

THE RESONANCE EFFECT OF THE HETEROATOM IN PYRROLE, FURAN, AND THIOPHEN

L.W. Deady, R.A. Shanks, and R.D. Topsom,

Department of Organic Chemistry, La Trobe University,

Bundoora, Victoria 3083, Australia

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There is considerable current interest in the relative effects of the heteroatom on the electron distribution in, and reactivity of, pyrrole, furan, and thiophen. During the past few years much new information has been published regarding electrophilic substitution in these compounds. This has been well summarised¹ and the accepted reactivity order is pyrrole > furan > thiophen with the 2-position being more reactive than the 3-position in each compound.

It has been strongly argued² that, in the ground state, inductive withdrawing effects predominate in both furan and thiophen and resonance donation by the heteroatom is in fact less important in furan. It was suggested² that the greater reactivity of furan than thiophen is a transition state phenomenon under conditions of strong electron demand explicable in terms of a lower localisation energy in furan.

In terms of substituent constants the suggestion is thus that $|\sigma_R^{\circ}|$ is larger for a thienyl than a furyl group but that $|\sigma_R^+|$ for electrophilic substitution is in the opposite order; thus $|\sigma_R^+ - \sigma_R^{\circ}|$ must be greater for furan than thiophen under conditions of strong electron demand. By contrast, for most substituted benzenes $|\sigma_R^+|$ is generally related³ to $|\sigma_R^{\circ}|$ and because of this only one set of σ_R^+ values is used for reaction involving various degrees of electron demand; the difference in demand is taken up in the reaction constant (ρ). If the arguments above are correct it seems likely that $|\sigma_R^+|$ values for furyl and thienyl groups will vary as the reaction considered and, in particular,

those for furyl will be less than those for thienyl for reactions of weak electron demand.

We report here evidence in favour of this hypothesis, viz, that under conditions of moderate electron demand, the sulphur of thiophen is still a better resonance donor than the oxygen of furan.

In a recent detailed study of substituent effects on the intensity of the $\text{-C}\equiv\text{N}$ stretching vibration in the infrared spectra of substituted benzonitriles,⁴ the previously reported correlation with the σ^+ constant⁵ was refined. The intensity for a wide range of meta and para substituted benzonitriles is given by equation 1. We have now applied this treatment to the five-membered ring heterocycles.

$$A_{\text{CN}}^{\frac{1}{2}} = -19.0\sigma^+ + 29.6$$

The cyano pyrroles, furans, and thiophens were synthesized according to the methods listed in the Table. The spectra were measured on a Perkin-Elmer 225 spectrophotometer in carbon tetrachloride solution and analysed as for the benzonitriles.⁴ The A values quoted are infinite dilution values to avoid effects associated with dimer formation. Multiple peaks were observed for the cyanopyrroles under high resolution. These have also been observed in spectra of 2-cyanopyridine⁶ and 2-cyanopyridine-1-oxide.⁷ The intensities were integrated together since the peaks probably arise from Fermi resonance with combination bands.

The cyanide frequencies and $A^{\frac{1}{2}}$ values for the measured compounds (including benzonitrile for comparison) are given in the Table. In order to give a comparison with aromatic substituents, σ^+ values derived from equation 1, and those from some reactivity studies are also included.

The results show that the heteroatoms are behaving as electron donor groups towards this probe. For pyrrole, the effect is very strong in accord with the known high reactivity of pyrrole to electrophilic substitution. However, for both the 2- and 3-positions, the results

TABLE

Compound	Prep. Method	ν_{CN}	A_{CN}^{h}	$\sigma^{\text{+d}}$	$\sigma^{\text{+e}}$	$\sigma^{\text{+f}}$
2-cyanopyrrole	a	2229.6	54.8	-1.33	-1.53	
		2223.0				
3-cyanopyrrole	b	2244.5	39.7	-0.54		
		2238.4				
		2228.2				
2-cyanothiophen	a	2225.7	37.8	-0.44	-0.79	-0.79
3-cyanothiophen	a	2234.1	31.5	-0.10	-0.52	-0.38
2-cyanofuran	a	2236.3	31.9	-0.13	-0.93	-0.89
3-cyanofuran	c	2246.2	29.5	0		-0.42
benzonitrile		2232.2	28.7	0	0	0

^a Acetic anhydride dehydration of the carboxaldoxime according to the method of Runde.⁸ Ether was used as solvent for 2-cyanopyrrole only. ^b From 1,4-dihydroxybut-2-ene.^{9,10} ^c From 3-furoic acid,¹¹ via the acid chloride (SOCl_2) and amide (dehydrated by 1 hr reflux with POCl_3). ^d From equation 1. ^e From electrophilic substitution reactions.¹ ^f From pyrolysis of 1-arylethyl acetates.¹²

indicate that towards the cyanide probe employed, sulphur is a better donor than oxygen. The numerical values obtained are lower than those from electrophilic substitution in accord with the lower electron demand.

It is important to note that for all three heterocycles the band intensity, and therefore the donating effect of the heteroatom, is greater at the 2- than at the 3-position. This is also the order encountered in electrophilic substitution and strongly suggests that a resonance effect of the heteroatom is the factor controlling the band intensity. In situations where inductive effects are predominant, for example as shown in the pK_a values of the appropriate carboxylic acids,² electron withdrawal occurs in the furyl and thienyl acids (relative to benzoic acid) and is greater from the 2-position.

These results therefore support the statement² that the greater reactivity of furan than thiophen to electrophilic attack "is not directly related to ground state electron distribution".

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