C-13 and O-17 NMR Studies on N-sulfinylanilines

Giovanni Cerioni [a]* Nicola Culeddu[b] Antonio Plumitallo[c]

a)Dipartimento di Scienze Chimiche Università, via Ospedale 72, I-09124 Cagliari, Italy
b) Istituto C.N.R. per l'Applicazione delle Tecniche Chimiche Avanzate ai Problemi Agrobiologici,
via Vienna 2, I-07100 Sassari. Italy
c)Dipartimento Farmaco Chimico Tecnologico, via Ospedale 72, I-09124 Cagliari Italy

Abstract: N-sulfinylanilines have been studied by C-13 and O-17 NMR in chloroform and pyridine; they interact with pyridine, yielding a complex which is stable in solution. The study by O-17 NMR spectroscopy shows that for the NSO group the S-O bond is a *true* π bond.

INTRODUCTION

N-sulfinylanilines are a class of organic compounds which, although known[1,2] since the end of the last century, have not been intensively studied till the second half of this century[3]. For the two possible geometrical isomers, shown for N-sulfinylaniline 1,
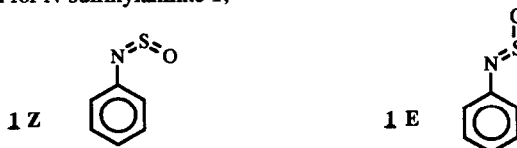
it has been acertained[4] that the Z configuration is the actual one. It is necessary, however, to point out that agreement is still not unanimous, as discussed in the paper by Hansen and Stone.[5]

It is also known[4] that the 2,6-substitution in the benzene ring modifies the dihedral angle between the ring and the plane defined by the N-sulfinyl group, as shown for compounds 1 and **12**.

Two points of the chemistry of N-sulfinylanilines attracted our interest, namely the interaction of these compounds with bases and the nature of their sulfur-oxygen bond.

It is known in fact that similar compounds such as N-sulfinyl sulphonamides[6] and N-sulfinylacylamides[7] react in presence of tertiary amines to yield disulfonylsulfodiimides and diacylsulfodiimides respectively. The analogous reaction is not known for the title compounds, albeit some twenty years ago controversial papers [8,9] appeared on the reaction of N-sulfinylaniline with triethylamine.

Regarding the nature of the sulfur-oxygen bond of these compounds, we observe that while several studies[3,4,10] were devoted to ascertain the nature of their sulfur-nitrogen bond, which is considered to be a

four electron bond, no particular attention seems to have been paid to the sulfur-oxygen bond, apart from some brief considerations on its length and a comparison with sulfur dioxide.[4] Since the nature of the SO bond in sulfoxides and sulfones is still, at least partly, an open question,[11,12] we thought that a comparison among these formally similar bonds could be useful.

RESULTS AND DISCUSSION

Oxygen-17 chemical shifts and half-height estimated line-widths for the compounds investigated in chloroform and pyridine solutions are shown in table 1.

Tab. 1: O-17 NMR Data of 2,4,6 substituted N-sulfinylanilines in Chloroform and Pyridine.[a]

	R(4)	R'(2,6)	δ-O17 CHCl$_3$	$V_{1/2}$ CHCl$_3$	δ-O17 Pyr		$V_{1/2}$ Pyr	
1)	H	H	406[b]	120	406	413	120	70
2)	NMe$_2$	H	372	240	378		253	
3)	OMe[c]	H	391	140	395.5		230	170
					413			
4)	CMe$_3$	H	401	225	404	413	323	145
5)	Me	H	401	160	403	412	180	90
6)	F	H	411[b]	130	409	412	partly overlaping	
7)	Cl	H	408	280	406.5		200	90
					415			
8)	CF$_3$	H	414	160	408	412	300	100
9)	CN	H	419	235	410		82[d]	
10)	NO$_2$[c]	H	432	66	409.4		83	
11)	NSO	H	412	185	408.5		260	110
					413.5			
12)	H	Me	418	120	416		150	
13)	H	Et	419	140	416.5		200	
14)	H	CH(Me)$_2$	418	185	415		270	
15)	CMe$_3$	CMe$_3$	427	270	433		480	

