supports the early conclusions [3–5]. Support for this view comes from such applications as the correlation of $J_1(C-H)$ with structure in strained systems [10, 11] and with the acidity of C–H bonds [12, 13].

The research reported here is based on experimental results that indicate an empirical relationship between $J_1(C-H)$ in methyl groups bonded to nitrogen atoms in a variety of structures. We find that $J_1(C-H)$ increases as the amount of formal positive charge on nitrogen increases. This enables insight into charge density and bonding at the nitrogen atom. The empirical relationship we have found is supported by concepts of bonding [8] and by the direct relationship [4, 5] between $J_1(C-H)$ and percent s-character in the carbon AO of the C–H bond, because change in structure and charge on nitrogen must cause a change in C–N bonding which, in turn, must cause a change in C–H bonding. From a simple viewpoint, a more positive N atom demands more p-character in the bonding of carbon to N; this, in turn, causes more s-character in the bonding of carbon to the H atoms, so the C–H coupling increases [3–5, 8, 9]. Although bonding is not localized from an LCAO viewpoint, the results fit with the valence-bond framework of concepts of structure and bonding. Our method is an intramolecular probe, via the methyl group, of the electropositive nature of the nitrogen atom.

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Table 1. Coupling constants for pyramidal N compounds [a].

Compound	Solvent	State of compound	J_1(C–H) (Hz)
$(CH_3)_3N$	neat	uncharged	131.7
	CCl_4	uncharged	131.9
	CF_3CO_2H	$(CH_3)_3NH^+$	144.1
$(CH_3)_3NH^+CL^-$	DOD	$(CH_3)_3NH^+$	143.6
	sulfuric acid	$(CH_3)_3NH^+$	144.6
	CF_3CO_2H	$(CH_3)_3NH^+$	144.2
$(CH_3)_4N^+Cl^-$	DOD	$(CH_3)_4N^+$	144.2
	sulfuric acid	$(CH_3)_4N^+$	144.5
	CF_3CO_2H	$(CH_3)_4N^+$	144.5
$(CH_3)_2NH_2^+Cl^-$	DOD	$(CH_3)_2NH_2^+$	143.3
	sulfuric acid	$(CH_3)_2NH_2^+$	144.8
$CH_3NH_3^+Cl^-$	DOD	$CH_3NH_3^+$	143.6
$(CH_3)_3N^+-O^-$	DOD	$(CH_3)_3N^+-O^-$	143.6
	CF_3CO_2H	$(CH_3)_3N^+-OH$	146.3
	sulfuric acid	$(CH_3)_3N^+-OH$	146.1
$(CH_3)_3N^+-OCH_3$	CD_3NO_2	$(CH_3)_3N^+-OCH_3$	146.1

[a] In some cases, the N atom is exactly tetrahedral, and in all these compounds the N atom has bond angles within a few degrees of tetrahedral.

Table 2. Coupling constants for trigonal N compounds including carboxylic amides.

Compound	Solvent	State of compound	J_1(C–H) (Hz)	Bond order [a]
$C_6H_5CH=NCH_3$	neat	uncharged	133.4	
CH_3NO_2	neat	neutral	146.7	
	CF_3CO_2H	neutral	146.7	
$HC(O)N(CH_3)_2$	neat	neutral	138.1	1.38
(dimethyl-	DOD	H-bonded	139.0	1.45
formamide)	sulfuric acid	protonated	144.1	1.86
$CH_3C(O)N(CH_3)_2$	neat	neutral	137.5	1.33
	CF_3CO_2H		141.1	1.62
$C_6H_5C(O)N(CH_3)_2$	CCl_4	neutral	137.6	1.34
	sulfuric acid	protonated	144.3	1.87
	$POCl_3$	phosphorylated	146.3	20.3

[a] The bond order refers to the C–N amide bond and is determined by the equation

$$\text{Bond order} = 1 + [(J_1(\text{C–H}) - 133.4\ \text{Hz})/12.5\ \text{Hz}]\,.$$

The value of 133.4 Hz comes from the top entry in this table, and the value of 12.5 Hz is the difference between trimethylamine and tetramethylammonium ion (Table 1); see the discussion in the text.

