^{15}N NMR OF NITRANIONS: OPPOSITE SHIFT EFFECTS OF σ AND π CHARGE

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Nitranions of pyrrole, aromatic and heteroaromatic amines, carboxamides and pyridyl carbanions are generated by deprotonation either of NH or CH acids. The positive or negative displacements undergone by the ^{15}N nucleus relative to the neutral precursor depend on whether a σ or π charge is increased. They are associated with the symmetry of the nitrogen orbital in which the electron pair is either generated or that to which it is delocalized.

INTRODUCTION

Organic chemists have devoted considerable attention recently to ^{15}N NMR[1] because of its relevance in important chemical[2] and biological[3] investigations. Nitranions are key intermediates in organic synthesis[4] and ^{15}N NMR spectroscopy is an appropriate and useful tool for their characterization. Nevertheless, it is only recently that a number of ^{15}N investigations have been published,[5-7] following the early appearance of a few reports on the ^{14}N NMR of these species.[1] Two main themes have emerged. First, ^{15}N NMR investigations have been carried out on nitranions in nonpolar (hydrocarbon)[5,6] or weakly polar (ether) solvents,[6,7] the favoured media of synthetic chemists. Emphasis was placed on the structural characterization of aggregates in solution,[5-7] and the results were correlated with solid-state x-ray structures[8] and theoretical investigations.[9] Second, nitranions and also carbanions, oxanions and thianions have been generated in the polar solvent dimethyl sulphoxide (DMSO) under conditions in which the organic anions are considered to be present as free ions or solvent-separated entities. Bordwell and co-workers[10] evaluated the relative nucleophilicities of such species through Brønsted plots (S_N2 rates vs DMSO acidities of the precursors). We have performed a ^{13}C NMR investigation on charge delocalization in nitranions in DMSO;[11] spectra of the same nitranions obtained in tetrahydrofuran (THF)[12] indicate that association phenomena are present.

In our previous ^{13}C investigations[11,13] on substituent effect treatment of the acidities of α-toluene carbon acids (A) and N-substituted-N-phenyl nitrogen acids

(B), and on α-substituted benzyl carbanions (A^-) and N-substituted-N-phenyl nitranions (B^-) we provided evidence that: (i) C_{para} shifts of both A^- and B^- respond to substituent effect treatment; (ii) C_{para} shifts in A^- are linearly correlated with DMSO pK_as of A; (iii) C_{para} shifts in B^- are *not* correlated with pK_as of B; (iv) while DMSO acidities of A are dominated by the mesomeric component of the effect exerted by the substituent X, the DMSO acidities of B are dominated

Ph—CH$_2$—X	Ph—CH$^-$—X
A	A$^-$
Ph—NH—X	Ph—N$^-$—X
B	B$^-$
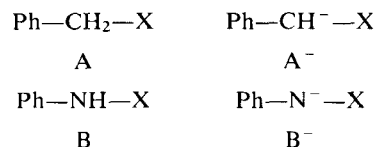
by the polar-inductive component of the effect exerted by the substituent X. We concluded[11] that the lone pair developed in nitranions by deprotonation of the conjugate nitrogen acid has limited chances of providing mesomerically an extra stabilization to the anion because it resides in an sp^2 orbital orthogonal to the π conjugated frame of the system. In the light of this conclusion, we decided to apply ^{15}N NMR spectroscopy in the investigation of a number of nitranions in DMSO, in which the nitrogen atom is present in a conjugated framework. We were interested in evaluating the influence of structural reorganization and charge delocalization on the shift variation between the neutral nitrogen acid and the nitranion. A ^{15}N shift–charge relationship, analogous to that well known for ^{13}C in its various modifications,[14] would be particularly welcome for nitranions in view of the possibility of correlating charge with reactivity through the second term of the

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Klopman–Salem equation.[15] We found that, relative to the neutral precursors, ionization causes upfield or downfield shifts of ^{15}N depending whether a π or σ charge is increased.

