

^{13}C NMR Studies of Some 2-Substituted Thieno[2,3-*b*]thiophenes and Thieno[3,2-*b*]thiophenes

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The ^{13}C NMR parameters of some 2-substituted thieno[2,3-*b*]thiophenes and thieno[3,2-*b*]thiophenes have been determined. The substituent-caused chemical shifts are discussed. Differences were observed for the transmittance of substituent effects to similar positions in the two systems. In comparison with the analogous shifts of the corresponding thiophenes great similarities were observed and good linear correlations were obtained. Linear correlations between some of the shifts and the reactivity parameters according to Swain and Lupton's two-parameter equation are also given.

In our previous papers, a detailed study of the ^{13}C NMR parameters of 2- and 3-substituted furans, thiophenes, selenophenes, and tellurophenes¹⁻⁴ was made. In order to study how substituent effects are transmitted over the heteroatoms, the thieno[3,2-*b*]thiophenes (Ia–c, e–i) and the thieno[2,3-*b*]thiophenes (IIa–i) were investigated and compared with the corresponding thiophenes (IIIa–i).

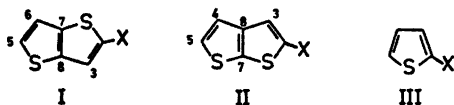


Fig. 1. X =

- | | |
|-------------------|--------------------|
| a, H | f, CHO |
| b, SCH_3 | g, COCH_3 |
| c, Cl | h, CN |
| d, Br | i, NO_2 |
| e, CH_3 | |

Bugge⁵ found linear correlations between the ^1H chemical shifts of I (a–e, g–i) and II (a–e, g–i) with the reactivity constants \mathcal{F} and \mathcal{R} of

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Swain and Lupton. A comparison was also made with similar calculations on thiophene by Rodmar *et al.*⁶

^{13}C NMR SPECTRA AND ASSIGNMENTS OF SIGNALS

In the ^{13}C NMR measurements, deuterioacetone was used as solvent. All shifts were determined from proton decoupled spectra using TMS as an internal standard.

In the ^{13}C spectra of 2-substituted thieno[3,2-*b*]thiophenes (Ib–i), C-8 and C-7 were identified by their lower intensity, as expected for quaternary carbons due to their relatively long relaxation times. For the unsubstituted Ia, the C-8 and C-7 absorptions are equivalent because Ia is symmetrical, while for the substituted derivatives (Ib–i) these positions are non-equivalent.

As seen from Fig. 3, C-7 in Ib–i should be compared with C-5 in 2-substituted thiophenes.¹ C-8 in Ib–i can in a similar way be compared with C-4 in 2-substituted thiophenes, showing small substituent-caused shifts.¹

In Ib–i, C-2 is a quaternary carbon giving an absorption with lower intensity. The substituent influence on the C-2 shift is the same as on the C-2 shift in the corresponding 2-substituted thiophenes. For the unsubstituted compound (Ia) there is a shift difference of 8 ppm between C- α and C- β . In order to get further information for the shift assignments, the undecoupled spectrum of 2-chlorothieno[3,2-*b*]thiophene (Ic) was determined (Fig. 2). The direct coupling constants were found to

