# Conformational Isomers and Rotational Barriers in the Ketyl Radicals of Thiophen and Thienothiophens

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The conformational isomers of the ketyl radicals (I)—(III) generated from di-2-thienyl ketone, bis-2-thieno-[3,2-*b*]thienyl ketone, and bis-2-thieno[2,3-*b*]thienyl ketone, have been detected by e.s.r. spectroscopy. The two preferred conformations are *cis–trans* and *trans–trans*. Study of the line shape variations with temperature of the e.s.r. spectra allowed the determination of the activation parameters for the rotation of the aromatic rings. The activation energies follow the same order as the electron-delocalizing power of the nuclei, the values being 31·30, 37·95, 35·73, and 26·57 kJ mol$^{-1}$ for (I), (II), (III) and for benzophenone ketyl, respectively.

CONFORMATIONAL analysis of several thiophen-containing radicals has been the subject of recent investigations. Different e.s.r. signals from distinct rotational isomers or the non-equivalence of some splitting constants due to restricted internal rotation have been detected for the radical anions of 2,2′-bithienyl and 2-phenylthiophen,[1] the 2- and 3-thenyl neutral radicals,[2] the anions of several mono- [3] and di-aldehydes [4] of thiophen and of condensed thiophens, and the radical anions of some dithienylethylenes.[5] In all these cases, however, at the highest temperatures which could be reached compatible with the stability of the radicals the e.s.r. lines from different rotational isomers remained sharp and no information on interconversion processes between these isomers could be obtained by studying line broadening of the e.s.r. spectrum.

This implies that the rate constant for internal rotation is always $<$ *ca.* $10^5$ s$^{-1}$; consequently the rotational barriers in these radicals should be $\geqslant 40$ kJ mol$^{-1}$.

A more favourable situation occurs in the ketyl radicals of diaryl ketones where both the slow and fast rotation limits, on the e.s.r. time scale, are attainable for a temperature range in which the radicals are still stable. In a previous paper we described the e.s.r. spectra of the ketyl radicals of dithienones and bisthienothienones.[6] At room temperature only the averaged spectrum could be observed, but with decreasing temperature the high-

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[1] P. Cavalieri D'Oro, A. Mangini, G. F. Pedulli, P. Spagnolo, and M. Tiecco, *Tetrahedron Letters*, 1969, 4179.

[2] A. Hudson, H. A. Hussain, and J. W. E. Lewis, *Mol. Phys.*, 1968, **16**, 519.

[3] A. Hudson and J. W. E. Lewis, *Tetrahedron*, 1970, 4413.

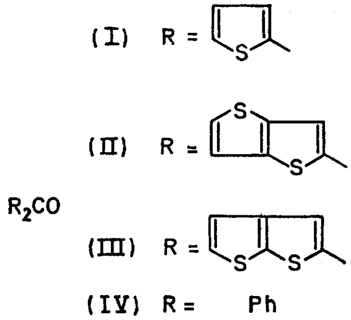
[4] L. Lunazzi, G. F. Pedulli, M. Tiecco, C. A. Veracini, and C. Vincenzi, *J.C.S. Perkin II*, 1972, 751.

[5] L. Lunazzi, A. Mangini, G. Placucci, P. Spagnolo, and M. Tiecco, *J.C.S. Perkin II*, 1972, 192.

[6] G. F. Pedulli, M. Tiecco, A. Alberti, and G. Martelli, *J.C.S. Perkin II*, 1973, 1815.

field part of the spectrum broadens and finally splits in new lines due to the rotational isomers of these radicals. A similar temperature dependence of the e.s.r. spectrum of benzophenone ketyl was found by Takeshita and Hirota[7] who observed complete equivalence of the *ortho*- and *meta*-splittings at room temperature, whereas at *ca.* −100° they became non-equivalent; by analysing the linewidth variations in the intermediate region they determined the rates of rotation and the relative activation energy as 19·45 kJ mol$^{-1}$.

