Electrophilic Aromatic Substitution. Part 34.[1] Partial Rate Factors for Detritiation of Dithieno[1,2-*b*:4,3-*b'*]benzene, Dithieno[1,2-*b*:3,4-*b'*]benzene, and Dithieno[2,1-*b*:3,4-*b'*]benzene

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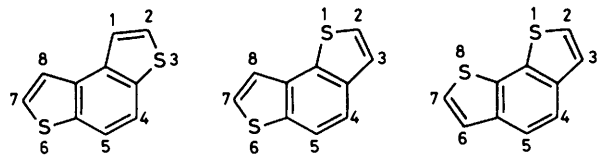
Dithieno[1,2-*b*:4,3-*b'*]benzene (I), dithieno[1,2-*b*:3,4-*b'*]benzene (II), and dithieno[2,1-*b*:3,4-*b'*]-benzene (III), specifically labelled with tritium in each position, have been synthesized. Their rates of protiodetritiation, in either anhydrous trifluoroacetic acid or mixtures of acetic acid and trifluoroacetic acid, have been measured at 70 °C. The rate–acidity profiles for each compound show that there is weak hydrogen bonding between sulphur and trifluoroacetic acid, and the extent of this is closely similar to that previously found for thienothiophens thereby confirming the general trend observed with sulphur-containing heterocycles *viz.* that the extent of hydrogen bonding is proportional to the number of sulphur atoms in the aromatic compound. Partial rate factors for detritiation, free from the effects of hydrogen bonding, are calculated as follows (position and compound in parentheses): 3.42×10^6 (1)-(I), 1.65×10^7 (2)-(I), 5.35×10^5 (4)-(I), 1.525×10^7 (2)-(II), 4.98×10^6 (3)-(II), 1.32×10^6 (4)-(II), 4.59×10^5 (5)-(II), 2.35×10^7 (7)-(II), 4.01×10^6 (8)-(II), 1.96×10^7 (2)-(III), 3.77×10^6 (3)-(III), 3.99×10^5 (4)-(III); the corresponding σ^+ values are −0.745, −0.825, −0.655, −0.82, −0.765, −0.70, −0.645, −0.84, −0.755, −0.835, −0.75, and −0.64. The positional reactivity orders both within a given molecule and between molecules are satisfactorily predicted by localization energies calculated by the simple Hückel method using the parameters α_S 1.0, β_{CS} 0.6, these having been found previously to predict correctly the positional reactivities in other sulphur-containing heterocycles.

In this series we have been determining the electrophilic reactivity of sulphur-containing heterocycles by means of acid-catalysed hydrogen exchange (protiodetritiation). Thus far we have described results for thiophen,[2] benzo[*b*]thiophen,[1] thienothiophens,[2] and dithienothiophens.[3] Data are also available for dibenzothiophen,[4] but the reported values must be corrected for the effects of hydrogen bonding and the correction is given in this paper. Hydrogen bonding manifests itself in rates of exchange for a hydrogen-bonded molecule which does not decrease on going to a weaker acid medium to the extent found for non-bonded molecules, *i.e.* in the stronger acid the exchange rates for the bonded molecule are artificially low. Rate data indicate that in a medium composed of 15% CF_3CO_2H–85% HOAc by volume, there is very little hydrogen bonding, and from the relative reactivities of non-bonded compounds in this medium and pure CF_3CO_2H, the exchange rates for bonded compounds can be calculated in pure CF_3CO_2H; hence their electrophilic reactivities can be determined. In making these corrections we have assumed that all ring positions are affected to the same extent including those in rings without a sulphur. The wide spread of rate coefficients has hitherto prevented any check on the correctness or otherwise of this assumption, but in the present work the rate data are such as to permit a reasonable conclusion to be drawn.

Two additional factors have emerged from this work, *viz.* that the extent of hydrogen bonding parallels the number of sulphur atoms in the molecules, and that the positional reactivities are very well predicted by localization energies calculated by the simple Hückel method, except for benzo[*b*]thiophen where π-densities give a precise prediction of the positional reactivities.

