STUDIES IN THE FIELD OF AROMATIC HETEROCYCLES

V. Proton Magnetic Resonance Spectra of Compounds of the 2,1,3-Selenadiazole and 2,1,3-Oxadiazole Series*

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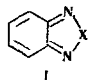
An analysis of the PMR spectra of benzo-2,1,3-selenadiazoles and also of compounds containing 2,1,3-oxadiazole and -thiadiazole nuclei has been carried out. It has been shown that the key atoms O, S, and Se ensure the possibility of the establishment of a ring current in the corresponding heterocycles. "Aromaticity" in the sense of a strong ring current in these compounds is somewhat weaker than in naphthalene. The estimates were obtained by calculating the difference $\nu_0\delta_{AB}$ of the chemical shifts of the protons of the benzene ring linked to the heterocycle from the experimental spectra (A_2B_2 system) and the subsequent comparison of these data with the theoretical dependence of $\nu_0\delta_{AB}$ on the distance separating the proton under study and the center of the contour of the ring current. In the case of the benzo-2,1,3-X-diazoles (X = O, S, Se), this contour is the heterocyclic ring. Direct measurements of the magnetic susceptibility of these compounds have confirmed the considerable equalization of the bonds in the heterocycle, i.e., the participation of the key atoms O, S, and Se in the formation of the ring system of delocalized electrons. It has been shown that the proposed structural scheme permits the prediction of the magnitudes of the chemical shifts and the PMR spectra of such compounds. The question has been raised of the evaluation of the real acceptor properties (electronegativity) of the key atoms completing the heterocycle.

We have previously [1, 2] come to the conclusion, on the basis of a study of the IR spectra and proton magnetic resonance (PMR) spectra of compounds of the 2,1,3-oxadiazole and 2,1,3-thiadiazole series, that these heterocycles must be regarded as compounds with a well-defined aromatic nature.

"Aromaticity" is not a measure of physical properties. It is a complex aggregate of various factors determining the characteristics of a molecule with an annular cloud of delocalized electrons. In proton magnetic resonance, "true aromaticity" is shown by the fact that when the sample is placed in a magnetic field H_0 ring currents proportional to the magnitude of H_0 can be detected. In the case of benzene, for example, the protons give a PMR signal shifted because of this effect by 1.5 ppm with respect to the methine protons of nonaromatic molecules. However, the shift of the signal to weaker fields alone by no means necessarily indicates the aromatic nature of the molecule studied.

The compounds of general formula I that we have investigated can be compared to naphthalene, since in each of these compounds there is a system of 10 electrons which can be generalized.



X = O benzofurazan
X = S piazthiole
X = Se piazselenole

I

The object of the present work was to establish the fact of such generalization. As was found, all the compounds studied give "naphthalene-like" PMR spectra. However, to demonstrate the presence of ring currents in these molecules we were obliged to undertake a comparison with work [2] essentially to broaden the argumentation and to bring in data on the change in the chemical shifts of the corresponding protons with an increase in the distance of the latter from the center of the heterocycle. The data obtained were also compared with the results of other methods of investigating the same compounds.

Table 1 gives the results of our measurements of the chemical shifts in the PMR spectra of compounds containing condensed oxadiazole and selenadiazole nuclei. The substances are arranged in the order of increasing screening of the protons of the benzene ring.

On comparing the data of Table 1 with the results of the previous work [2], it can be seen that the general laws for the piazselenoles (I, X = Se) are the same as in the piazthiole series (I, X = S). However, for the selenium-containing compounds the screening of the ring protons is greater than for the thio analogs. The acceptor properties of the nitro group (Table 1, Nos. 1, 3) and the sulfo group* (Table 1, Nos. 5, 6) are shown in the usual way and are responsible for the minimum screening of the benzoid protons. Chlorine as a substituent exhibits weak electron-accepting properties (Table 1, Nos. 7, 8). The difference in the degree of screening for the protons in the methyl groups in 4- and 5-methylpiazselenoles (Table 1, Nos. 11, 12) considerably exceeds the analogous difference in the methyl piazthioles. To a smaller extent, but with the same sign, this difference also appears for the amino derivatives (Table 1, Nos. 13 and 14). An increase in the nonuniformity of the carbon-carbon bonds of the benzoid ring in the piazselenole system as compared with the piazthiole system should be regarded as the most natural explanation of these facts. In general, however, the influence of substituents of different types on the redistribution of the electron density in the benzoid ring of the piazselenoles is approximately the same as in the substituted piazthioles. We recall that in the piazthioles the influence of the substi-

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*For part IV, see [6].