We report here an analogous kinetic investigation on the ketyls (I)—(III) from thiophen and the thienothiophens together with the results of a more accurate determination of the energy barrier to rotation in benzophenone ketyl. The assignment of stereochemistry to the observed conformational isomers of ketyls (I)—(III) is also presented.



## EXPERIMENTAL

The ketones of thiophen and the thienothiophens were prepared as described previously[6] while benzophenone was a commercial product.

The ketyl radicals were produced by photolysis in deoxygenated solutions of sodium methoxide–methanol–dimethoxyethane (DME) (1 : 3 : 4) or by reduction with potassium in tetrahydrofuran (THF) or in THF–dimethylformamide (DMF). In the latter case the ketyls were prepared by introducing purified DMF through a vacuum line into a sample tube containing the radical generated in THF by alkali-metal reduction.

The temperature of the sample was controlled using standard variable temperature accessories and measured with a chromel–alumel thermocouple placed in the Dewar insert just above the sensitive part of the cavity.

## RESULTS AND DISCUSSION

*Conformational Isomers.*—The room temperature e.s.r. spectra of the ketyls (I)—(III) have already been described;[6] however, as an example, Figure 1a gives the spectrum of di-2-thienyl ketyl (I) which shows the coupling of the unpaired electron with three pairs of equivalent protons. This equivalence indicates that the averaged spectrum is being observed. When the temperature is lowered the asymmetry in the linewidth, which can be seen even at room temperature, becomes more evident and finally new lines appear in the high-field part of the spectrum as shown in Figure 1b. Since this change of spectral shape with temperature also occurs for the bisthienothienyl ketyls (II) and (III) and because the radical species detected at low temperature have the same number of coupled protons, very similar hyperfine splittings, and slightly different *g* factors, they were identified as the rotational isomers of these radicals. The main features of the low temperature spectra of the three ketyls are very similar, in every case the low-field signals being practically superimposable and the high-field ones well separated.

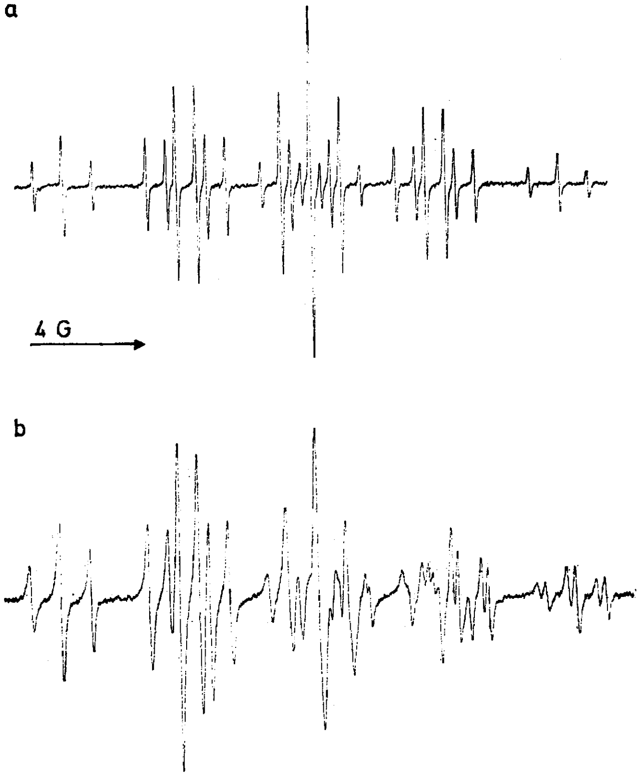
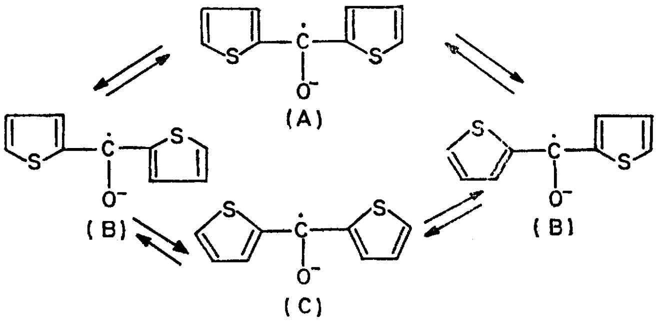