In order to examine these aspects further, we have undertaken a study of the quantitative electrophilic reactivity of each position of the dithienobenzenes (I)—(III), molecules for which there are virtually no other reactivity data at all. The sum total of these results is the most comprehensive set of electrophilic reactivity data available for aromatic heterocycles, which may in due course prove valuable for testing more refined methods of predicting electrophilic reactivity.



(I) (II) (III)

Results and Discussion

Rates of exchange were measured at each position of each dithienobenzene in various mixtures of trifluoroacetic acid and acetic acid, and the rate coefficients under the various conditions are given in Table 1. The values relating to the medium consisting of 15% CF_3CO_2H–85% HOAc, the medium in which hydrogen bonding is negligible, are mostly calculated ones and the justification for their accuracy is given below. Before discussing the rate data we note again that hydrogen bonding causes the rate coefficients in the more acidic media to be depressed and increasingly so the greater the acidity.[1-3] Consequently on going to a weaker acid the exchange rates decrease less than they do for a compound which is less or non-bonded.† With this in mind we can establish the following.

(i) For each of the positions measured in both 100% CF_3CO_2H and 75% CF_3CO_2H–25% HOAc, the rate in the former acid is 6.03 ± 0.07 times faster than in the latter. The constancy of this factor shows that hydrogen bonding lowers the reactivity of each position by virtually identical amounts and independent of whether the position undergoing exchange is in a benzenoid ring or one containing sulphur. In a previous part of this series which dealt with benzo[*b*]thiophen we assumed that this would be true but were unable to confirm it because of the inaccessibility of the rate data under weakly

† We assume that for compounds which bond, all molecules will be bonded in media stronger than 15% CF_3CO_2H–85% HOAc. The results indicate that the strength of the bonding will vary according to the nature of the compound and the acidity of the medium.

Table 1. Rate coefficients ($10^7 k/s^{-1}$) for detritiation of dithienobenzenes in trifluoroacetic acid and trifluoroacetic acid–acetic acid [a]

		CF_3CO_2H in HOAc (v/v)				
Compound	Position	100	75	50	15	$\frac{k(100)}{k(75)}$
(I)	1	29 000	4 800		*1.66*	6.04
	2	140 000	23 000		8.00	6.08
	4	4 600	770		*0.263*	5.97
(II)	2		21 300		*7.41*	
	3	42 400	6 950		*2.42*	6.10
	4	11 200	1 850	80	*0.64*	6.05
	5	3 900			*0.223*	
	7		32 800		*11.4*	
	8	34 100	5 700		*1.95*	5.98
(III)	2		27 500	1 240	*9.57*	
	3	32 000	5 250		*1.83*	6.10
	4	3 400	570		*0.194*	5.96
(Mesitylene)	1	674 500		1 675	3.45	

[a] Italicised values are calculated from data obtained at higher acidities—see text.

Table 2. Factors by which the exchange rate in the medium shown is smaller than that in 100% trifluoroacetic acid

	No. of sulphur	CF_3CO_2H in HOAc (v/v)			
Compound	atoms	75	50	35	15
Mesitylene	0		403	5 230	195 500
Thiophen	1		297	2 420	46 300
Benzo[*b*]thiophen	1		276	2 190	
Dithienobenzenes	2	6.03	140		17 500
Thienothiophens	2	5.93	134	1 010	16 550
Dithienothiophens	3			550	4 750

acidic conditions.[1] The result is not unexpected since the reactivities of the benzenoid ring positions are greatly enhanced through resonance with the lone pair on sulphur, in the same way as are the positions in the sulphur-containing rings, and this resonance must be diminished if the sulphur is hydrogen bonded.