(a) External reference.deionized water. b) 410 ppm (1) and 412 ppm (6) in ref.13
(c) OMe 60 ppm (CHCl$_3$ and Pyr), NO$_2$ 533 ppm (CHCl$_3$) and 538 ppm (Pyr) (d)Without weighting prior transformation

When the carbon-oxygen bond is studied by Oxygen-17 NMR spectroscopy, a very easy discrimination is possible between a single and a double bond.[14,15] The same holds for nitrogen -oxygen bonds, while

whether it is possible to do the same for sulfur - or phosphorus-oxygen bonds is still discussed.[14,15] This difficulty has been attributed to a possible participation of the d-orbitals of these second row elements to the formation of these bonds.

We will now demonstrate that this difficulty in distinguishing between 'single' and 'double' bonds in the sulfur-oxygen case is to be attributed partly to a lack of data and, also, to a misunderstanding of these bonds. As a first point we note that, roughly, the difference between single and double CO bonds is 550-600 ppm, with a deshielding effect for the double bonded oxygen. If we compare the O-17 NMR shifts of dimethylsulfoxide[15] (+13 ppm) and sulfur dioxide[15] (+513 ppm), we can already observe a difference (500 ppm) of the same order noted for CO bonds. It is also worthwhile observing that, for carbon-oxygen bonds, the O-17 NMR chemical shifts vary continuously with bond order variation as demonstrated by various examples, such as carboxylic acids[15] (about 250 ppm) or carbonyl groups conjugated to a diazo group[16] (about 450 ppm) or by the difference between aliphatic and aromatic ethers,[15] the latter being deshielded up to 150 ppm (dimethyl ether -52.5 ppm. diphenylether +101 ppm).

While one must be aware that the variation of the π bond order is not the only cause of variation in chemical shift, it is also clear that, for the chosen examples, the π bond order variation is by far the principal cause.

The same trend is observed with sulfur-oxygen bonds. For sulfoxides[17] the O-17 NMR chemical shift range is usually between -35 and +60 ppm, for sulfones[17] between +120 and +188 ppm and for the title compounds around +410 ppm.

Preliminary results[18] obtained for N,N-dimethyl-phenylthioamide-S-oxide gave an O-17 NMR chemical shift of +330 ppm. We can see now that also for the sulfur-oxygen bond the whole O-17 NMR chemical shift range is covered and some pertinent observations will help understand the limits and the opportunities offered by these findings.

In the introduction it was noted that the sulfur -nitrogen bond of N-sulfinyl anilines was assumed[3] to be a "four electron bond"; this assumption implies that, since the title compounds are imido derivatives of sulfur dioxide,[3] the sulfur-oxygen bond both in sulfur dioxide and in N-sulfinylanilines is also a " four electron bond". The correctness of this assumption is demonstrated by the value of the O-17 NMR chemical shift of sulfur dioxide. The difference in shift between SO_2 and N-sulfinylanilines (c.a. 100 ppm) is to be attributed to the difference in electronegativity between nitrogen and oxygen, so that charge density on oxygen will be greater in the latter compounds. This observation is confirmed by the results[18] obtained with N,N-dimethyl-phenylthioamide-S-oxide, where nitrogen has been substituted by a carbon atom, which not only is less electronegative than nitrogen but actually shares the lone pair of the adjacent nitrogen as is shown by the existence of a rotational barrier detectable by NMR spectroscopy.[18] The same ability to conjugate is shown by the NSO group in the title compounds as will be demonstrated in the following when discussing the effect of *para* substitution. This behaviour is typical of π systems and is not present for instance in sulfones[19] and sulphonamides[20,21] and related compounds.[21] Dahn[21] gives a clear demonstration that, in the classes of compounds studied by his group, the S-O bond is not a true π-bond.