FIGURE 1 E.s.r. spectra of the di-2-thienyl ketyl (I) in MeOH–DME, a, at room temperature and b, at −50 °C

In principle, three rotational isomers may be expected for each radical: *cis–cis* (A), *cis–trans* (B), and *trans–trans* (C) as exemplified for the 2,2′-dithienyl ketyl (I) (Scheme). However in every case only two species were detected, one having a larger overall splitting and a smaller *g* factor. Among the three permutations (A) and (C) can be rejected since the isomers observed have different values of the hyperfine splittings for 3- and 3′-H



SCHEME

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[7] T. Takeshita and N. Hirota, *J. Chem. Phys.*, 1969, **51**, 2146.

TABLE 1

Hyperfine splitting constants (G) of the ketyl radical from (I)—(III). $\Delta B_0 = B_{0cis\text{-}trans} - B_{0trans\text{-}trans}$ is the difference between the resonant fields of the spectral centres of the *cis–trans*- and *trans–trans*-isomers

| Ketyl | Solvent | Isomer | $a_{3},a_{3'}$ | $a_{4},a_{4'}$ | $a_{5},a_{5'}$ | $a_{6},a_{6'}$ | $\Delta B_0$ |
|---|---|---|---|---|---|---|---|
| (I) | MeOH–DME | *trans–trans* | 4·80 | 1·03 | 4·08 | | 0·123 |
| | | *cis–trans* | 4·855, 4·96 | 1·055 | 4·21 | | |
| (II) | MeOH–DME | *trans–trans* | 4·81 | | 2·40 | 0·615 | 0·08 |
| | | *cis–trans* | 4·87, 4·98 | | 2·41, 2·48 | 0·64 | |
| (II) | THF–DMF | *trans–trans* | 4·49 | | 2·35 | 0·60 | 0·153 |
| | | *cis–trans* | 4·59, 4·73 | | 2·40 | 0·618 | |
| (III) | MeOH–DME | *trans–trans* | 5·58 | 0·06 | 0·485 | | 0·14 |
| | | *cis–trans* | 5·65, 5·70 | 0·06 | 0·50 | | |

while they should be degenerate in the symmetric conformers (A) and (C). Consequently only the possibilities (A) and (B) and (B) and (C) need be taken into account.

The primary cause of the difference in the splitting constants and $g$ factors is the strong electrostatic interaction between the negative oxygen and the adjacent ring atoms. This interaction induces larger spin densities on the atom of the aromatic ring which is *trans* to the carbonyl group;[8] therefore, in thiophen derivatives we should expect a greater $g$ value and a smaller splitting of 3-H in the isomer with sulphur *trans* to oxygen in that position, but a smaller $g$ and a larger $a_3$ splitting when sulphur is *cis* to the carbonyl group.

This has been verified in recent work on some dialdehydes of thiophen and condensed thiophens where the assignment could be made independently by experimental methods.[4] In these radicals and also in the radical anions of thiophen-2-carbaldehyde and 2-acetylthiophen,[3] the more stable conformer was always found to be that having the sulphur atom *cis* to the carbonyl oxygen atom.