(ii) The factor of 6.03 is closely similar to that (5.93) previously found for the thienothiophens which also contain two sulphur atoms (Table 2). The other factors given in Table 2 for dithienobenzenes *viz.* 140 {from rate measurements on [4-^{3}H]-(II)] and [2-^{3}H]-(III)} and 17 500 {from rate measurements on [2-^{3}H]-(I)} are also very close to and slightly greater than the values obtained with thienothiophens. Both sets of molecules are evidently hydrogen bonded to almost identical extents and taken overall the data in Table 2 reinforce our earlier conclusions [1-3] that the extent of hydrogen bonding is directly proportional to the number of sulphur atoms present in the heterocycle.

(iii) The results under (i) lead us to assume that the rate–acidity profile for each position in the dithienobenzenes will be the same. This assumption is reinforced by the very similar rate factors between 75% CF_3CO_2H–25% HOAc and 50% CF_3CO_2H–50% HOAc of 23.1 and 22.2 for [4-^{3}H]-(II) and [2-^{3}H]-(III), respectively (and again these are very close to the value of 22.6 obtained for the thienothiophens). Since the rate for [2-^{3}H]-(I) in 15% CF_3CO_2H–85% HOAc is 2 875 times less than in the 75% CF_3CO_2H–25% HOAc medium and 17 500 times less than in 100% CF_3CO_2H then we may use these factors to calculate the rate coefficients for the other positions in the former acid. Previous work on [1-^{3}H]mesitylene (which is not hydrogen bonded) has shown that the exchange rate in 100% CF_3CO_2H is 195 500 times faster than in 15% CF_3CO_2H–85% HOAc (Table 1).[5] We may therefore multiply the rate coefficients for the dithienobenzenes in the latter acid by this factor to obtain the true rate coefficients in 100% CF_3CO_2H, free from the effects of hydrogen bonding, and these are given in Table 3 along with the partial rate factors and derived σ^+ values; the true rate coefficients are 11.2 times greater than the observed ones.

Table 3. Rate coefficients, corrected for the effect of hydrogen bonding, for detritiation of dithienobenzenes in 100% trifluoroacetic acid, partial rate factors, and σ^+ values

Compd.	Position	$10^7 k/s^{-1}$	f	σ^+
(I)	1	3.245×10^5	3.42×10^6	−0.745
	2	1.565×10^6	1.65×10^7	−0.825
	4	5.08×10^4	5.35×10^5	−0.655
(II)	2	1.45×10^6	1.525×10^7	−0.82
	3	4.73×10^5	4.98×10^6	−0.765
	4	1.25×10^5	1.32×10^6	−0.70
	5	4.36×10^4	4.59×10^5	−0.645
	7	2.23×10^6	2.35×10^7	−0.84
	8	3.81×10^5	4.01×10^6	−0.755
(III)	2	1.87×10^6	1.97×10^7	−0.835
	3	3.58×10^5	3.77×10^6	−0.75
	4	3.79×10^4	3.99×10^5	−0.64

(iv) For thiophen and benzo[*b*]thiophen a similar analysis [1,2] showed the rates in 100% CF_3CO_2H to be reduced 4.22 fold by hydrogen bonding and in view of the parallel between the number of sulphur atoms and the extent of hydrogen bonding, it is reasonable to assume that this factor applies also to dibenzo[*b*]thiophen. The literature partial rate factors [4] for the 1-, 2-, 3-, and 4-positions thus become 1 150, 7 720,

Table 4. Hückel localization energies and π-electron densities

Compound	Position	No.	π densities	$\Delta L_r^+/-\beta$
(I)	1	1	1.176	1.877
	2	2	1.119	1.745
	4	3	1.060	2.063
(II)	2	4	1.120	1.740
	3	5	1.175	1.840
	4	6	1.064	1.996
	5	7	1.060	2.043
	7	8	1.117	1.732
	8	9	1.177	1.848
(III)	2	10	1.120	1.756
	3	11	1.174	1.862
	4	12	1.063	2.043
Dibenzo[*b*]thiophen	1		1.038	2.119
	2		1.021	2.340
	3		1.051	2.175
	4		1.007	2.262