RESULTS

Table 1 reports the ^{15}N shifts of the amino functionality and of the pyridyl nitrogen of a number of derivatives in both the neutral and anionic forms. It can be seen that the amino group of aniline, diphenylamine, aminopyridines and carboxamides undergoes a low-field ^{15}N shift on deprotonation. Also, the ^{15}N shift of pyrrole undergoes a low-field displacement on deprotonation. Deprotonation of 2- and 4-aminopyridines promotes considerable upfield displacements of the pyridyl nitrogens, in contrast with the already described low-field shifts of the amino nitrogens; in the 3-isomer the pyridyl ^{15}N moves only slightly, as expected on the basis of the limited delocalization of an electron pair on to a *meta* position. Benzylic deprotonation of 2- and 4-benzylpyridine induces, relative to neutrals, an upfield shift of the pyridyl nitrogen of 58 and 96 ppm, respectively. In both nitranionic and carbanionic pyridyl derivatives, generation of a negative charge in the side-chain at position 4 has a much larger effect than that in position 2.

DISCUSSION

Inspection of the results in Table 1 indicates that there is a different behaviour of the amine, pyrrolic and carboxamidic nitrogen (low-field variation) relative to the pyridyl nitrogen (high-field variation). The observed low-field displacement subsequent to deprotonation of systems such as pyrrole, aromatic amines and carboxamides cannot be ascribed to the rehybridization of the nitrogen atom (tetrahedral to trigonal). In fact, neutral pyrrole is flat;[16] the trigonal configuration of the nitrogen atom must also be maintained in the anion, as confirmed by recent x-ray analysis of N-lithiocarbazole.[17] Of the two electron pairs belonging to the nitrogen atom of the pyrrole anion (1), the first is already placed in the p orbital perpendicular to the plane of the ring, and it is delocalized within the ring to contribute to the aromaticity of the system. The second electron pair is generated in the sp^2 orbital originally used by the nitrogen atom for bonding with the hydrogen atom and therefore does not have the correct symmetry for overlapping with the π frame of the ring. Because of this limitation we interpret that the sp^2 electron pair can contribute only in an indirect way to the electron donation from the nitrogen atom to the ring. The relatively modest ^{13}C shift variations between the anion and the neutral (ΔC-2 = 6·2 ppm, ΔC-3 = $-3\cdot6$ ppm in DMSO) support this reasoning. The indirect charge donation might be envisioned as an orbital repulsion effect[18] by the sp^2 electron pair on the other p–π electron pair of nitrogen towards the carbon atoms of the ring or, alternatively, as a leakage of the new electron pairs into the p orbital. In analogy with the pyrrolic nitrogen, the nitrogen atoms of acetanilide and benzanilide are trigonal in both the neutral and anionic states.[9a] Also, a trigonal configuration must be attributed to the aromatic amine nitrogen on the basis of x-ray structures of p-chloroaniline,[19] m-nitro-N, N-dimethylaniline,[20] 4,4'-dichlorodiphenylamine,[21] and triphenylamine.[22] Low-field shifts associated with the generation of an electron pair in an sp^2 orbital are not unprecedented: (a) the ^{15}N low-field shift in the pyrrole anion (1) relative to the pyrrole is analogous to that of ^{13}C in phenyllithium (2) relative to benzene (171·9 and 128 ppm, respectively;[23] (b) the low-field shift of ^{15}N in the anion of carboxamides relative to the neutrals is analogous to that of the ^{13}C in vinyl carbanions relative to their precursors;[24] (c) deprotonation of the trigonal nitrogen in the pyridinium cation to pyridine induces a low-field shift (214·6 and 316·7 ppm, respectively, in DMSO referred to liquid NH$_3$).[1] We can therefore generalize that the deprotonation of a GH group (G = trigonal nitrogen or carbon) that will place the lone

