σ Values of *N*-Substituted Azoles

By **Philippe Bouchet, Claude Coquelet,** and **José Elguero,*** Laboratoire de synthèse et d'étude physico-chimique d'hétérocycles azotés, Université des Sciences et Techniques du Languedoc, Place E. Bataillon, 34060 Montpellier Cedex, France

The σ_p coefficients of azoles and their benzo-derivatives have been determined by i.r. and n.m.r. spectroscopy, based on the study of the NH_2 bands arising from 1-*p*-aminophenylazoles.

KAUFFMANN[1] suggested that 'azoles containing more than one N atom bound by way of an N atom correspond to halogen and other good negative leaving groups.' In this work we have attempted to make quantitative comparison on this basis by determining the σ_p coefficients of *N*-substituted azoles.

Two examples of good correlation between spectroscopic properties and Hammett σ coefficients exist for the aniline series. In the first case,[2] the physical property which is measured is the symmetrical or antisymmetrical stretching vibration of the NH_2 group determined in carbon disulphide [equations (1)]; the

$$\left.\begin{aligned}\nu_s(NH_2) &= -1{\cdot}92 + 28{\cdot}47\sigma_p\ (r\ 0{\cdot}979)\\ \nu_{as}(NH_2) &= -3{\cdot}30 + 40{\cdot}31\sigma_p\ (r\ 0{\cdot}968)\end{aligned}\right\}\quad(1)$$

second[3] is the proton chemical shift of the NH_2 group in dimethyl sulphoxide (DMSO). Thus we have prepared a series of 1-*p*-aminophenylazoles in order to study their i.r. and n.m.r. behaviour and to determine their σ_p coefficients by these two independent methods.

$$\delta(NH_2) = 290{\cdot}6 + 79{\cdot}27\sigma\ (\sigma_m \text{ and } \sigma_p)\ (r\ 0{\cdot}997)\quad(2)$$

EXPERIMENTAL

The fifteen compounds studied were prepared by reduction of the corresponding *p*-nitrophenyl derivatives (Table 1) by the following procedure. A mixture of 1-*p*-nitrophenylazole (0·01 mol), stannous chloride (10 g), and concentrated hydrochloric acid (12 g) was heated until a clear solution was obtained. A dilute sodium hydroxide solution was added (basic pH) and the 1-*p*-aminophenylazole was extracted either with chloroform or with ethyl acetate. Yields were *ca.* 90%.

All n.m.r. spectra were recorded at 31·5° on a Varian A60 spectrometer. Solutions in anhydrous $[^2H_6]$DMSO were 0·2—0·4M (we were able to verify that in some cases, in this range of concentration, the NH_2 chemical shifts were independent of the concentration). Measurements are given in Hz at 60 MHz and are accurate to ±0·5 Hz.

I.r. spectra were measured using 10^{-3}M solutions in CCl_4 with a Perkin-Elmer 225 spectrometer equipped with 1 cm cells (scan width, 5 cm^{-1} per cm of paper; scan speed, 30 s per cm^{-1}). In contrast to literature data,[2] we found that CS_2 is not a suitable solvent because it reacts with anilines to yield dithiocarbamic acids;[4] for this reason experiments were carried out in CCl_4 in spite of possible amine–CCl_4 interactions.[2] The $\nu_{as}(NH)$ and $\nu_s(NH)$ values were obtained for anilines with conventional substituents and are in good agreement with literature data. Our measurements are accurate to $\pm 0{\cdot}3\ cm^{-1}$.

TABLE 1

Synthesis of 1-(*p*-aminophenyl)azoles

No.	Azole	M.p. (°C) [lit. m.p. (°C)]
(1)	Pyrrole	74—76 [79 [a]]
(2a)	Pyrazole	42—44 [45 [e]]
(2b)	3,5-Dimethylpyrazole	96—98 [101—102 [b]]
(2c)	3,5-Di-t-butylpyrazole	203—205
(3)	Imidazole	143—145 (141—143 [c]]
(4a)	1*H*-1,2,4-Triazole	138—140 [142 [d]]
(4b)	3-Methyl-1*H*-1,2,4-triazole	174—177
(5)	4*H*-1,2,4-Triazole	192—195
(6)	1*H*-1,2,3-Triazole	130—132 [139—140 [e]]
(7)	2*H*-1,2,3-Triazole	51—54 [Eb_2 165 [f]]
(8)	1*H*-Tetrazole	143—146 [145—145·5 [g]]
(9)	2*H*-Tetrazole	123—124
(10a)	3-Methylindazole	135—136 [136—137 [h]]
(11)	Benzimidazole	106—108 [116 [i]]
(12)	Carbazole	Oil