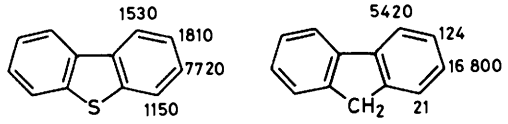


Figure 1. Partial rate factors for detritiation in CF_3CO_2H at 70 °C

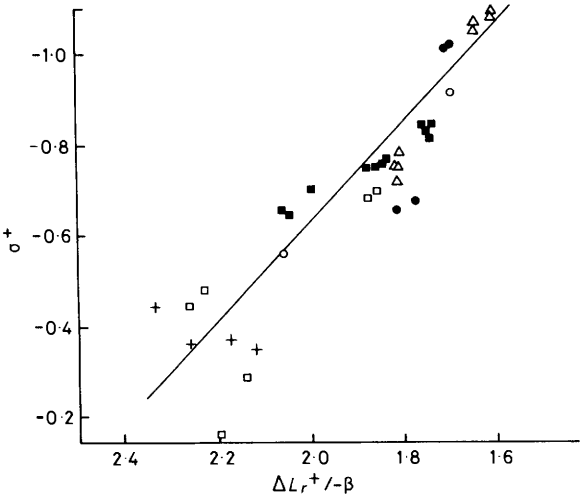


Figure 2. Correlation of localization energies with electrophilic aromatic reactivity (σ^+ values): ○, thiophen; ●, thienothiophens; △, dithienothiophens; ■, dithienobenzenes; □, benzo[*b*]thiophen; +, dibenzo[*b*]thiophen

1 810, and 1 530, respectively, the corresponding σ^+ values being −0.350, −0.444, −0.372, and −0.364. The modified partial rate factors are now more readily understandable when compared to those for fluorene (Figure 1)[6] since the differences can be accommodated in terms of the greater conjugative electron release of *o,p*-S relative to *o,p*-CH_2, and the greater $-I$ effect of *m*-S relative to *m*-CH_2.

Theoretical Calculations of Reactivity.—Taken along with the other data on sulphur-containing heterocycles, the present results provide by far the most comprehensive set of electrophilic reactivity data for aromatic heterocycles, and these are uniquely free from the effects of steric hindrance. In due course these results may provide a valuable test of more refined methods of theoretical prediction of aromatic reactivity. However at present the required amount of computer time for such large molecules is unreasonably large and here we confine ourselves to the simple Hückel method because it is, surprisingly, much the most successful at predicting the reactivity of polycyclics and heterocyclics. Thus localization energies calculated in this way and using the recommended parameters[7] of α_S 1.0 and β_{CS} 0.6 correctly predict the positional orders in thiophen, thienothiophens, and dithienothiophens. For benzo[*b*]thiophen, however, these give the correct order in the sulphur-containing ring, but not in the benzenoid ring and overall π-electron densities (calculated with the same parameters) are more successful for this molecule and predict all six positions in the correct order.[1]

We have calculated both reactivity indices for dithienobenzenes using the recommended parameters (Table 4) and there is no question here that the localization energies are the most successful set. They correctly predict the reactivity order $2 > 1 > 4$ for (I), $7 > 2 > 3 > 8 > 4 > 5$ for (II), and $2 > 3 > 4$ for (III). It is in our experience typical of the Hückel method that it is very good within a given molecule but not so satisfactory when comparing one molecule with another. Thus for the dithienobenzenes the overall reactivity order predicted is (using the compound positional numbers given in Table 4): $8 > 4 > 2 > 10 > 5 > 9 > 11 > 1 > 6 > 7 = 12 > 3$, compared with the observed order of $8 > 10 > 2 > 4 > 5 > 9 > 11 > 1 > 6 > 3 > 7 > 12$. For so many positions involved with small differences in reactivity the correlation is perhaps quite remarkable and these data are displayed in Figure 2 along with those for all the other sulphur-containing heterocycles the σ^+ values for which are assembled in Figure 3. The extent to which improvement in the theoretical techniques is required is evident from Figure 2, and especially from the results for dibenzothiophen (Table 4) since neither π-densities or localization energies predict the correct order.