*The preparation and some properties of the isomeric piazselenolesulfonic acids will be reported separately.

Table 1

Chemical Shifts in the PMR Spectra of the Compounds Studied

No.	Compound	Chemical shift, ppm		Solvent *
		ring protons	substituent protons	
1	5-Nitropiazselenole	8.7; 8.0	—	b
		8.8; 8.1	—	d
2	Benzo(4, 5)piazselenole (naphtho-(1,2)-selenadiazole)	8.6; 7.6	—	a
3	4-Nitropiazselenole	8.50; 7.85	—	d
4	Benzo(4,5)benzofurazan (naphtho-(1, 2)-furazan)	8.5; 7.7	—	a
5	Sodium piazselenole-5-sulfonate	8.22; 7.87	—	f
6	Sodium piazselenole-4-sulfonate	7.75	—	f
7	5-Chloropiazselenole	7.7	—	a
8	4-Chloropiazselenole	7.6	—	a
9	Benzofurazan	7.59	—	a
10	Piazselenole	7.52	—	c
11	4-Methylpiazselenole	7.4	2.7	a
		7.4	2.65	c
12	5-Methylpiazselenole	7.3	2.4	a
		7.3	2.32	c
13	4-Aminopiazselenole	6.9	5.3	e
14	5-Aminopiazselenole	6.8	4.9	e

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*The interpretation of the symbols is given in the experimental part.

Table 2

Comparison of Various Physicochemical Characteristics of the Benzo-2, 1, 3-X-diazoles (I; X = O, S, SE)

No.	Magnitudes compared	Compounds compared			
		I, X=O	I, X=S	I, X=Se	Naphthalene
1	$\nu_0\delta_{AB}$, Hz	15.6[1*] 14.4[2*]	17.6	18.8	14.3
2	μ, D	4.03	1.73	0.94	—
3	Spin densities on the nitgrogen atom in anion radicals from I	0.22	0.21	0.24	—
4	Difference in the spin densities in the α and β positions of the anion radicals from I and from naphthalene	0.058	0.041	0	0.112
5	$(\Delta pK_a)_{\beta-\alpha}/(pK_a)_\beta$[3*]	+0.033	+0.0023	−0.038	—
6	$E_{1/2}$, V[4*]	−1.412	−1,453	−1.325	—

[1*] According to [16].

[2*] From the data given in the monograph [17].

[3*] $(\Delta pK_a)_{\beta-\alpha}$ is the difference between the pK_a values of the corresponding 5- and 4-oxa-substituted compounds (I).

[4*] For the first reversible one-electron waves for reduction in dimethyl-

tuents proved to be qualitatively and quantitatively similar to the corresponding effects in substituted benzenes. Fig. 1 gives the average chemical shift of the ring protons of the piazselenoles as functions of Hammett's σ_m and σ_n constants.

It can be seen that the general tendency of the change in the chemical shifts agrees satisfactorily with the facts well known in organic chemistry of the influence of donor or acceptor substituents in the distribution of the local charges in benzene. Gotô and Tôei [3] came to the same conclusion in a recent paper in which they compared the wavelengths of the absorption of 5-substituted piazselenoles in the UV region with the Hammett $\sigma_m + \sigma_n$ magnitudes. However, it is impossible on the basis of such correlations to obtain quantitative evaluations of the degree of similarity of the benzene ring in the piazselenoles to the corresponding benzenes.