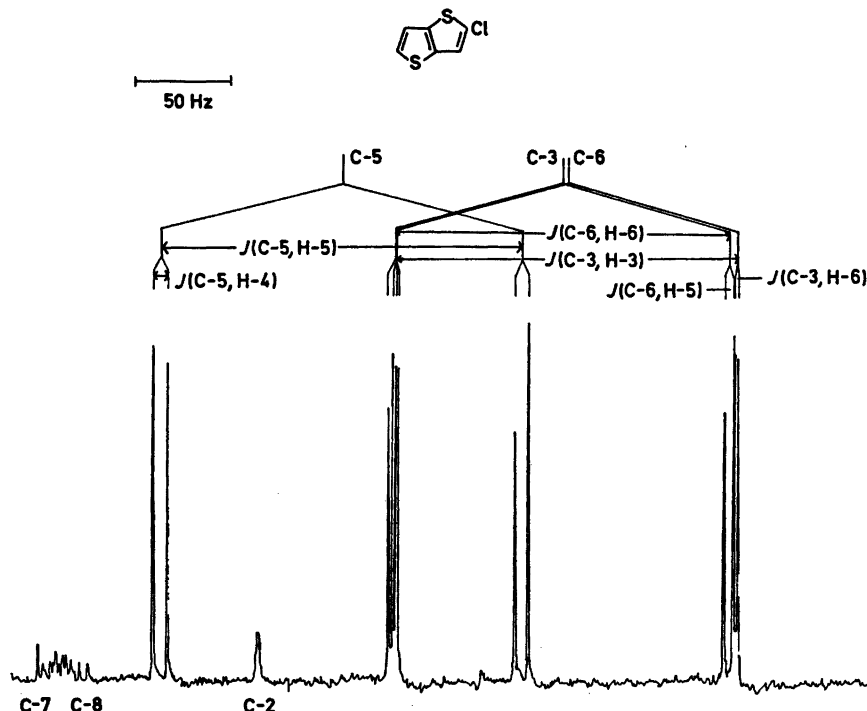


Fig. 2. ^{13}C NMR Spectra of 2-chlorothiopheno[3,2-*b*]thiophene in hexadeuterioacetone solution at 15.00 MHz.

be 177.7 Hz, 188.2 Hz and 174.8 Hz, showing that the C-5 absorption occurs at lower field than the C-3 and C-6 absorptions because $J_{\text{C}-\alpha, \text{H}-\alpha}$ is larger than $J_{\text{C}-\beta, \text{H}-\beta}$.¹ For C-3, adjacent to the substituent, the substituent-caused shifts are expected to vary more than those of the C-6-position. (Cf. Table 2: the intervals for C-3 are 11.3–1.7 ppm and for C-6 1.4–0.1 ppm.) The assignments of the C-3 and C-6 carbons in the 2-chloro derivative could also be obtained from the long-range couplings by comparison with the 2-substituted

thiophenes,¹ where $J_{\text{C}-4, \text{H}-5}$ and $J_{\text{C}-5, \text{H}-4}$ are about 5 and 7 Hz, respectively. The long-range couplings obtained for Ic were $J_{\text{C}-3, \text{H}-6}$ 1.7 Hz, $J_{\text{C}-6, \text{H}-5}$ 7.1 Hz and $J_{\text{C}-6, \text{H}-3}$ 4.7 Hz (Fig. 2).

In the thieno[2,3-*b*]thiophene series (IIb-i), C-2, C-8 and C-7 are quaternary carbon atoms. These carbons can be identified in the same way as described above. C-2 exhibits the largest substituent effects. C-7, with the character of a *para* position (Fig. 3), should also be rather sensitive to the variation of substituent, while C-8, which can be compared with a *meta* posi-

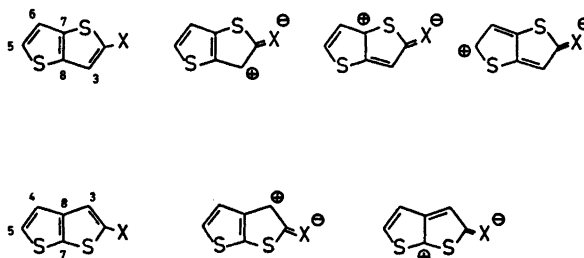


Fig 3.

Table 1. ¹³C NMR chemical shifts for some 2-substituted thieno[3,2-*b*]thiophenes (I) in deuterioacetone solution at 15.0 MHz using TMS as an internal standard.

| X | C-2 | C-3 | C-5 | C-6 | C-7 | C-8 | CH ₃ | C=O |
|-------------------|-------|-------|-------|-------|-------|-------|-----------------|-------|
| H | 127.9 | 119.9 | 127.9 | 119.9 | 139.9 | 139.9 | | |
| SCH ₃ | 139.2 | 124.5 | 128.3 | 120.2 | 141.6 | 139.8 | 22.3 | |
| Cl | 130.7 | 120.0 | 127.8 | 120.0 | 137.4 | 137.6 | | |
| CH ₃ | 142.8 | 118.2 | 126.3 | 120.1 | 138.3 | 139.6 | 16.2 | |
| CHO | 146.3 | 130.7 | 135.2 | 121.1 | 145.8 | 140.1 | | 184.4 |
| COCH ₃ | 146.9 | 126.6 | 133.9 | 121.1 | 145.6 | 140.1 | 30.7 | 191.5 |
| COOH | 136.9 | 126.8 | 133.1 | 120.8 | 144.8 | 139.6 | | 163.6 |
| CN | 114.9 | 131.2 | 134.9 | 121.0 | 144.1 | 139.3 | | 110.4 |
| NO ₂ | 152.2 | 123.6 | 136.5 | 121.3 | | | | |