Experimental

[2-^{3}H]-*Dithieno*[1,2-b:4,3-b′]*benzene.*—This was prepared according to the route shown in Scheme 1.

[5-^{3}H]-2-*Methylthiophen.* Thiophen was converted into 2-methylthiophen in 77% yield by the literature method,[8] and the latter brominated *via* reaction with n-butyl-lithium followed by bromine as described in the literature[9] to give 5-bromo-2-methylthiophen (76%), b.p. 51—52 °C at 10 mmHg. The Grignard reagent from this was hydrolysed with tritiated water in the usual way to give [5-^{3}H]-2-methylthiophen (74%), b.p. 114 °C at 760 mmHg.

[5-^{3}H]-2-*Bromomethylthiophen.* A solution of [5-^{3}H]-2-methylthiophen (6.5 g, 0.067 mol) in AnalaR carbon tetrachloride (30 ml) was heated to reflux and benzoyl peroxide (150 mg) was added. A mixture of *N*-bromosuccinimide (12 g, 0.067 mol) and benzoyl peroxide (150 mg) was added to the mixture through a dropping funnel at as fast a rate as the vigorous foaming allowed. The mixture was heated at reflux during 1 h, cooled to room temperature, filtered to remove succinimide, and concentrated *in vacuo* to give a yellow-orange highly lachrymatory oil which was not purified further. G.l.c. analysis (5 ft column packed with 5% OV 101 on 100—120 mesh Chromosorb G, operated at 150 °C) indicated the product to be 90% pure.

[5-^{3}H]-2-*Thienylmethyltriphenylphosphonium bromide.* The crude [5-^{3}H]-2-bromomethylthiophen (10.7 g) was dissolved in sodium-dried benzene (50 ml), added to a stirred refluxing solution of triphenylphosphine (17 g, 0.065 mol) in sodium-dried benzene (50 ml) under nitrogen, and heated under

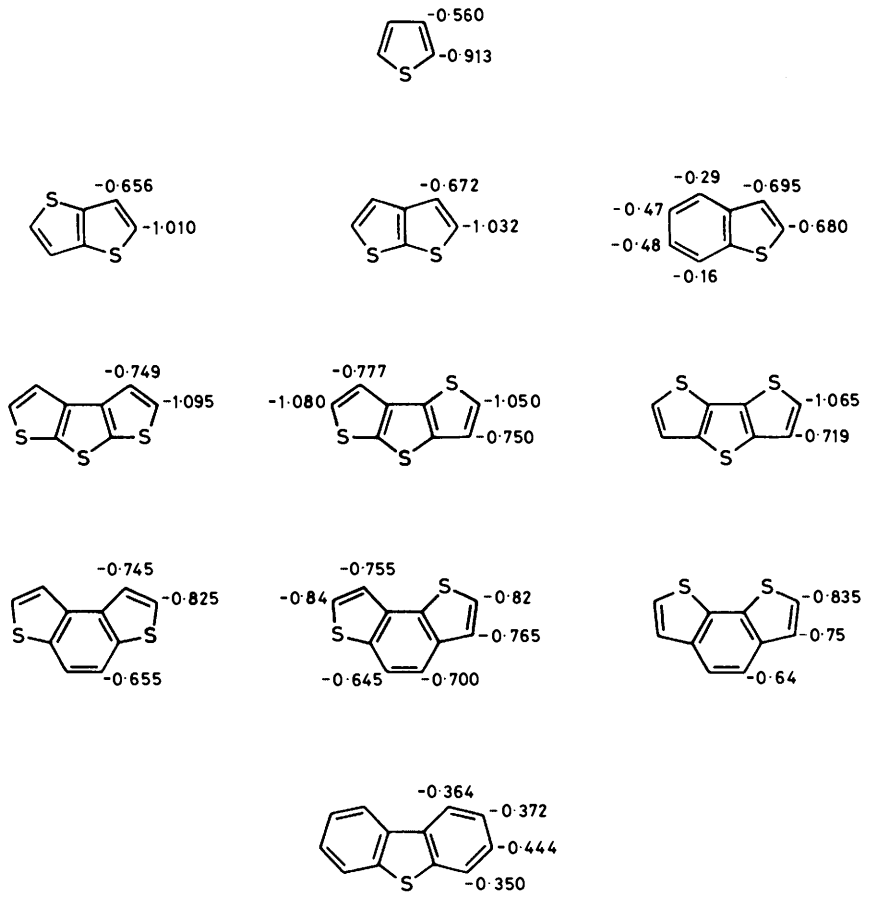
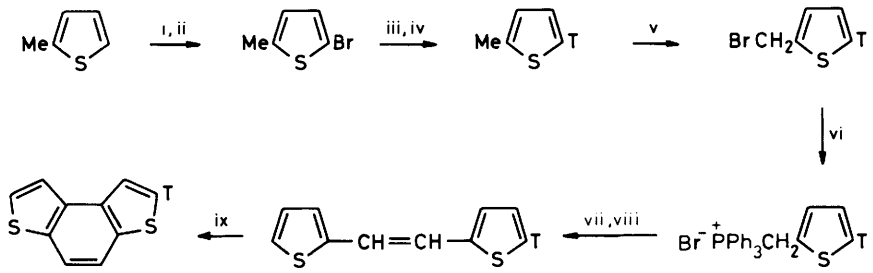