Additional data on this question can be obtained by comparing the PMR spectra of the A_2B_2 system for naphthalene, benzofurazan (I, X = O), piazthiole, and piazselenole. Figure 2 gives the PMR spectrum of piazselenole at limit resolution.

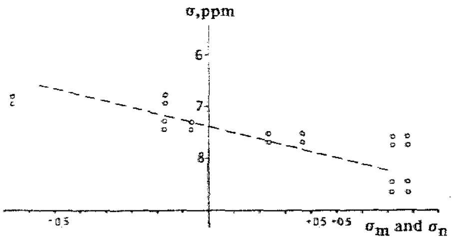


Fig. 1. Correlation of the chemical shifts studied and the corresponding Hammett σ_m and σ_n constants.

Calcuation in accordance with the method of Pople et al. [4] gives the spectral parameters shown in Fig. 3. The main interest is a comparison of the chemical shift $\nu_0\delta_{AB}$ for the four compounds just mentioned. These data are given in the first column of Table 2. The other columns of Table 2 give the dipole moments of these molecules [5], the spin densities on the nitrogen atoms, and the differences in the spin densities in positions A and B of the anion radical from I (compare [6]), the same difference characterizing the anion radical of naphthalene [7] and also the relative changes in the ionization constants of the corresponding 4- and 5-hydroxy derivatives [8] and the polarographic halfwave potentials (see [9,10]).

All of these experimental data permit a more detailed discussion of the question on the presence of conjugation in the heterocycle posed in our previous papers [1,2]. We have already mentioned that an increase in the chemical shift $\nu_0\delta_{AB}$ in piazthiazole as compared with napthalene cannot in any case be regarded as due to an increase in the ring current in the heterocycle as compared with benzene: apart from the influence of magnetic anisotropy there is the contribution to $\nu_0\delta_{AB}$ from the difference in the local electron densities of cloud on the protons in the nonequivalent A and B positions (4 and 5).

The absence of any relationship between $\nu_0\delta_{AB}$ and the dipole moment (see lines 1 and 2 in Table 2) shows that the Buckingham-Musher effect [12], the polarization of a bond by the electric field of charges concentrated on other atoms of the molecule under consideration, makes no appreciable contribution to the difference in the screening of the A and B protons. We have carried out direct calculations which show that with different assumptions for the magnitudes of the partial charges on the atoms of the heterocyclic ring, their influence is approximately an order of magnitude less than the observed shift. On comparing the PMR and EPR data (for the latter, see lines 3 and 4 in Table 2) it can be seen that there is no connection whatever between the changes in $\nu_0\delta_{AB}$ and the spin densities. This indirectly confirms our opinion that the observed chemical shift cannot be ascribed wholly to differences in the local screening of the A and B protons. Attention is also attracted by the absence of a correlation between $\nu_0\delta_{AB}$ and the values of pK_a the greatest value of δ_{AB} and a negative value of pk_a (line 5 in Table 2). Thus, the greatest value of δ_{AB} and a negative value of pK_a for the corresponding hydroxy derivative corresponds to piazselenole. Since the value of pK_a must undoubtedly be connected with the local electron density on the C-atoms bearing the OH groups, we again come to the conclusion that the local screening does not make a dominant contribution to $\nu_0\delta_{AB}$. All of the cited data show that the chemical shift $\nu_0\delta_{AB}$ observed in the series of 2,1,3-X-diazoles (X = O, S, Se) is due mainly to the magnetic anisotropy of the heterocyclic ring.

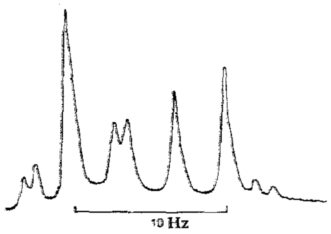


Fig. 2. Half (right-hand) of the PMR spectrum of piazselenole at a resolution of $1 \cdot 10^{-8}$.