Table 1. ^{15}N chemical shifts of sodium salts of nitranions and their precursors[a]

| Compound[b]	State[c]	δN(amine)	$\Delta\delta$[d]	δN(py)	$\Delta\delta$[d]
PhNH$_2$	N	58·2			
	A[e]	124·8	+66·6		
Ph$_2$NH	N	90·0			
	A	175·5	+85·5		
2-NH$_2$py	N	72·8		265·7	
	A	146·5	+73·7	246·0	−19·7
3-NH$_2$py	N	58·6		315·5	
	A	122·3	+63·7	310·2	−5·3
4-NH$_2$py	N	67·8		275·0	
	A	150·0	+82·2	234·3	−40·7
PhNHCOMe	N	133·0			
	A[e]	206·4	+73·4		
PhNHCOPh	N	127·0			
	A	201·8	+74·8		
2-PhCH$_2$py	N			314·5	
	A			256·2	−58·3
4-PhCH$_2$py	N			309·0	
	A			212·4	−96·6
Pyrrole	N	154·1			
	A	239·0	+84·9		

[a] Nitrogen shielding relative to liquid NH$_3$ (0·0 ppm), 380·23 ppm from neat nitromethane.
[b] py = pyridine.
[c] N = neutral, DMSO-d_6 solutions 1 M in substrate; A = anion, DMSO solution 0·5 M in substrate, 1 M in base.
[d] $\Delta\delta$ = δ(anion) − δ(neutral): positive values represent low-field displacements.
[e] ^{15}N-enriched substrate used for the anionic solution.

1

2

a   b

3 G = N   R =

4 G = C   R = Ph
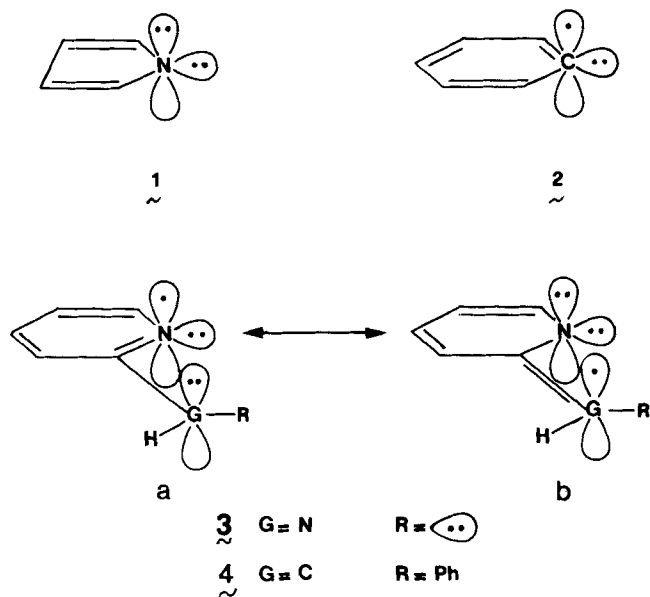
pair in an sp^2 orbital, orthogonal to the p orbital that is part of the unsaturated conjugated frame, will induce a low-field shift of the atom G.

The low-field displacement for the anion of aniline in THF has been interpreted by Ide et al.[7a] as the composite result of a low-field shift due to $sp^3 \rightarrow sp^2$ rehybridization and a high-field shift due to the negative charge; our results on pyrrole conflict with this interpretation. The low-field displacement observed for the ¹⁵N nucleus on deprotonation of the planar N—H of the aromatic amines should be primarily ascribed to the same effects as in pyrrole and carboxamides. This conclusion is important because it answers the first of the two prerequisites that must be fulfilled for obtaining a charge-shift relationship: (a) the hybridization of the negatively charged atom should be known; only in this case it is possible to evaluate fully the significance of the shift variation between the neutral precursor and the anion; and (b) no shielding effect due to variable ion pairing and/or aggregation should contribute to the actual shift of the negatively charged atom under consideration. The choice of DMSO as a solvent for generating and studying nitranions again appears as the most appropriate answer. In the light of the above comments, the validity of the shift–charge relationship proposed by Ide et al.[7a] (high-field contribution due to the negative charge = 900 ppm per electron) is questionable.