[a] J. Dhont and J. P. Wibaut, *Rec. Trav. chim.*, 1943, **62**, 177. [b] D. Dal Monte, A. Mangini, and R. Passerini, *Boll. sci. Fac. Chim. ind. Bologna*, 1954, **12**, 147. [c] Merck, Neth. P. Appl., 6,413,474. [d] G. Cipens, D. Duka, and V. Grinsteins, *Khim. Geterotsikl. Soedinenii Akad. Nauk. Latvian S.S.S.R.*, 1966, 117. [e] Farbenfabriken Bayer, Neth. P. Appl. 6,610,038. [f] J. L. Riebsomer, *J. Org. Chem.*, 1948, **13**, 815. [g] J. C. Kauer and W. A. Sheppard, *J. Org. Chem.*, 1967, **32**, 3580. [h] A. R. Frasca, *Tetrahedron Letters*, 1962, 1115. [i] F. Montanari and R. Passerini, *Boll. sci. Fac. Chim. ind. Bologna*, 1953, **11**, 42.

The numerical treatment of the data used the multilinear regression program REGMUL of Phan Tan Luu and Mathieu.[5] For a detailed description of the capabilities of this program, see ref. 6.

DISCUSSION

To clarify the meaning of the intercept, we preferred to calculate our own regression lines using $\Delta\nu = \nu^X - \nu^H$ and $\Delta\delta = \delta^X - \delta^H$ rather than the frequencies [equation (1)] or the chemical shifts themselves [equation (2)].

A series of eleven *para*-substituted anilines with groups of known σ coefficients[7] was considered; in the case of CO_2Me, COMe, and NO_2, σ^- coefficients[7] were used. The results are listed in Table 2.

As has been pointed out by Bellamy and Williams[8] there is a good correlation between the ν_s and ν_{as} vibrations of the NH_2 groups of aliphatic and aromatic primary amines; the use of $\Delta\nu_s$ and $\Delta\nu_{as}$ values from

---

[1] T. Kauffmann, *Angew. Chem. Internat. Edn.*, 1971, **10**, 743.

[2] C. Laurence and B. Wojtkowiak, *Bull. Soc. chim. France*, 1971, 3124.

[3] B. M. Lynch, B. C. Macdonald, and J. G. K. Webb, *Tetrahedron*, 1962, **24**, 3595.

[4] J. Zabicky in 'The Chemistry of the Amino Group,' ed. S. Patai, Wiley, London, 1968, p. 106.

[5] R. Phan Tan Luu and D. Mathieu, unpublished results.

[6] J. W. ApSimon, J. Elguero, A. Fruchier, D. Mathieu, and R. Phan Tan Luu, *Canad. J. Chem.*, submitted for publication.

[7] H. Hine, 'Physical Organic Chemistry,' McGraw-Hill, New York, 1962, pp. 87 and 90.

[8] L. J. Bellamy and R. L. Williams, *Spectrochim. Acta*, 1957 **9**, 341.

Tables 2 and 3, leads to equation (3) (correlation coefficients r and confidence limits of all the equations in this paper are shown in Table 5).

$$\Delta\nu_{as} = 1{\cdot}465\Delta\nu_s + 0{\cdot}749 \qquad (3)\,^*$$

Instead of making two distinct correlations, one with $\Delta\nu_{as}$ and the other with $\Delta\nu_s$, we preferred to use the points situated on the regression line [equation (3)] of the co-ordinates $\Delta\nu_{as}{}^{c}$† and $\Delta\nu_s{}^{c}$. For this purpose, the experimental points have been projected perpendicularly to the straight line in order to minimise the sum $(\Delta\nu_{as}{}^{c} - \Delta\nu_{as})^2 + (\Delta\nu_s{}^{c} - \Delta\nu_s)^2$. The corresponding $\Delta\nu_{as}{}^{c}$ values are shown in Tables 2 and 3.