By analogy, we might therefore expect that in the present case the two isomers observed are the *cis–cis* (A) and the *cis–trans* (B). However, the *cis–cis*-conformation in spite of favourable conjugative and inductive interactions may be destabilized by steric interactions between 3- and 3′-H. This point may be clarified by considering the symmetry of the observed species and the relative values of the e.s.r. parameters in the light of the considerations above concerning the spatial effect of the carbonyl group on the spin density of the adjacent atoms. Since the spin density on the sulphur atoms should increase when going from (A) to (C), the $g$ factors of the three isomers should follow the order $g_A < g_B < g_C$. If the two isomers detected at low temperature are (A) and (B), the species having the lowest $g$ factor and hence centred at higher field should be the symmetric conformer (A), whereas the asymmetric conformer (B) will resonate at higher field if (B) and (C) are present. Therefore complete interpretation of the spectra of both isomers will allow this problem to be solved.

The more suitable radical for this purpose is the bis-2-thieno[3,2-*b*]thienyl ketyl (II) generated in THF–DMF since the differences in the coupling constants of the two isomers are larger than in the other derivatives and the resolution of the low temperature spectrum (Figure 2) is better than that in alcoholic solution. By simulating this spectrum accurate values of the hyperfine splitting constants could be determined. As shown in Table 1, the species centred at higher field and hence having a smaller $g$ factor has different proton splittings for 3- and 3′-H; it can thus be identified as the asymmetric *cis–trans*-isomer (B). Therefore, for the reasons given previously, we conclude that the second isomer is the *trans–trans* (C). Although the low temperature spectra recorded in alcoholic solution are partially broadened because of the high viscosity of the solvent, they could be interpreted for each of the ketyls (I)—(III) and the hyperfine splitting constants are reported in Table 1; the resonance of the asymmetric species was always at higher field than that of the symmetric one. The two

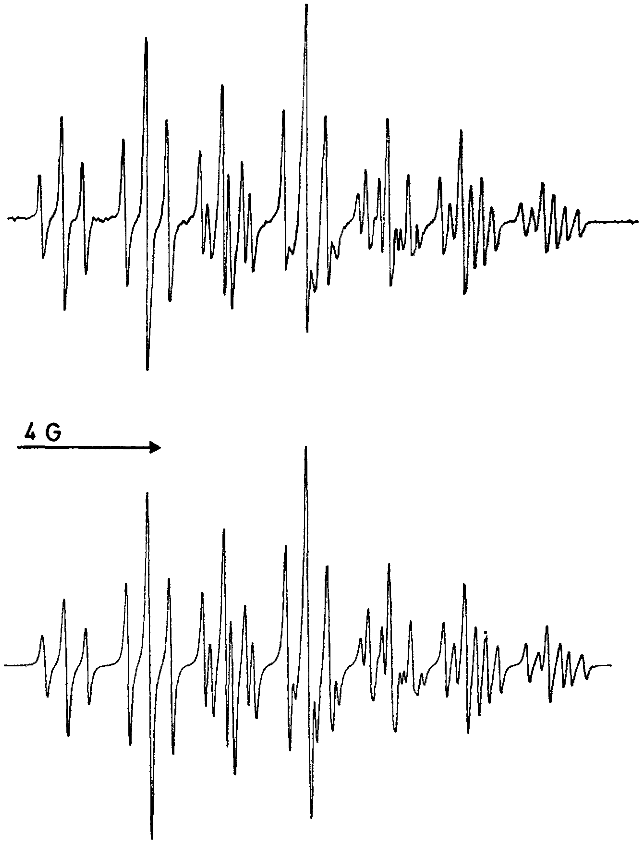

FIGURE 2 Experimental (upper) and simulated e.s.r. spectrum of bis-2-thieno[3,2-*b*]thienyl ketyl (II) in THF–DMF at −50 °C

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[8] N. Steinberger and G. K. Fraenkel, *J. Chem. Phys.*, 1964, **40**, 723.

more stable isomers were in every case (B) and (C), in the ratio at *ca.* −50° 1·30 : , 0·68 : , and 0·55 : 1 for radicals (I)—(III) respectively. Despite the close similarity of the systems, the stability of the *cis–trans*-conformation is much greater for the di-2-thienyl ketyl (I) than for the bisthienothienyl ketyls (II) and (III).