In 2- and 4-aminopyridines, the observed high-field shift of the pyridyl nitrogen relative to pyridine itself is due to the π donation of the electron pair of the amine nitrogen.[2] Analogously, the high-field shifts of the pyridyl nitrogen of the pyridine nitranions (3) and carbanions (4) must be attributed to the higher π electron densities in the p orbital of the pyridyl nitrogen.

Whereas in 4 the electron pair is generated in a p carbon orbital and hence is conjugatively delocalized on the pyridyl nitrogen, in 3 the electron pair is generated in an sp^2 orbital of the amine nitrogen and therefore is not directly involved in the delocalization. We suggest that the higher π electron density of the pyridyl nitrogen in 3 is the result of the mechanism already discussed in the case of the pyrrole anion 1. The high-field displacements presented by the pyridyl nitrogen in 3 and 4 closely mimic the ¹³C behaviour of the corresponding de-aza compounds: ¹⁵N in the benzyl-4-pyridyl carbanion vs C_{para} in the diphenylmethyl carbanion,[13] ¹⁵N in the 4-aminopyridine nitranion vs C_{para} in the aniline nitranion.[11] This indicates a strict $^{13}C(sp^2)-^{15}N(sp^2)$ analogy.

According to the present results, there is an increase in the nitrogen σ electron density on deprotonation of trigonal nitrogen acids, whereas there is an increase in the π electron density of the pyridyl nitrogen on deprotonation of side-chain nitrogen or carbon acids. This conclusion does not conflict with the S_N2 reactivity data of the carbazolide ion that Bordwell and co-workers[10] interpreted as evidence that the nitrogen atom utilizes a p rather than an sp^2 orbital. In fact, although the electron pair generated by deprotonation of carbazole is in an sp^2 orbital, this has minor chances of being more available, and thus more reactive, than the electron pair residing in the $p-\pi$ orbital, because of its 30% component of s character. Also, the conclusion does not contradict the finding of extensive charge delocalization in nitranions of aromatic amines[10d] and of their N-derivatives,[11] if the orbital repulsion mechanism is considered. One important aspect that emerges is that in nitranions the ¹⁵N chemical shift and the nitrogen reactivity have a different dependence on σ and π charge. Our results, moreover, fully substantiate the opposite shift effects predicted by Fliszar et al.[25] for σ and π charge on the ¹⁵N shifts; they further explain why electron-withdrawing groups acting predominantly by mesomeric mechanisms (e.g. CO_2R, COR, aryl rings, C=C) have a much smaller effect on the acidity of the NH acids than on the CH acids.[11]

Contrary to the case in ¹³C NMR, experimental charge-shift relationships centred on the ¹⁵N nucleus have been frustrated until now by the shift dichotomy of the charge effects, the origin of which was not fully recognized; it is believed that the considerations reported here will help in the experimental search for a π charge–¹⁵N relationship.

CONCLUSION

Generation of a negative charge in a free or solvent-separated nitranion induces a high- or low-field ¹⁵N displacement relative to the precursor. In this study we chose molecules in which the nitrogen atom is part of a

π-conjugated system to avoid its possible rehybridization. Deprotonation of a planar tricoordinated nitrogen acid places the electron pair in an sp^2 orbital; we conclude that such an increase in σ electron density is associated with a ^{15}N low-field shift. The opposite behaviour is found when the charge can be delocalized into a p orbital of a trigonal dicoordinated nitrogen atom: an increase in π electron density is associated with a high-field shift. The dichotomous behaviour is thus ascribed to the symmetry of the orbital in which the electron pair is generated or that to which it is localized.

EXPERIMENTAL

Most of the compounds studied were purchased from Aldrich and, ^{15}N-labelled compounds, from MDS Isotopes. Their purities were checked by proton NMR before taking ^{15}N spectra. Other compounds were prepared by previously published methods.[11,13] Anions were prepared following the procedure already described.[14] The ^{15}N spectra were obtained at 23 °C using a Varian XL-300 spectrometer operating at 30·4 MHz. Typically, we used the gated decoupled experiment with a delay between pulses of 20 s and a pulse angle of ca 70° for 30 µs.

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