Results and Discussion

The data in Tables 1 and 2 indicate that J_1(C–H) correlates with charge at the nitrogen atom. In $N(CH_3)_3$, the J_1(C–H) coupling is 131.8 Hz (Table 1). When nitrogen is quaternized, the coupling increases to about 144 Hz and remains very close to this value regardless of concentration, the nature of the counterion, or other perturbations. On the other hand, it is possible to perturb the coupling; for example, trimethyl ammonium ion in D_2O has a coupling about 1 Hz less than in sulfuric acid, presumably owing to hydrogen bonding of D_2O to the NH hydrogen.

Trigonal Nitrogen (see Table 2). The J_1(C–H) values for $N-CH_3$ groups change from 131.7 Hz for $N(CH_3)_3$ to 133.4 Hz for $C_6H_5CH=NCH_3$. The higher coupling constant for the sp^2-state of N is explained by considering the increase in the electronegativity of the nitrogen, as the amount of s-character in the bonding atomic orbital of nitrogen to the methyl is increased; that is, the sp^2-orbital of planar, trigonal N is more electron-withdrawing than the sp^3-orbital of pyramidal N, because the electron density in the sp^2-orbital is closer to the N atom [8]. Our findings are consistent with the increase of 2 Hz in the J_1(C–H) of the methyl groups of $(CH_3)_2C=CH_2$ compared to neopentane [4]; that is, the effect on J_1(C–H) in the attached methyl groups is the same in converting an attached carbon from sp^3 to sp^2, as we find for nitrogen by comparing $(CH_3)_3N$ and $C_6H_5CH=NCH_3$.

Effect of Charge on Nitrogen. The J_1(C–H) value of a methyl group on a positive nitrogen in the sp^3-state is 144.2 Hz for $(CH_3)_4N^+$ in D_2O (Table 1); that is, there is a 12.5 Hz increase in coupling constant on quaternizing trimethylamine. Other data in Table 1 support this value: note the values for trimethylamine in trifluoroacetic acid, trimethylammonium ion, and tetramethylammonium ion. There is significant deviation from this value only when there are strong solvation effects on trimethylammonium ion in D_2O or sulfuric acid and, moreover, those solvation effects are in the expected direction and they are not large. The values for trimethylamine oxide also support this number. Neutral trimethylamine oxide with a coupling of 143.6 Hz is only marginally lower than 144.2 Hz for the tetramethylammonium ion; as expected, when trimethylamine oxide is protonated, there is a significant increase in coupling.

The J_1(C–H) value of a methyl group on a positive nitrogen in the sp^2-state can be estimated from the value for neutral nitrogen, 133.4 Hz for $C_6H_5CH=$ $=NCH_3$, and the increase in coupling when N is quaternized, 12.5 Hz, as discussed in the previous paragraph. The result, 145.9 Hz, is supported by the coupling for nitromethane: 146.3 Hz. Because of the

special bonding in nitromethane, we prefer to use 12.5 Hz, the value from pyramidal N, for the effect of conversion of a neutral N compound to the cation.

Carboxylic Amides. The N atom is trigonal in carboxylic amides [13, 14]. Therefore we use a base value of J_1(C–H) = 133.4 Hz for neutral, trigonal nitrogen. Table 2 demonstrates that neutral amides have couplings considerably greater than this value. This suggests that J_1(C–H) values might be used to estimate the amount of positive charge on N due to electron delocalization. For a full positive charge on N, the coupling should increase by about 12.5 Hz (previous paragraph). This enables an estimate of the amount of positive charge on nitrogen in the neutral carboxylic amides in Table 2 using the equation

$$\%N^+ \text{ contributor} = [J_1(\text{C–H}) \text{ observed} - J_1(\text{C–H}) \text{ for neutral N}]/12.5 \text{ Hz}, \quad (1)$$

which is based on the discussion in the previous paragraphs.

The formamide coupling of 138.4 Hz leads to an estimate of $\%N^+$: $(138.1 - 133.4)/12.5 = 38\%$ N^+. Similarly, the couplings for dimethylacetamide and dimethylbenzamide give 33% and 34% N^+. The average value for the three compounds is 35%, leading to a C–N bond order of 1.35.