The enhanced stability observed in these radicals of the *trans*-conformations relative to the thiophen mono- and di-aldehydes where the *cis*-isomers are favoured, is probably due to steric hindrance between 3- and 3′-H, which prevents the *cis–cis*-structure from being planar and strongly reduces the conjugation between carbonyl group and the aromatic nuclei. The existence of a dihedral angle of 56° between the two phenyl rings in benzophenone [9] supports this explanation.

Attempts to detect the rotational isomers of di-3-thienyl ketyl were unsuccessful as, with decreasing temperature, the intensity of the spectrum also decreases and at *ca.* −10° the radical decays completely. Even at the lowest temperature we could not observe any asymmetry of the spectral pattern, suggesting that rotation of the thiophen ring is much faster than in corresponding 2-substituted ketyl. This conclusion is supported by a similar investigation we are carrying out on some aryl nitroxides where rotation of the 3-thienyl ring could also be studied.[10]

*Barriers to Rotation.*—Quantitative information on the kinetics of isomerization and on the relative activation parameters may be obtained by determining the rate constants for the rotation of the aromatic rings from the line shape of the e.s.r. spectra taken at various temperatures. The linewidth variations may be analysed using relaxation theory [11] which holds only for the fast exchange limit or density matrix theory [12] which covers the full range of rates. In the present case, since the range of temperatures giving major changes in the spectral shape is not too large, we preferred to use the density matrix theory to get more accurate results. In principle a four-jump model should be chosen for the interconversion process as, for each ring, there are two possible orientations with respect to the carbonyl group; however, the absence of detectable amounts of the *cis–cis*-isomer, prevented us from applying this model. Therefore the *trans–trans* ⟶ *cis–trans*-interconversion was described by a two nonequivalent-sites model with rates of exchange $k_1$ and $k_{-1}$.

Takeshita and Hirota [7] made a kinetic study of the rotation of the phenyl rings in benzophenone ketyl using the relaxation theory based on a four-jump model. They determined the activation energy and the frequency factor as 19·45 ± 1·25 kJ mol$^{-1}$ and 11·7 respectively. The latter values should be somewhat larger since a factor of $\pi^2$ is missing in the spectral densities quoted; moreover the activation energy was calculated from rate constants determined by comparing the widths of two peaks only. We repeated the experimental measurements and estimated the rate of exchange from computer simulated spectra, which of course give much more reliable results.

Before discussing the details of calculations we first give a short account of the density matrix theory in the Liouville representation [12] and summarize briefly the derivation of equations (5) and (6) which have been used to reconstruct the theoretical spectra.

The shape of the absorption spectrum in a low power e.s.r. experiment is given by expression (1) [13] where

$$\mathrm{L}(\omega) = \mathrm{Re}(\mathbf{S}^{-}\mathbf{M}_0^{-1}\boldsymbol{\sigma}) \qquad (1)$$

$\mathbf{S}^{-}$ and $\boldsymbol{\sigma}$ are a row vector composed of the matrix elements of the lowering operator and a column vector containing the populations of the sites $P_i$. The matrix $\mathbf{M}_0$ is given by (2), where $\mathbf{L}_0$ is the Liouville superoperator

$$\mathbf{M}_0 = i\mathbf{L}_0 + \mathbf{R} + \mathbf{X} \qquad (2)$$

arising from the electron Zeeman and hyperfine Hamiltonians, and $\mathbf{X}$ and $\mathbf{R}$ are respectively the exchange and relaxation superoperators; the latter is assumed to be diagonal with all the elements identical to $-T_2^{-1}$.