The correctness of the Dahn findings, as far as regards the sulfonyl group, is further demonstrated also by our paper,[22] concerning the stabilization achieved by the carbanionic center of α-diazosulfones. The ability of the sulfonyl group to stabilize adjacent negative charges is well known but it is still an open question[11a] whether this group operates by conjugation or by polarization of the sulfur atom. In ref. 22 we demonstrate,

by O-17 NMR spectroscopy, that, also for planar carbanions, the polarization mechanism is the used one. We think that the lack of conjugation can be a sufficient proof of the lack of π electrons for the sulfur oxygen bond of this group. Thus we will call electrons allowing conjugation "mobile" electrons, irrespective of sulfur or oxygen hybridization but only resting on this phenomenological characteristic.

It is necessary to comment on the difference in O-17 chemical shift between sulfones and sulfoxides, even though the subject is slightly outside the main purpose of this paper. We think that the sulfur-oxygen bond in both classes is essentially the same, but since in sulfones the sulfur atom has a formal double positive charge, when their structure is written with two sulfur-oxygen dative bonds, the negative charge moves from oxygen toward sulfur, thus causing the observed deshielding of sulfones as compared to sulfoxides. In doing so, the electrons do not become " mobile " electrons in the above sense as proved by the lack of ability of conjugation.

Large differences in   O-17 NMR chemical shifts of the N-sulfinylanilines are caused by para substitution; the observed range (CHCl$_3$) is about 60 ppm, a value even greater than that determinated for, acetophenones e.g. (56 or 50 ppm)[23,24], a striking evidence of the mobility of electrons in this SO bond, particularly if compared to the already discussed insensitivity of sulfones. Computing $\Delta\delta$ O-17 against σ or σ^+ values[25] for CHCl$_3$ solutions, a good correlation can be obtained with r^2 coefficients 0.919 and 0.942 respectively. The better correlation obtained with σ^+ is indicative of enhanced interaction of donor substituents. To get a better knowledge of the relative importance of the resonance and polar terms, we analyzed the data for compounds **1 -11**, by the dual substituent parameter (DSP) approach[25] obtaining

$\Delta\delta$ O-17 $_{SCS}$ = 27.43 σ_I + 19.68 σ_R with a multiple correlation coefficient r= 0.978.

The value of λ (ρ_R/ρ_I) = 0.71 indicates that polar effects play a more important role than resonance effects in determining O-17 NMR chemical shifts in this series of compounds. Compounds **12 - 14** show an invariant chemical shift. Also steric hindrance is quite similar for all the compounds as the alkyl groups can adopt conformations with a hydrogen atom pointing towards the oxygen. When this in no longer possible, as in compound **15**, a deshielding effect can clearly be observed, as usual[26] with crowded groups.

As reported also in other cases, e.g. acetophenones,[23] a quite good correlation is found between O-17 NMR shifts (CHCl$_3$ solution) and IR SO stretchings.(r^2=0.986) It is apparent also from this observation that in title compounds the SO bond is similar to the carbonyl CO bond, i.e. it is a π bond.

When performing the DSP analysis for the data from pyridine solutions, relative to the group of signals showing variation with para substitution (including **2,9** and **10**), we found $\Delta\delta$ O-17$_{SCS}$ = 7.44 σ_I + 13.73 σ_R .

with r= 0.939, still a reasonable correlation. These results could be improved by performing the DSP treatment without the point for compound **6**, thus obtaining $\Delta\delta$ O$_{SCS}$-17 = 3.23 σ_I + 14.93 σ_R with r = 0.978.

The strong variation of λ on going from chloroform to pyridine solutions and the large value of σ_R obtained in chloroform should be accounted for in the same way, i.e. the high polarizability of the sulfur atom.[11b] By enhancing the σ_I coefficent, this high polarizability allows for the large amplitude of the range of chemical shifts and is partly inhibited in pyridine.

Moreover we observe that for a large majority of 4-substituted compounds we have two signals in pyridine solution.

A reaction between solute and solvent can be ruled out considering that the reaction product would be a sulfodiimide, a compound lacking oxygen atoms, thus unable to yield O-17 NMR spectra; sulfur dioxide, which would be generated by this reaction has a very different chemical shift[14] and, unless it reacts with pyridine, it should escape. If sulfur dioxide reacts with pyridine, different C-13 NMR signals for pyridine itself should be observed, which is not (see table 2). Moreover, the solute can be recovered unchanged by removing the solvent by vacuum distillation.