The structural research on carboxylic amides [14, 15] demonstrates that the N atom is trigonal planar (sp^2), and the bond lengths indicate contributions to structure of about 40% from the contributor with a C=N double bond and a positive charge on nitrogen. Our results are in reasonable agreement with these structural studies. In fact, since the standard bond lengths for single and double C–N bonds in the sp^2-state are difficult to establish, and since the dipolar character of amides may lead to bond contraction beyond the amount induced by π-bonding, the J_1(C–H) values may be a better guide to bond order than the observed bond lengths. Rotational barriers in amides also correlate with the bond order of about 35% calculated from J_1(C–H) [16].

The addition of D_2O to an amide increases J_1(C–H). For example, the coupling constants of the N-methyl groups of N,N-dimethylformamide and N,N-dimethylmethanesulfonamide increase by 0.9 Hz and 0.8 Hz when D_2O is used as solvent. This observation is consistent with hydrogen bonding of D_2O to the oxygen atom and, as a result, increased charge on nitrogen.

When the amides are protonated or phosphorylated (known to occur at the O atom), the resulting bond orders are in reasonable agreement with the expectation that protonation or phosphorylation occurs on the O atom, leading to dominance of the $>C=N^+(CH_3)_2$ contributor to the structure. For example, dimethylformamide in sulfuric acid gives a coupling only slightly smaller than for the tetramethylammonium ion.

Application of J_1(C–H) to the Structure of Phosphorus and Sulfur Amides. In view of the results on carboxylic amide structure in uncharged and protonated forms from J_1(C–H) values, we have applied our method to amides where the structure is not well understood. The data and results are in Table 3.

In agreement with expectations, there appears to be a higher bond order in sulfonamides than in sulfinamides. The sulfonamides do not appear to be protonated in trifluoroacetic acid, based on the similarity to the couplings in D_2O. In sulfuric acid, the sulfonamides are clearly protonated and the coupling is even larger than that expected for an ammonium ion. This suggests that the N atom bears much of the positive charge in a protonated sulfonamide.

In the phosporus amides there is a large difference between $(CH_3)_2NP(C_6H_5)_2$ and $(CH_3)_2NP(O)(C_6H_5)_2$. A bond order of 1.15 for N,N-dimethylaminodiphenylphosphine indicates a minor amount of π-interaction of the lone-pair electrons on nitrogen with the d-orbitals of phosphorus. This is consistent with the observed nucleophilic behavior of these compounds. It has been shown that the phosphorus atom is more nucleophilic toward various electrophiles than is the nitrogen atom [17–20].

Sufficient structural data exist to allow a rough estimate to be made of the P–N bond order in N,N-dimethyldiphenylphosphinamide, $(CH_3)_2NP(O)(C_6H_5)_2$; the structure of this amide has been reported [21] with a P–N bond length of 0.167 nm. The length of the P–N bond in the phosphoramidate ion, $(H_3N^+–PO_3)^-$, is reported to be 0.177–0.179 nm [22], whereas in a phosphonitrile tetramer the length of the exocyclic P–N bonds is reported to be 0.175–0.184 nm [23].

Taking the value of a single P–N bond to be 0.179 nm, that of a P–N bond of bond order 0.15 to be 0.16 nm [24] and assuming that the relation between bond length and bond order is linear over this range, results in a structure-based [21] bond order for the P–N bond in N,N-dimethyldiphenylphosphinamide of 1.32. The bond order of N,N-dimethyl-

Amide	Solvent	State of amide	J_1(C–H) (Hz)	Bond order [a]
$CH_3SO_2N(CH_3)_2$	$CDCl_3$	neutral	139.3	1.47
	DOD	H-bonded	141.1	
	H_2SO_4	protonated	147.8	≈ 2
$C_6H_5SO_2N(CH_3)_2$	CCl_4	neutral	138.8	1.43
	CF_3CO_2H		141.9	1.60
	H_2SO_4	protonated	148.5	≈ 2
$C_6H_5SON(CH_3)_2$	neat	neutral	137.4	1.32
$(C_6H_5)_2PN(CH_3)_2$	neat	neutral	134.4	1.08
$(C_6H_5)_2P(O)N(CH_3)_2$	$CDCl_3$	neutral	137.3	1.31
	H_2SO_4	protonated	145.5	$P-N^+H(CH_3)_2$ [b]
	CF_3CO_2H	protonated	144.8	$H_2N^+(CH_3)_2$ [b]
$[(CH_3)_2N]_3PO$	neat	neutral	135.4	1.16

Table 3. Coupling constants for sulfur and phosphorus amides.