By neglecting the nonsecular terms in the hyperfine Hamiltonian the $\mathbf{M}_0$ matrix can be factorized into submatrices $\mathbf{M}_{0j}$ of dimensions equal to the number of sites. The shape function L(ω) can then be rewritten in the more suitable form (3),[14] with $N = \Pi_i\ (2n_iI_i + 1)$,

$$\mathrm{L}(\omega) \propto \mathrm{Re} \sum_{j=1}^{N} D_j\,(\mathbf{S}^{-}\mathbf{M}_{0j}^{-1}\boldsymbol{\sigma}) \qquad (3)$$

where $n_i$ is the number of completely equivalent nuclei of the $i$th group having spin quantum number $I_i$, and $D_j$ the degeneracy of the transition.

Since the e.s.r. spectrum is usually measured as the derivative of the absorption curve, it is more convenient to derive L(ω) to obtain expression (4).[15]

$$\mathrm{L}'(\omega) \propto -\mathrm{I_m} \sum_{j=1}^{N} D_j\,(\mathbf{S}^{-}\mathbf{M}_{0j}^{-2}\boldsymbol{\sigma}) \qquad (4)$$

The only problem faced in practical application is the inversion of the $\mathbf{M}_{0j}$ matrix at each point of the spectrum. When the number of sites does not exceed four, the inversion can be performed analytically without too much difficulty. In the present case we are interested in obtaining formulae for two nonequivalent sites and four equivalent sites. In the first case the derivative of the absorption curve is given by equation (5), while for the

$$\mathrm{L}'(\omega) \propto -\,\mathrm{I_m} \sum_{j=1}^{N} D_j \frac{P_1x_{2j}^2 + P_2x_{1j}^2 + k_{12}k_{21} - (P_1k_{12} + P_2k_{21})(x_{1j} + x_{2j})}{(x_{1j} + x_{2j} - k_{12}k_{21})^2} \qquad (5)$$

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[9] E. B. Fleischer, N. Sung, and S. Hawkinson, *J. Phys. Chem.*, 1968, **72**, 4311.

[10] M. Camaggi, L. Lunazzi, G. F. Pedulli, G. Placucci, and M. Tiecco, unpublished results.

[11] J. H. Freed and G. K. Fraenkel, *J. Chem. Phys.*, 1963, **39**, 326.

[12] G. Binsch, *Mol. Phys.*, 1968, **15**, 469.

[13] G. Binsch, *J. Amer. Chem. Soc.*, 1969, **91**, 1304.

[14] J. Heinzer, *Mol. Phys.*, 1971, **22**, 167.

[15] G. R. Luckhurst and G. F. Pedulli, *Mol. Phys.*, 1971, **22**, 931.

four sites it takes the form (6), with $\alpha_p = (x_{pj} - k')^2$,

$$L'(\omega) \propto -\,\mathrm{I_m}\sum_{j=1}^{N} D_j \frac{(\alpha_1 + \alpha_4)(\beta_{23} - k\gamma_{23})^2 + (\alpha_2 + \alpha_3)(\beta_{14} - k\gamma_{14})^2}{(\beta_{14}\beta_{23} - k^2\gamma_{14}\gamma_{23})^2} \quad (6)$$

$\beta_{pq} = x_{pj}x_{qj} - k'^2$, and $\gamma_{pq} = x_{pj} + x_{qj} - 2k'$. $x_{pj} = i(\omega - \omega_{pj}) - T_2^{-1} - \sum_{i \neq p}^{n} k_{pi}$, $\omega_{pj}$ is the interchanging frequency, $k_{pi}$ is the first-order rate constant for a transition from site $p$ to site $i$, and $n$ is the number of sites. In the four equivalent-sites problem $k = k_{12} = k_{21} = k_{13} = k_{31} = k_{24} = k_{42} = k_{34} = k_{43}$ and $k' = k_{14} = k_{41} = k_{23} = k_{32}$.