Tab.2: C-13 NMR Data for **1** and **1'**(complexed species) in pyridine and triethyamine solution.[a]

%1	M	1	1'	2	2'	3	3'	4	4'	$C\alpha$[b]	$C\beta$[b]	$C\gamma$[b]
90	2.4[c]	141.3	146.0	125.4	112.8	127.4	127.2	128.3	115.4	---	---	---
96.8	2.4[d]	143.2	149.2	127.4	115.3	129.8	129.8	130.8	117.6	149.9	123.7	135.8
97.5	1.2[d]	142.7	148.9	126.9	114.8	129.4	129.4	130.4	117.1	149.5	123.3	135.3
79.2	0.6[d]	142.7	149.0	126.9	114.8	129.4	129.4	130.4	117.0	149.5	123.3	135.3
55.1	0.3[d]	142.7	149.0	126.9	114.8	129.4	129.4	130.4	117.0	149.5	123.3	135.3
30.9	0.15[d]	142.7	149.0	126.8	114.7	129.4	129.4	130.4	116.9	149.5	123.3	135.3
0	0.075[d]	---	149.2	---	114.9	---	129.6	---	117.0	149.7	123.4	135.4

(a) Internal references: HDMS. Most spectra were run without lock. (b) Pyridine carbons.(c) Triethylamine solution. (d) Pyridine solution.

We also note that one of the two signals is insensitive to para substitution; a result difficult to justify by the presence of both E or Z configurations since it would require that either E or Z configuration is insensitive to the effect of substituent.

To ascertain that pyridine was not able to stabilize the rotational state whit a dihedral angle between the ring and the NSO group of about 90 degree, we run an O-17 NMR spectrum of **1** at 343 °K,obtaining the same results observed at R.T.

Moreover the C-13 NMR chemical shifts of the two species are very similar to those obtained in chloroform in one case and to those of the parent anilines in the other, as checked for the whole series of compounds This should not be the case if conjugation between the nitrogen lone pair and benzene ring was prevented owing to a twisted dihedral angle. The origin of the second signale cannot either be found in an ASIS effect as **1** in benzene yielded only one signal. It seems to us that all these observations can be rationalised by an interaction solute-solvent, strong enough to generate an equilibrium between "complexed" and "free" species, as roughly described by formulas **1'a-c**.

1'a   1'b   1'c
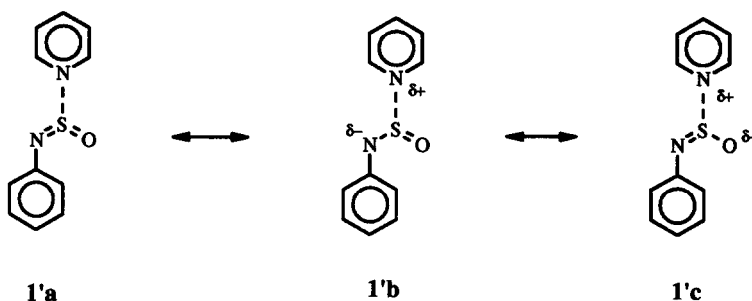
We dare say that the depicted interaction between the sulfur atom and pyridine 'cuts' N-sulfinylanilines in two parts, no longer interacting; the nitrogen of the N-sulfinyl group has now an electronic situation similar to that of an aniline and can share its lone pair with the ring, thus justifying the observed C-13 NMR shifts; the SO part is no longer conjugating with the ring and this fact explains why O-17 NMR shifts are almost constant and do not change with para substitution.

From table 2 we can also observe that, by dilution, it is possible to transform completely the 'normal' form **1** into the complexed **1'**. This can be an indication that the real situation, even though for simplicity it is depicted by formulas **1'a-c**, actually is different for the number of pyridine molecules interacting with every single molecule of N-sulfinylaniline. A fast exchange of pyridine molecules occurs so that only N-sulfinylaniline is modified and we observe two sets of signals both at C-13 and O-17 NMR while pyridine itself does not change. An indication that this idea is correct can be given by the fact that the results obtained using triethylamine (a stronger base) show a doubling also for the solvent signals (CH_2 44.7;44.4 and CH_3 10.3;10.1). Further studies with a variety of basic solvents, different for strength and steric hindrance are under way.