This means that the question of interest to us on the existence of conjugation in the heterocyclic ring reduces to a choice between two alternative explanations of the observed shifts δ_{AB}; the shift may be caused either by the ring current in the heterocyclic ring or by the magnetic anisotropy of the C=N bonds in compounds I (X = O, S, Se). The anisotropy of the C=N bond is ~$5 \cdot 10^{-6}$ [13], which gives the maximum difference in the screening for the protons A and B

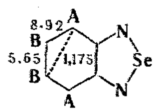


Fig. 3. Parameters of the PMR spectrum of piazselenole. $\nu_0\delta_{AB} = 18.8$ Hz.

$$\delta_{AB}^{(C=N)} = \frac{3\Delta\chi}{2RN}\left(\frac{1}{R_A^3} - \frac{1}{R_B^3}\right) \approx 3 \cdot 10^{-7}.$$

This is less than the shift observed in any of the compounds considered. The influence of the anisotropy of the N—X bonds is smaller by yet another order; this is due to the increase in the distances R_A and R_B from the dipole μ(N—X) to the A and B protons and to a decrease in the difference between these distances. In evaluating the magnitude $\delta_{AB}^{(C=N)}$, no account was taken of its dependence on the orientation of the magnetic dipole of the anisotropic bond relative to the vectors $r_{\mu A}$ and $r_{\mu B}$. In actual fact, $\delta_{AB}^{(C=N)}$ is substantially smaller than $3 \cdot 10^{-7}$.

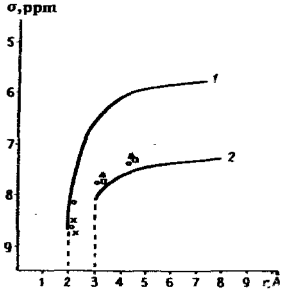


Fig. 4. Chemical shift as a function of the distance separating the corresponding proton and the center of the ring contour for the following compounds: benzofurazan (•), piazthiazole (Δ), piazselenole (□), furazan (○), and thiadiazole (×). The points for the last two compounds reflect the chemical shifts of the protons of both the pure liquids and their solutions in CCl_4. For the plotting of the reference curves 1 and 2, see text.

Taking $3 \cdot 10^{-7}$ as the upper limit of the contribution of the magnetic anisotropy of the C=N bond to δ_{AB} and subtracting this magnitude from the observed value of δ_{AB}, we find the following minimum estimates for the "aromatic" contribution: benzofurazan 3.6 Hz; piazthiole 5.6 Hz; piazselenole 6.8 Hz; naphthalene 14.3 Hz.

This result is completely obvious: within the framework of ideas on the constant magnetic anisotropy independent of the key atom X of the C=N bonds, the PMR data will always lead to a sequence in which the "aromaticity" (in the sense of the intensity of the ring current) will rise in the order just given.

But it is important that even in such a rough approximation we are undoubtedly detecting the influence of the ring current in the heterocyclic ring on the observed shifts δ_{AB}. A refinement of the values of these currents i_{heter} in the molecules I (X = 0, S, Se) can be made in the following way. The contribution of the ring current to the screening of a proton present in the plane of the ring at a sufficient distance r from the center of the contour about which the current i_{heter} circulates is

$$\delta_i = \frac{i_{heter} \cdot Q}{r^3},$$

where Q is the area comprised by the ring contour.

In Fig. 4, curve 1 shows the experimental relationship for the benzene ring. Curve 2 expresses the corresponding relationship for napthalene:

$$\delta_{naphth} = \delta_{benz}\left[1 + \left(\frac{r_{benz}}{r}\right)^3\right],$$

where r_{benz} is the distance of the proton under consideration from the center of "its" phenyl nucleus and r is the distance of the same proton from the center of the neighboring ring.