The determination of the rate constants for rotation was made by visually fitting to the experimental spectra those calculated by a computer program based on equation (5) for the ketyls of thiophen and the thienothiophens, and based on equation (6) for benzophenone ketyl. For (I)—(III) the kinetic study of isomerization was performed for alcoholic solutions while for benzophenone ketyl THF–DMF was used because of the better spectral resolution at temperatures below −40°. Because of the difficulties in getting accurate values for the complete set of e.s.r. parameters and also to save computer time, only the low and high field triplets were simulated when dealing with the radicals from (I)—(III). From the low field triplet it is possible to obtain at each temperature the contribution to the linewidth in the absence of exchange because of the almost complete superposition of the lines from the two isomers, while the high field one, which shows the largest line shape variations with temperature, has been used for the determination of the rate constants of rotation. The coupling constants and $g$ shifts employed in the calculations are reported in Table 1. As an example, Figure 3 shows some spectra, with the simulations, of the bis-2-thieno-[3,2-*b*]thienyl ketyl (II), where $k$ is the forward rate for the *trans–trans* ⟶ *cis–trans*-isomerization.

In the case of benzophenone ketyl (IV) the complete low field half spectrum has been simulated by employing the hyperfine splittings reported in ref. 7. At first both the rates for the flip of one ring $k$ and for the simultaneous flip of two rings $k'$ were allowed to vary. However when the values of $k'$ were greater or comparable with that of $k$, no agreement between simulated and experimental spectra could be obtained, thus indicating that the probability for the simultaneous rotation of the two rings is very small. Then $k'$ was set equal to $10^2$ s$^{-1}$ and the spectra simulated by changing only $k$.

The activation parameters which can be derived from these measurements and the thermodynamic constants $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ for the activated complex obtained by standard least squares procedures, are collected in Table 2. The latter have been calculated using the Eyring equation with a transmission coefficient equal to 1.

An examination of the data of Table 2 shows that the activation entropies are quite small, in agreement with the value expected for restricted rotation which should be very close to zero. The activation energies for the rotation of the aromatic rings increase in order phenyl < 2-thienyl < 2-thieno[2,3-*b*]thienyl < 2-thieno[3,2-*b*]thienyl. Since these energy barriers should reflect the double bond character of the link between the aromatic nuclei and the carbonyl group they should also be proportional to the electron-withdrawing ability of a given ring.