Figure 3. σ^+ Values



Scheme 1. *Reagents:* i, Bu^{n}Li; ii, Br_2; iii, Mg–Et_2O; iv, T_2O, H^+; v, NBS, peroxide; vi, PPh_3; vii, Bu^{n}Li; viii, thiophen-2-carbaldehyde; ix, $h\nu$, I_2

reflux during 12 h. The cooled mixture was filtered to remove the product which was washed twice with sodium-dried benzene and dried *in vacuo* during 12 h, yield 26 g (88%), m.p. >300 °C.

Thiophen-2-carbaldehyde. This was prepared by two methods.

Method A. Dimethylformamide (30.0 g, 0.5 mol, distilled from phosphorus pentaoxide) and phosphoryl chloride (76.5 g, 0.5 mol) were mixed in a flask protected by a calcium chloride drying tube, and left during 45 min to cool to room temperature. The temperature was kept between 24 and 30 °C as thiophen (46.2 g, 0.55 mol) was added dropwise. The mixture was allowed to stand overnight and then poured into stirred ice-water to give an oil which was extracted three times with ether. Normal work-up gave thiophen-2-carbaldehyde (71.7 g, 64%), b.p. 63—65 °C at 4 mmHg (lit.,[10] 66—67 °C at 4 mmHg) which was stored under nitrogen and darkened rapidly.

Method B. n-Butyl-lithium (260 ml of a 1.6N solution in hexane, 0.41 mol) was added dropwise during 30 min to a stirred solution of thiophen (33.6 g, 0.4 mol) in THF (70 ml; dried over $LiAlH_4$) under nitrogen. The mixture was stirred for 30 min more, dimethylformamide (36.6 g, 0.5 mol) was added, and after a further 45 min stirring it was poured into ice–water, acidified with hydrochloric acid and worked up as before to give thiophen-2-carbaldehyde (40 g, 89%), b.p. 66—67 °C at 4 mmHg, n_D^{20} 1.5917 (lit.,[10] n_D^{20} 1.5920).