The experimental points that we obtained lie close to curve 2 in Fig. 4*. It is assumed that the chemical shifts of the protons of benzofuran, piazthiazole, and piazselenole are due mainly to the ring currents in the ten-electron closed system, the corresponding points of Fig. 2 must lie on curves described by the equation:

$$\delta_{het} = \delta_{benz}\left[1 + \varkappa\left(\frac{r_{benz}}{r}\right)^3 \cdot \frac{Q_{het}}{Q_{benz}}\right],$$

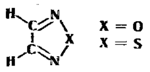
where Q_{het} is the area of the heterocycle, Q_{benz} is the area of the hexagon formed by the six C-atoms in benzene, and $\varkappa = i_{het}/i_{benz}$ is the ratio of the intensity of the ring current in the heterocycle to the corresponding current for benzene.

The evaluation of the applicability of this approach proves favorable. For all three molecules of the general formula I, we have used a value of $\varkappa$ less than unity and one that is completely reasonable in magnitude. Under these conditions the relative intensities of the ring currents in the various compounds proved to be dissimilar: for benzofurazan, $\varkappa = 0.8$, for piathiole, $\varkappa = 0.35$, and for piazselenole, $\varkappa = 0.4$ (i.e., this intensity is greatest for benzofurazan and the values for piazthiole and piazselenole are similar).

This result is in striking contrast to evaluations of the "current" contribution of the heterocycle to the PMR chemical shifts made on the basis of routine ideas on the constant values of the electronegativity of the O, S, and Se atoms.

Consequently, the measurements that we carried out open up a route to determining the real acceptor properties of the key atoms present in a heterocycle. We are doing work along this line.

In furazan (II, X = O) and in thiadiazole (II, X = S), the PMR signals [14] relative to benzene are shifted substantially in the direction of weak fields (Fig. 4), although the ring current in these nuclei is, as we have just shown, weaker than in benzene. This permits the conclusion that the electron density of the C—H bonds in the heterocycles II is smaller.



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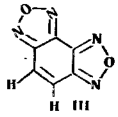

III

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*By also introducing into the calculation data on the shifts of the protons in the spectra of furazan [14], thiadiazole [14], and selenadiazole [18], we arrive at a system of points which is located correspondingly on curve 1 (for benzene) in Fig. 4.

At the same time, the sulfur-containing rather than the oxygen-containing ring proves to be more electrophilic ($\delta_H = 8.19$ for **II**, X = 0, and $\delta_H = 8.58$ for X = S; solutions in CCl_4)* (see also the values of $E_{1/2}$ in line 6 of Table 2). It is interesting to note that the use of the method developed here gives good agreement with experiment for the PMR spectrum of benzodifurazan III [15]: $\delta_{exp} = 8.14$, $\delta_{calc} = 8.05$. The difference $\delta_{exp} - \delta_{calc}$ permits the additional conclusion that the presence of a second condensed 2, 1, 3-oxadiazole ring somewhat increases the drawing off of the electrons from the C—H bonds as compared with benzofurazan.

It was of interest to confirm our conclusion of the existence of a ring current by measurements of magnetic susceptibility. It was found that the van Vleck susceptibility in all three benzo-2, 1, 3-X-diazoles **I** is substantially less than in compounds with nonconjugated multiple bonds [11].

This confirms the conclusion of the existence of a definite delocalization of the electrons in the molecules studied.

EXPERIMENTAL

To record the spectra, solutions of the substances in carbon tetrachloride (denoted by the symbol a in the column "solvent" of Table 1), tetrachloroethane (symbol b), tetrachloroethylene (symbol c), dimethylsulfoxide (d), dioxane (e), and water (f) were used. Acetone was used as the internal standard for the aqueous solutions and tetramethylsilane or hexamethyldisiloxane for the other cases. Sealed uncentered tubes with a diameter of 4.7 or 4 mm were used. The spectrometers were a PLA-5535 with a working frequency of 40 MHz and a Hitachi H-60 (60 MHz). The accuracy of the measurements of the chemical shifts was limited by the complex nature of the spectra, but was not worse than $1 \cdot 10^{-7}$.

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*The electrophilicity of the selenium-containing ring proves to be greatest: in CCl_4 solution the protons of **II**, X = Se, are characterized by a chemical shift $\delta_H = 9.28$ [18].

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