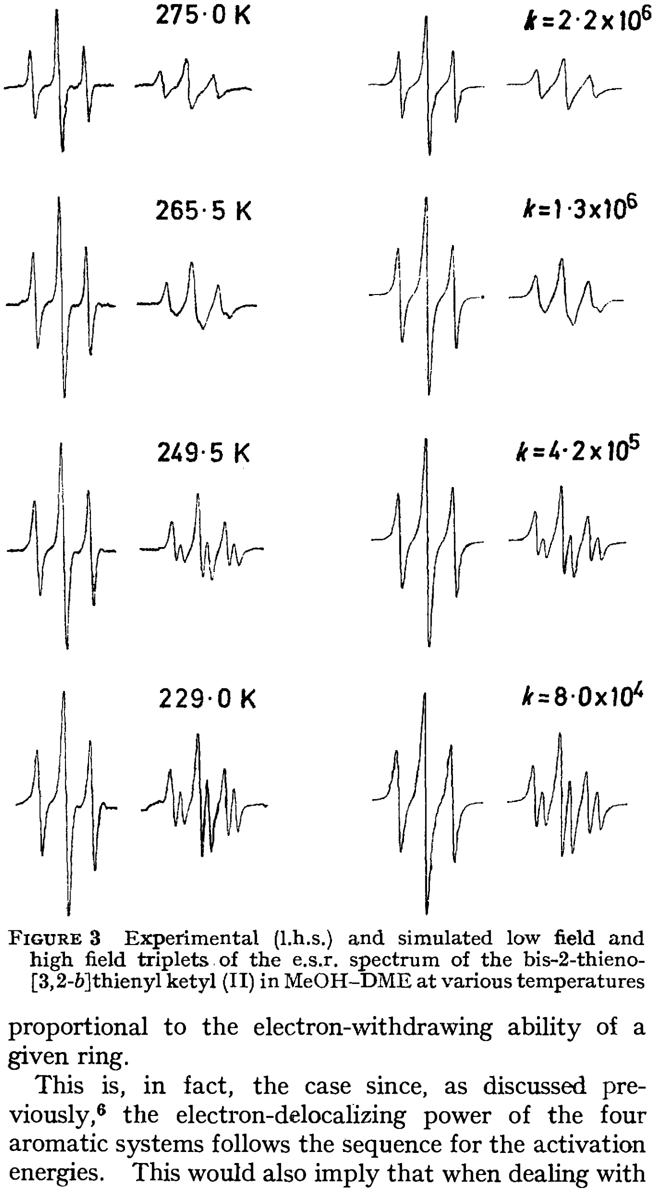

FIGURE 3 Experimental (l.h.s.) and simulated low field and high field triplets of the e.s.r. spectrum of the bis-2-thieno-[3,2-*b*]thienyl ketyl (II) in MeOH–DME at various temperatures

This is, in fact, the case since, as discussed previously,[6] the electron-delocalizing power of the four aromatic systems follows the sequence for the activation energies. This would also imply that when dealing with asymmetric ketyls we should expect an increase of the rotational barrier for rings showing greater delocalizing power with respect to the corresponding symmetric ketyl; a decrease of $E_a$ should occur for the other ring. This has been tested by examining 2-thieno[3,2-*b*]thienyl 2-thienyl ketyl which contains the two heterocyclic nuclei with the greatest difference in delocalization power. As expected, the 2-thieno[3,2-*b*]thienyl system stops rotating, on the e.s.r. time scale, at higher temperature than the 2-thienyl ring. This can be deduced

TABLE 2

Activation and thermodynamic parameters for the *cis–trans* ⟶ *trans–trans* forward isomerisation

| Ketyl | $E_a$/kJ mol$^{-1}$ | log $A$ | $\Delta H^‡$/kJ mol$^{-1}$ | $\Delta S^‡$/J mol$^{-1}$ K$^{-1}$ | $\Delta H_0$/kJ mol$^{-1}$ | $\Delta S_0$/J mol$^{-1}$ K$^{-1}$ |
|---|---|---|---|---|---|---|
| (IV) | 26·57 ± 0·25 | 13·1 ± 0·06 | 24·69 ± 0·29 | −0·38 ± 1·30 | | |
| (I) | 31·30 ± 0·88 | 12·68 ± 0·19 | 29·41 ± 0·92 | −8·28 ± 3·68 | 2·09 ± 0·84 | 7·95 ± 3·77 |
| (II) | 37·95 ± 0·42 | 13·55 ± 0·09 | 35·86 ± 0·46 | 7·53 ± 1·88 | 0·84 ± 0·42 | |
| (III) | 35·73 ± 0·67 | 13·12 ± 0·14 | 33·64 ± 0·67 | −0·88 ± 2·55 | 1·26 ± 0·42 | |

from the spectral changes of the high field quartet of the e.s.r. spectrum; in fact, with decreasing temperature, broadening is observed until new lines appear which become very sharp at *ca.* 0°. A further decrease in temperature produces broadening of these and at −30° a new spectrum having sharp lines can again be recorded. From the higher coalescence temperature (22°) the free energy of activation $\Delta G^‡$ for the 2-thieno[3,2-*b*]thienyl ring can be approximately estimated as 37·41 kJ mol$^{-1}$ which could be compared with the value of 34·01 kJ mol$^{-1}$, determined in the same way, for the symmetrical ketyl (II). A reliable value for the 2-thienyl ring cannot be obtained owing to overlap of the spectral lines.

[3/1581 *Received*, 26*th July*, 1973]