1-([5-^{3}H]-2-*Thienyl*)-2-(2-*thienyl*)*ethene.* n-Butyl-lithium (13.8 ml of a 1.6N solution in hexane, 0.0215 mol) was added to a suspension of [5-^{3}H]-2-thienylmethyltriphenylphosphonium bromide (8.8 g, 0.02 mol) in $LiAlH_4$-dried THF (20

ml) at 0 °C under nitrogen. The deep red mixture was stirred at room temperature during 2 h, treated with a solution of thiophen-2-carbaldehyde (2.5 g, 0.022 mol) in $LiAlH_4$-dried THF (7 ml), stirred at room temperature during 4 h, and poured into ice–water. The mixture was acidified with hydrochloric acid and worked up in the usual way to give a product which was worked into a dryish powder with silica. This was placed on a short silica-packed chromatography column and eluted with benzene (to remove the residual triphenylphosphine oxide) to give a *cis-trans* mixture of the required product. This was dissolved in toluene (10 ml) containing iodine (10 mg) and heated until no *cis*-isomer could be detected by g.l.c. (5 ft column packed with 5% OV101 on 100—120 mesh Chromosorb G at 200 °C). The cooled solution was washed with sodium thiosulphate and worked up in the normal way to give needles of *trans*-1-([5-^{3}H]-2-thienyl)-2-(2-thienyl)ethene (1.5 g, 39%), m.p. 134 °C after recrystallisation from methanol (lit.,[11] 133—134 °C).

A solution of *trans*-1-([5-^{3}H]-2-thienyl)-2-(2-thienyl)ethene (1 g, 0.005 mol) in sodium-dried benzene (500 ml) containing iodine (*ca.* 10 mg) was irradiated through a quartz vessel with a 125 W medium pressure mercury-vapour lamp. After 7 h the reaction was indicated by g.l.c. analysis to be complete (conditions as above), and the mixture was washed with sodium thiosulphate and worked up in the usual way to give an oil. This was chromatographed on alumina (activity grade 1) with elution with hexane mixtures containing increasing amounts of benzene to give needles (recrystallised from hexane) of [2-^{3}H]-dithieno[1,2-*b*:4,3-*b*′]benzene (0.8 g, 80%), m.p. 118 °C (lit.,[11] 117—118 °C for the inactive compound) (Found: C, 63.2; H, 3.2. Calc. for $C_{10}H_6S_2$: C, 63.1; H, 3.2%).

[4-^{3}H]-*Dithieno*[1,2-b:4,3-b′]*benzene*.—This was prepared along the lines given in Scheme 1, in this case tritium being introduced into the side chain.

[α-^{3}H]-2-*Thienylmethanol*.[12] Tritiated water (100 μl of 500 mCi g^{-1} activity) was added to a stirred suspension of lithium borohydride (0.55 g, 0.025 mol) in dry THF (30 ml) under nitrogen, and the mixture heated to reflux during 20 min. A solution of thiophen-2-carbaldehyde (5.6 g, 0.05 mol) in dry THF was added dropwise to the cooled solution which was then heated to 50 °C during 1 h, then cooled, and concentrated *in vacuo*. The residue was treated with water followed by dilute hydrochloric acid and worked up in the usual way to give [α-^{3}H]-2-thienylmethanol (5.1 g, 89%), b.p. 205—208 °C at 760 mmHg (lit.,[13] 208 °C at 760 mmHg), n_D^{20} 1.5274.

[α-^{3}H]-2-*Chloromethylthiophen*.[14] A solution of freshly distilled thionyl chloride (3.9 ml, 0.053 mol) in methylene dichloride (5 ml) was added dropwise to a stirred solution of [α-^{3}H]-2-thienylmethanol (5 g, 0.044 mol) and triethylamine (7.4 ml, 0.05 mol) in methylene dichloride (25 ml), the temperature being kept below 20 °C. It was then raised to 40 °C during 1 h, poured onto crushed ice, and worked up in the usual way to give a highly lachrymatory light brown oil which was not purified further.

[α-^{3}H]-2-*Thienylmethyltriphenylphosphonium chloride*. The crude [α-^{3}H]-2-chloromethylthiophen (5.8 g, *ca.* 0.045 mol) in dry benzene was added to a stirred solution of triphenylphosphine (11.8 g, 0.045 mol) in dry benzene (30 ml) under nitrogen. The mixture was heated under reflux during 48 h, cooled, filtered, and the residue washed with benzene to give, after vacuum drying, [α-^{3}H]-2-thienylmethyltriphenylphosphonium chloride (15.4 g, 86%), m.p. >320 °C (lit.,[14] 340 °C).