TABLE 2

I.r. stretching vibrations and n.m.r. chemical shifts of the NH_2 group of *para*-substituted anilines

No.	Substituent	σ_p	ν_{as}(NH)/cm^{-1}	$\Delta\nu_{as}{}^{c}$/cm^{-1}	ν_s(NH)/cm^{-1}	$\delta(NH_2)$/Hz	$\Delta\delta$/Hz
(13)	None	0	3480·3	+0·2	3395·8	297	0
(14)	NH_2	−0·660	3455·1	−25·3	3377·8	246	−51
(15)	OMe	−0·268	3461·8	−18·3	3383·1	273	−24
(16)	CH_3	−0·170	3472·2	−8·2	3389·6	283	−14
(17)	F	+0·062	3474·0	−5·9	3391·8	293	−4
(18)	Cl	+0·226	3485·6	+5·3	3399·0	311	+14
(19)	Br	+0·232	3487·5	+7·1	3400·0	312	+15
(20)	I	+0·276	3489·4	+9·0	3401·2	313	+16
(21)	CO_2Me	+0·636	3501·3	+20·9	3409·4	353	+56
(22)	COMe	+0·874	3502·4	+21·7	3409·6	359	+62
(23)	NO_2	+1·270	3508·5	+28·6	3415·3	398	+101

TABLE 3

I.r. stretching vibrations and n.m.r. chemical shifts of the NH_2 group of 1-*p*-aminophenylazoles

No.	ν_{as}(NH)/ cm^{-1}	ν_s(NH)/ cm^{-1}	$\Delta\nu_{as}{}^{c}$/ cm^{-1}	$\delta(NH_2)$/ Hz	$\Delta\delta$/ Hz
(1)	3483·2	3397·0	+2·8	303	+6
(2a)	3483·6	3397·4	+3·2	310	+13
(2b)	3487·1	3400·0	+6·8	314·5	+17·5
(2c)	3489·3	3401·6	+9·1	317	+20
(3)	3491·0	3402·0	+10·1	314	+17
(4a)	3490·3	3402·6	+10·4	324	+27
(4b)	Insufficient sample			321	+24
(5)	Insoluble			321·5	+24·5
(6)	3491·6	3403·5	+11·5	326·5	+29·5
(7)	3488·0	3400·3	+7·6	323	+26
(8)	Low solubility	3408·0	+18·9	336·5	+39·5
(9)	3496·1	3406·5	+16·0	342	+45
(10a)	3484·4	3398·0	+4·0	316	+19
(11)	3492·3	3403·6	+12·1	325	+28
(12)	3490·2	3401·8	+9·8	325·5	+28·5

The results from Table 2 allow a calculation of the regression lines from equations (4) and (5). In theory,

$$\sigma_p = 3{\cdot}11 \times 10^{-2}\,\Delta\nu_{as}{}^{c} + 12{\cdot}6 \times 10^{-2} \qquad (4)$$

$$\sigma_p = 1{\cdot}25 \times 10^{-2}\,\Delta\delta + 3{\cdot}06 \times 10^{-2} \qquad (5)$$

the straight line should pass through the origin, owing to the definition of the σ scale; this is actually observed in the case of equation (5) which is deduced from n.m.r. measurements, since the intercept is very small and less than its calculated confidence interval (Table 5). However i.r. experiments do not afford such a good fit and the intercept is larger and significant. The origin of the non-zero intercept is still to be explained (presence of solute–solute associations?); it is noteworthy that Laurence and Wojtkowiak[2] also found a significant constant for their correlations.

Using the lines determined as described and the values of $\Delta\nu_{as}{}^{c}$ and $\Delta\delta$ found for the 1-*p*-aminophenylazoles (see Table 3), it has been possible to obtain the σ_p coefficients of azoles (Table 4). The agreement between the two methods is relatively satisfactory [except in the case of 1*H*-tetrazole (8) and imidazole (3)] although the values deduced from i.r. studies are less precise and slightly larger [equation (6)].