Compounds **12-15** (see introduction) have a 90 degree dihedral angle between the NSO group and the ring as a stable conformation. We note that, apart from **15** which is deshielded by steric compression, their O-17 NMR chemical shifts are similar in both solvents and similar to those of the "complexed species". These findings, while could support the interruption on conjugation proposed for the general case, do not allow to clarify if **12-15** interact with pyridine.

Compounds **2,9** and **10** need to be examined individually. In the case of **2** we note that only C-13 NMR signals different from those of the parent aniline are obtained and the two following possible causes can be adduced: a) the sulfur atom is already interacting with the N-dimethylamino group of other molecules, so that interaction with pyridine is inhibited; b) the electron-donating ability of the N-dimethylamino group hinders ring delocalization of the negative charge (formula **1'b**) so that interaction with pyridine is no longer possible. We think that this second reason is the right one since in case a) we would have C-13 NMR signals similar to those of the parent aniline as it happens when N-sulfinylanilines interact with pyridine. For **10**, we have the opposite , i.e., by C-13 NMR we observed only signals similar to those of the parent aniline. We can also note that the O-17 NMR signals for **2** have close chemical shifts in both chloroform and pyridine solutions, while the opposite is noted for **10**.

It is important to quote now a paper published by Katritzky, Topson et al.[27] They observed that the NSO group is capable of resonance donation or acceptance in the presence of a second substituent, depending on the electron demand. While pertinent to a different situation, this observation seems to support our previous arguments in its extreme limits. As discussed in the introduction, N-sulfinylsulfonamides and N-

sulfinylacylamides react in presence of tertiary amines and pyridine is the base of choice.[6,7] Both classes of compounds differ from the title compounds, which do not react, because an electron-attracting group is directly bound to the N-sulfinyl group. When we have a strong electron-attracting group in 4-position in title compounds, as the nitro in **10**, we only observe the signals of the species interacting with pyridine while when the group is electron-donating as in **2** we only obtain the signal for the non-interacting species. Compound **9** should behave like **10** and it partly does; it shows only one sharp line in its O-17 NMR spectrum but two sets of signals at C-13 NMR. The reason for this is not clear to us at present but we hope that a planned study of interactions of various basic solvents with the title compounds will lead to a better understanding.

CONCLUSIONS

It has been demonstrated that the trend of O-17 NMR chemical shifts for sulfur-oxygen bonds in organic compounds is very similar to that already well documented for carbon-oxygen bonds, thus providing evidence, by comparison with O-17 NMR chemical shifts values of sulfoxides and sulfones in the literature, for the double bond character of the SO bond in the title compounds. Further proof of this point has been achieved through the phenomenological definition of π electrons as 'mobile electrons' and the observation of the large conjugative ability of the SO bond in N-sulfinylanilines, which is particularly striking if compared to the lack of this ability shown by the sulfonyl group in all known examples.

Moreover it has been possible to study the interaction of pyridine and the N-sulfinyl group and to obtain more detailed information about the mechanism of this important reaction.

It is also worth to mention that through this interaction we have further demonstrated the already well known[3] 'four electron nature' of the sulfur-nitrogen bond of N-sulfinylanilines, a point, in our opinion, of capital importance in understanding the nature of the sulfur-oxygen bond and usually overlooked in the chemical literature.

EXPERIMENTAL

All the compounds investigated are known compounds and have been prepared by standard methods.[3,27,28,29]

NMR spectra were acquired using a Varian VXR 300 spectrometer equipped with a 10 mm broad band probe, at room temperature (probe temperature = 294°K), except one spectrum at 343°K (see discussion), and at natural isotopic abundance. Solvents and reference lines are reported in the tables. Infrared spectra were recorded on a Perkin Elmer 1702 FTIR spectrophotometer.

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