Table 2. ¹³C NMR chemical shifts for some 2-substituted thieno[2,3-*b*]thiophenes (II) in deuterioacetone solution at 15.00 MHz using TMS as an internal standard.

| Substituent | C-2 | C-3 | C-4 | C-5 | C-7 | C-8 | CH ₃ | C=O |
|-------------------|-------|-------|-------|-------|-------|-------|-----------------|-------|
| H | 129.1 | 120.4 | 120.4 | 129.1 | 137.6 | 147.9 | | |
| SCH ₃ | 140.3 | 126.0 | 120.5 | 129.0 | 139.0 | 147.3 | | |
| Cl | 130.8 | 119.5 | 119.5 | 128.8 | 134.6 | 145.3 | | |
| Br | 113.3 | 124.1 | 120.2 | 129.1 | 136.1 | 146.7 | | |
| CH ₃ | 143.7 | 118.7 | 120.3 | 128.1 | 135.2 | 147.8 | 16.2 | |
| CHO | 148.0 | 130.6 | 121.7 | 131.4 | 145.9 | 147.5 | | 184.1 |
| COCH ₃ | 148.7 | 126.6 | 121.7 | 131.0 | 145.0 | 147.7 | 26.3 | 191.2 |
| COOH | | 126.9 | 121.6 | 130.8 | | | | |
| CN | 114.8 | 131.5 | 121.1 | 132.5 | 143.3 | 146.5 | 111.8 | |
| NO ₂ | 153.4 | 122.9 | 122.4 | 131.0 | 144.0 | 146.4 | | |
| CHNOH | | 123.9 | 120.9 | 129.5 | 141.5 | 146.1 | | |

Table 3. Chemical shifts (ppm)^a of the carbons of 2-substituted thieno[3,2-*b*]thiophenes (I) and thieno[2,3-*b*]thiophenes (II) relative to corresponding carbons of unsubstituted I and II in deuterioacetone solution.

| Substituent | I | | | | | | II | | | | | |
|-------------------|-------|------|------|------|------|------|-------|------|------|------|------|------|
| | ΔC-2 | ΔC-3 | ΔC-5 | ΔC-6 | ΔC-7 | ΔC-8 | ΔC-2 | ΔC-3 | ΔC-4 | ΔC-5 | ΔC-7 | ΔC-8 |
| H | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SCH ₃ | 11.3 | 4.6 | 0.4 | 0.3 | 1.7 | -0.1 | 11.2 | 5.6 | 0.1 | -0.1 | 1.4 | -0.6 |
| Cl | 2.8 | 0.1 | -0.1 | 0.1 | -0.5 | -0.3 | 1.7 | -0.9 | -0.9 | -0.3 | -3.0 | -2.6 |
| Br | | | | | | | -15.4 | 3.6 | -0.1 | 0.0 | -1.5 | -1.2 |
| CH ₃ | 14.9 | -1.7 | -1.6 | 0.2 | -1.6 | -0.3 | 14.6 | -1.7 | -0.1 | -1.0 | -2.4 | -0.1 |
| CHO | 18.4 | 10.8 | 7.3 | 1.2 | 5.9 | 0.2 | 18.9 | 10.2 | 1.3 | 2.3 | 8.6 | -0.4 |
| COCH ₃ | 19.0 | 6.7 | 6.0 | 1.2 | 5.7 | 0.2 | 19.6 | 6.2 | 1.3 | 1.9 | 7.4 | -0.2 |
| COOH | 9.0 | 6.9 | 5.2 | 0.9 | 4.9 | -1.3 | - | 6.5 | 1.2 | 1.7 | - | - |
| CN | -13.0 | 11.3 | 7.0 | 1.1 | 4.2 | -0.6 | -14.3 | 11.1 | 0.7 | 3.4 | 5.7 | -1.4 |
| NO ₂ | 24.3 | 3.7 | 8.6 | 1.4 | - | - | 24.2 | 2.5 | 2.0 | 2.9 | 6.4 | -1.5 |

^a ΔC=C(substrate)-C(reference); positive values are downfield.