TABLE 4

Comparison of σ_p values determined in the present work with other spectroscopic and theoretical quantities

No.	σ_p(n.m.r.) *	σ_p(i.r.)	ν(C=O)/cm^{-1} for 1-acetylazoles	$q_{\pi} + {}_{\sigma}$(N-1) [e]
(1)	0·10 ± 0·04	0·21 ± 0·10	1732 (CCl_4) [a]	5·14
(2a)	0·19 ± 0·04	0·23 ± 0·10	1746 (CCl_4) [b]	5·09
(3)	0·24 ± 0·04	0·45 ± 0·11	1747 (CCl_4) [a]	5·12
(4a)	0·365 ± 0·04	0·44 ± 0·11	1765 (CCl_4) [a]	5·05
(5)	0·33 ± 0·04	Insoluble (see Table 3)		5·08
(6)	0·40 ± 0·045	0·48 ± 0·12	1762 (CCl_4) [c]	5·05
(7)	0·355 ± 0·04	0·36 ± 0·10	1780 (CCl_4) [c]	5·04
(8)	0·52 ± 0·05	0·71 ± 0·14		5·01
(9)	0·59 ± 0·05	0·62 ± 0·13	1779 (CCl_4) [a]	4·98
(10a)	0·27 ± 0·04	0·25 ± 0·10	1720 ($CHCl_3$) †,[b]	
(11)	0·38 ± 0·045	0·50 ± 0·12	1730 ($CHCl_3$) [d]	
(12)	0·385 ± 0·045	0·43 ± 0·10	1692 ($CHCl_3$) [d]	

* For *C*-substituted derivatives, the following values have been obtained: 3,5-dimethylpyrazole (2b), 0·25 ± 0·04; 3,5-di-t-butylpyrazole (2c) 0·28 ± 0·04; 3-methyl-1H-1,2,4-triazole (4b), 0·33 ± 0·04. † This value is for indazole itself.

[a] W. Otting, *Chem. Ber.*, 1956, **89**, 1940. [b] J. Elguero and A. Fruchier, unpublished results. [c] L. Birkofer and P. Wegner, *Chem. Ber.*, 1967, **100**, 3485. [d] H. W. Thompson and R. J. L. Popplewell, *Z. Elektrochem.*, 1960, **64**, 746. [e] Ref. 12.

$$\sigma_p\ (\text{n.m.r.}) = 0{\cdot}80\sigma_p\ (\text{i.r.}) \qquad (6)$$

The following discussion is based on the σ_p values obtained from the n.m.r. measurements. The first remark to be made is that the σ_p values varying from 0·10 (pyrrole) to 0·60 (2*H*-tetrazole) agree well with

---

* Use of ν values instead of those of $\Delta\nu$ gives the equation $\nu_s = 1025{\cdot}7 + 0{\cdot}681\nu_{as}$; this seems quite different from the Bellamy–Williams equation[8] in its classical form ($\nu_s = 345{\cdot}5 + 0{\cdot}875\nu_{as}$). In fact both equations give comparable results in the 3300—3500 cm^{-1} region, but ours is better for *para*-substituted anilines, even using the less accurate experimental values of Califano and Moccia.[9]

† $\Delta\nu_{as}{}^{c} = (1{\cdot}465\,\Delta\nu_s + 1{\cdot}465^2\Delta\nu_{as} + 0{\cdot}749)/(1{\cdot}465^2 + 1)$.

[9] S. Califano and R. Moccia, *Gazzetta*, 1956, **86**, 1014.