[a] The bond order refers to the S–N or P–N amide bond and is determined by the equation

Bond order $= 1 + [(J_1(C-H) - 133.4\ Hz)/12.5\ Hz]$.

[b] Methyls are a doublet indicating that the P–N bond is intact.

[c] Methyls are a 1:2:1 triplet indicating that the P–N bond as been cleaved, generating the dimethylammonium ion which is exchanging slowly.

diphenylphosphinamide determined by the J_1(C–H) coupling constant (1.36) is in good agreement with this. Our previous work on phosphorus amides defined the pK and is consistent with protonation on N in both sulfuric and trifluoroacetic acids [25], but apparently the lability in the latter acid caused cleavage of the P–N bond before the spectrum was taken (Table 3).

Solvent Effects. The solvent effects observed in Tables 1–3 indicate that these couplings give useful information even when the effects are small. For example, the trimethylammonium ion (Table 1) has a lower coupling in D_2O than in trifluoroacetic acid and the value in trifluoroacetric acid is lower than in sulfuric acid, as would be expected by the relative ability of these solvents to function as hydrogen bond acceptors. A similar effect is seen for the dimethylammonium ion. In Tables 2 and 3, amides show the expected increase in coupling due to hydrogen bond donation from D_2O.

Experimental

N-Benzylidenemethylamine was prepared by adding methylamine (0.26 moles) to benzaldehyde (0.26 moles) in 100 ml of methanol at room temperature. The mixture was refluxed for 1–1.5 hours. Distillation gave a product boiling between 179° and 182 °C (b.p. C_6H_5CHO 179 °C; b.p. $C_6H_5CH{=}NCH_3$ 180 °C. The ^{1}H-nmr spectrum indicated that approximately 15% of the benzaldehyde remained unreacted.

N,N-Dimethylformamide was obtained from Matheson, Coleman and Bell Chemical Company and used without further purification.

N,N-Dimethylbenzamide was prepared by adding an excess of dimethylamine directly to benzoyl chloride at 0 °C in an open flask. The amide was taken up in acetone and the amine hydrochloride filtered off. After removal of the acetone by evaporation, the amine was purified by vacuum distillation: b.p. 115 °C at 0.5 Torr, m.p. 41 °C.

N,N-Dimethylmethanesulfonamide was prepared by adding an excess of dimethylamine directly to methanesulfonyl chloride at 0 °C in an open flask. The amide was taken up in acetone and the amine hydrochloride filtered off. The acetone was removed by evaporation and the amide recrystallized from water, m.p. 48.5–49.5 °C; reported m.p. 48 °C [26].

N,N-Dimethylbenzenesulfonamide was prepared by adding an excess of dimethylamine directly to benzenesulfonyl chloride at 0 °C in an open flask. The amide was taken up in acetone and the amine hydrochloride filtered off. The acetone was removed by evaporation and the amide recrystallized from n-heptane: m.p. 48 °C.

N,N-Dimethylbenzenesulfinamide was prepared by adding dimethylamine in diethyl ether directly to benzenesulfinyl chloride (prepared according to Douglas [27]) with stirring and dry-ice cooling. The mixture was warmed to room temperature, the amine hydrochloride filtered off, and the ether removed by vacuum. The amide was purified by vacuum distillation, b.p. 130 °C at 20 Torr.

N,N-Dimethyldiphenylphosphinamide was prepared by adding dimethylamine directly to diphenylphosphinyl chloride (prepared by oxidation of chlorodiphenylphosphine at ice-bath temperature). The residue was partially taken up in aqueous sodium bicarbonate, extracted several times with carbon tetrachloride, the carbon tetrachloride removed, and the amide recrystallized from acetone-hexane: m.p. 104 °C (lit. [28] 103–105 °C).

Measurement of J_1(C–H). The C^{13}–H coupling constants were measured using an audio-oscillator and frequency counter at a sweep width of 50 or 100 Hz. Duplicate measurements on different days with different samples indicated that the data are

accurate to ± 0.2 Hz; generally, these duplicate determinations were accurate to ± 0.1 Hz. In some cases the coupling was more difficult to determine because of interference from other peaks or because of peak broadening; in these cases the error in the reported coupling may be as high as ± 0.3 Hz.

[1] Abbreviations: $J_1(C-H) = {}^{13}C-{}^{1}H$ nuclear coupling constant through one bond; AO = atomic orbital.
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