Table 4. Linear correlations obtained for ^{13}C chemical shifts of 2-substituted thieno[3,2-*b*]thiophenes (Ib-i) and thieno[2,3-*b*]thiophenes (IIb-k) versus those of corresponding 2-substituted thiophenes (III).

| | r | n | |
|---|-------|-----|-----|
| I | | | |
| C-7 = (0.62 ± 0.04) C-5 - (0.25 ± 0.27) | 0.990 | 7 | (1) |
| C-5 = (0.81 ± 0.09) C-5 - (0.46 ± 0.63) | 0.966 | 7 | (2) |
| C-3 = (1.00 ± 0.04) C-3 - (0.34 ± 0.27) | 0.995 | 8 | (3) |
| C-2 = (0.92 ± 0.03) C-2 + (0.67 ± 0.43) | 0.998 | 8 | (4) |
| II | | | |
| C-7 = (0.98 ± 0.09) C-5 - (2.04 ± 0.64) | 0.972 | 8 | (5) |
| C-5 = (0.33 ± 0.06) C-5 - (0.53 ± 0.31) | 0.939 | 8 | (6) |
| C-3 = (1.01 ± 0.05) C-3 - (0.43 ± 0.31) | 0.992 | 9 | (7) |
| C-2 = (0.93 ± 0.03) C-2 - (0.41 ± 0.50) | 0.997 | 9 | (8) |

tion, should be rather insensitive to shift effects.

The other three carbons were assigned from the uncoupled spectrum of 2-formylthieno[2,3-*b*]thiophene, II*f*. The direct coupling constants were found to be 171.1, 173.1 and 190.0 Hz. The largest direct coupling was observed for the carbon atom that has its absorption at lowest field, demonstrating it to be C-5. C-3, adjacent to the substituent, also shows the largest substituent effects, while C-4 is almost uninfluenced. The assignments of C-3 and C-4 carbons in II*f* could also be obtained with the same procedure as above from the

long-range coupling constants. The long-range couplings obtained for II*f* were $J_{\text{C-3,H-5}}$ 1.0 Hz, $J_{\text{C-3,H(CHO)}}$ 0.5 Hz, $J_{\text{C-4,H-5}}$ 4.2 Hz, $J_{\text{C-4,H-3}}$ 1.0 Hz and $J_{\text{C-5,H-4}}$ 7.6 Hz. The ^{13}C parameters are given in Tables 1 and 2 and the chemical shifts relative to the unsubstituted compounds Ia and IIa are presented in Table 3.

DISCUSSION

In both thieno[3,2-*b*]thiophene and thieno[2,3-*b*]thiophene, the 3-carbon is *ortho* to the substituent and the substituent-caused shifts

Table 5. Regression equations relating ^{13}C chemical shifts a of 2-substituted thieno[3,2-*b*]thiophenes (I) and thieno[2,3-*b*]thiophenes (II) to substituent constants \mathcal{F} and \mathcal{R} .

| | G^b | R^c | N^d |
|---|-------|-------|-------|
| I | | | |
| $\Delta\text{C-5} = (0.6 \pm 0.6) + (3.9 \pm 1.0)\mathcal{F} + (18.0 \pm 3.5)\mathcal{R}$ | 0.7 | 0.99 | 6 |
| $\Delta\text{C-6} = (0.5 \pm 0.2) + (0.2 \pm 0.2)\mathcal{F} + (2.8 \pm 0.9)\mathcal{R}$ | 0.2 | 0.95 | 6 |
| $\Delta\text{C-7} = (1.3 \pm 0.9) + (0.9 \pm 1.7)\mathcal{F} + (17.2 \pm 4.8)\mathcal{R}$ | 1.0 | 0.95 | 5 |
| II | | | |
| $\Delta\text{C-5} = (-0.9 \pm 0.4) + (1.7 \pm 0.7)\mathcal{F} + (7.4 \pm 2.5)\mathcal{R}$ | 0.5 | 0.96 | 6 |
| $\Delta\text{C-7} = (1.4 \pm 0.7) + (0.1 \pm 1.1)\mathcal{F} + (27.5 \pm 3.2)\mathcal{R}$ | 0.8 | 0.99 | 5 |
| $\Delta\text{C-8} = (0.3 \pm 0.4) - (2.7 \pm 0.6)\mathcal{F} + (5.0 \pm 2.0)\mathcal{R}$ | 0.4 | 0.91 | 5 |
| III | | | |
| $\Delta\text{C-5} = (2.1 \pm 0.4) + (2.5 \pm 0.7)\mathcal{F} + (26.5 \pm 2.5)\mathcal{R}$ | 1.1 | 0.99 | 6 |

a The shifts are given in ppm relative to those of the parent compounds I and II (*cf.* Table 3). b Standard deviation 1 ppm. c Correlation coefficient. d Number of substituents in the regression analysis.