Kauffmann's statement which likened azoles to halogens (σ_p *ca.* 0·25 [7]). The second concerns the σ_p value of 1*H*-tetrazole (0·52 ± 0·05). This value is in excellent agreement with those determined by Kauer and Sheppard [10] from two other methods: $\sigma_p = 0{\cdot}57$ from basicity measurements of anilines and 0·50 from the ^{19}F chemical shifts of fluorobenzenes. The third point concerns the effect of *C*-substituents. When 1*H*-1,2,4-triazole is methylated in the 3-position, the σ_p value decreases by *ca.* 0·04 units [compare (4a and b)]. To verify that this effect does not depend on the azole, we studied 1-*p*-aminophenyl-3-methylpyrazole (2d). In the n.m.r. spectrum ([$^2H_6$]DMSO) the NH_2 signal appears at 306 Hz (at 60 MHz) which corresponds to a σ_p value of 0·14 ± 0·04, and therefore the observed decrease in the σ_p value is similar [0·05 units, compare (2a and d)]. In the case of 3,5-disubstituted pyrazoles (2b and c) the increase in σ_p (*ca.* 0·08 units) can be attributed to the effect of the substituent at C-5, which overcompensates the effect of the substituent at C-3. This point also involves the influence of fused benzo-groups, each of which causes an increase in σ_p of *ca.* 0·14 units: compare (2d) and (10a), (3) and (11), or (1) and (12).

TABLE 5

Correlation coefficients *r* and 95% confidence limits [a] of various regression lines obtained in this paper

$y = ax + b$	*r*	95% Confidence limit Slope	 Intercept
$\Delta\nu_{as} = 1{\cdot}465\Delta\nu_s + 0{\cdot}749$	0·998	0·036	0·32
$\nu_s = 0{\cdot}681\nu_{as} + 1026$	0·999	0·016	56
$\sigma_p = 3{\cdot}11 \times 10^{-2}\ \Delta\nu_{as} + 12{\cdot}6 \times 10^{-2}$	0·967	$0{\cdot}613 \times 10^{-2}$	$10{\cdot}1 \times 10^{-2}$
$\sigma_p = 1{\cdot}25 \times 10^{-2}\ \Delta\delta + 3{\cdot}06 \times 10^{-2}$	0·995	$0{\cdot}092 \times 10^{-2}$	$4{\cdot}08 \times 10^{-2}$
$\sigma_p(\text{n.m.r.}) = 0{\cdot}80\ \sigma_p(\text{i.r.}) - 0{\cdot}007$	0·888	0·27	0·12
$\sigma_p = 0{\cdot}0103\nu(C{=}O) - 17{\cdot}7$	0·983	0·003	5·3
$\sigma_p = -2{\cdot}90q + 15{\cdot}0$	0·983	0·77	4·1

[a] N. R. Draper and H. Smith, ' Applied Regression Analysis,' Wiley, New York, 1966, p. 65.

Finally, we have added to Table 4 the values of the stretching vibrations of 1-acetylazoles, which are the arenologues [1] of acetyl chloride. In the case of monocyclic derivatives a linear relation between σ_p and $\nu(C{=}O)$ has been established: $\sigma_p = 0{\cdot}0103\nu(C{=}O) - 17{\cdot}7$ (the value for 2*H*-1,2,3-triazole which was too far from the linear plot has not been introduced in the regression).

For the bicyclic derivatives (10)—(12) the $\nu(C{=}O)$ vibrations are at lower frequencies than expected from the σ_p values (especially striking in the case of carbazole). This is inconsistent with the calculations of Gross and Rush [11] who found that in these compounds the $\nu(C{=}O)$ bands are at higher frequencies than those corresponding to the calculated C=O bond order.

In the case of *N*-unsubstituted azoles, relationship (7) can be established between σ_p and the total charge on N-1, calculated by the EHT method.[12] It is likely that

$$\sigma_p = -2{\cdot}90q_{\pi+\sigma}(\text{N-1}) + 15{\cdot}00 \qquad (7)$$

MO calculations for the cases under study would give a better account of the experimental results than the σ_p coefficients determined in the present work; however our method, because of its simplicity and efficiency, is a good approach to the study of the behaviour of *N*-substituted azoles.

We thank A. Fruchier, this laboratory, for help in the numerical computations.

[3/1422 *Received*, 10*th July*, 1973]

---

[10] J. C. Kauer and W. A. Sheppard, *J. Org. Chem.*, 1967, **32**, 3580.

[11] J. M. Gross and D. G. Rush, *Chem. and Ind.*, 1968, 1766.

[12] M. Roche and L. Pujol, unpublished results; M. Roche, Thesis, Marseille, 1970.