($\Delta C-3$) show good linear correlations with $\Delta C-3$ in 2-substituted thiophenes (*cf.* eqns. 3 and 7 in Table 4). These equations also show that the sensitivity to the substituent effects is the same in the three systems (I–III). The substituted carbon atoms in the three series also show comparable sensitivity to the substituent effects (eqns. 4 and 8, Table 4). By correlating $\Delta C-5$ of 2-substituted thiophenes with $\Delta C-7$ of the two fused systems (eqns. 1 and 5, Table 4), it is found that the transmission over the heteroatom to C-7 is of the same magnitude in thiophene and system II, while it is much lower in system I. However, when $\Delta C-5$ of I and $\Delta C-5$ of II are correlated with $\Delta C-5$ of thiophene, the sensitivity is much lower in the II-series than in the I-series. Simple resonance structures (Fig. 3) indicate that for an –I-M-substituent the positive charge can be placed in three positions, on C-3, C-5, and C-7 in the I-series, but only in two positions in the II-series (C-3 and C-7). This supports the assumption that the substituent effect can be efficiently transmitted to the 5-carbon in the I-series but not in the II-series.

In our previous investigations of ¹³C spectra of furans, thiophenes and selenophenes,^{1–3} we successfully correlated the substituent-caused shifts with the two-parameter equation of Swain and Lupton.⁷ In this way, we obtained some information about the resonance and inductive contributions to the chemical shifts. Bugge⁶ has obtained good correlations of the ¹H chemical shifts of I and II with the reactivity constants ρ and ρ' of Swain and Lupton.

The correlations obtained with I and II are given in Table 5. The substituents Br and SCH₃ were excluded from the least-squares fit calculations as the values calculated from the regression equations deviate considerably more from the experimental ones for these substituents than for the others.

The only positions which gave good correlations in both I and II were C-5 and C-7. By comparing the equations for C-5 of I and II in Table 5 it is interesting to note that the resonance effect is much more efficiently transmitted over two sulfur atoms in system I than in system II; the r -values are 18.0 and 7.4, respectively. This is in agreement with reasoning

based on simple resonance structures, as a positive charge in the 5-position can only be written for system I and not for system II without violating the octet rule for sulfur (Fig. 3).

On the other hand, for the 7-position, where the interaction with the substituent is only over one sulfur atom, system II shows great similarities with the monocyclic system (III). The equations for $\Delta C-7$ of II and $\Delta C-5$ of III have comparable f - and r -values, while the equation for C-7 of I shows a much lower r -value. In the latter system, the effects of the substituents are more equally divided between the 7- and 5-position ($r=17.2$ and 18.0). The transmission of the resonance effects in system II is reflected in the r -values 7.4 and 27.5 for the 5- and 7-positions, respectively.

The low value of the slope of eqn. 1 compared to eqn. 5 in Table 4 is consequently due to the continued transmission of the resonance effects over both of the sulfur atoms of system I, while system II allows transmission mainly over one sulfur atom, and therefore shows similarities to the monocyclic system.

EXPERIMENTAL

All 2-substituted thieno[2,3-*b*]thiophenes (Ia-i) and thieno[3,2-*b*]thiophenes (IIa-i) used in this study are known.^{5,8,9} The purity and structure of the compounds were checked by gas chromatography, IR and ¹H NMR analysis.

All ¹³C NMR spectra were obtained at 15.0 MHz with a Jeol JNM-FX 60 spectrometer with a built-in Jeol 980A computer with 12 K memory. For all spectra the proton noise decoupling technique was used. The R_f pulse width was 6 μ s, corresponding to a pulse angle of 45 degrees and the pulse repetition rate was 1 s. The shifts were determined with an accuracy of ± 0.1 ppm.

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