[1-^{3}H]-1,2-*Di*-(2-*thienyl*)*ethene*. The general Wittig method as described above, using [α-^{3}H]-2-thienylmethyltriphenylphosphonium chloride (15 g, 0.038 mol), n-butyl-lithium (25 ml of a 1.6N solution in hexane, 0.039 mol) and thiophen-2-carbaldehyde (4.5 g, 0.04 mol) gave pure *trans*-[1-^{3}H]-1,2-di-(2-thienyl)ethene (3.0 g, 40%), m.p. 131—132 °C.

This compound was photocyclized as described above to give [4-^{3}H]-dithieno[1,2-*b*:4,3-*b*′]benzene (70%), m.p. 112—113 °C.

[1,2-^{3}H$_2$]-*Dithieno*[1,2-b:4,3-b′]*benzene*.—This was prepared along the lines given in Scheme 1, tritium being introduced initially into all nuclear positions of one ring.

[3,4,5-^{3}H$_3$]-2-*Methylthiophen*. Trifluoroacetic acid (11.4 g, 0.1 mol), 2-methylthiophen (5 g, 0.051 mol), and tritiated water (50 μl of 500 mCi g^{-1} specific activity) were sealed in an ampoule and heated at 70 °C during 30 min. (Longer times of heating result in extensive acid-catalysed polymerisation.) Normal work-up gave [3,4,5-^{3}H$_3$]-2-methylthiophen (3.5 g, 70%), b.p. 111—112 °C at 760 mmHg, n_D^{20} 1.5278 (lit.,[15] 112—113 °C at 760 mmHg), specific activity 0.9 mCi g^{-1} (after dilution to 15 g with inactive 2-methylthiophen), *cf.* 2.85 mCi g^{-1} calculated.

[3,4,5-^{3}H$_3$]-2-*Bromomethylthiophen*. This was obtained as a crude product from [3,4,5-^{3}H$_3$]-2-methylthiophen (5 g, 0.106 mol) by the method described above.

[3,4,5-^{3}H$_3$]-2-*Thienylmethyltriphenylphosphonium bromide*. This was obtained from [3,4,5-^{3}H$_3$]-2-bromomethylthiophen (8.8 g, *ca.* 0.05 mol) and triphenylphosphine (13.1 g, 0.05 mol) by the method described above.

1-([3,4,5-^{3}H$_3$]-2-*Thienyl*)-2-(2-*thienyl*)*ethene*. Reaction of [3,4,5-^{3}H$_3$]-2-thienylmethyltriphenylphosphonium bromide (8.8 g, 0.02 mol) with n-butyl-lithium (13.8 ml of a 1.6N solution, 0.0215 mol) and thiophen-2-carbaldehyde (2.5 g, 0.022 mol) as described above gave *trans*-1-([3,4,5-^{3}H$_3$]-2-thienyl)-2-(2-thienyl)ethene (1.9 g, 49%), m.p. 132—134 °C.

Photocyclization of this compound as described above gave [1,2-^{3}H$_2$]-dithieno[1,2-*b*:4,3-*b*′]benzene (0.72 g, 72%), m.p. 117.5—118 °C (Found: C, 63.1; H, 3.2%).

[2,3-^{3}H$_2$]-*Dithieno*[1,2-b:3,4-b′]*benzene*.—This was prepared according to the route shown in Scheme 2.

[2,4,5-^{3}H$_3$]-3-*Methylthiophen*. This was prepared from 3-methylthiophen in exactly the same way as described above for tritiation of 2-methylthiophen.

[2,4,5-^{3}H$_3$]-3-*Bromomethylthiophen*. [2,4,5-^{3}H$_3$]-3-Methylthiophen (6.5 g, 0.067 mol) was brominated with *N*-bromosuccinimide (12 g, 0.067 mol) as described above to give a light red, highly lachrymatory oil estimated by g.l.c. to be 90% pure, and this product was not purified further.

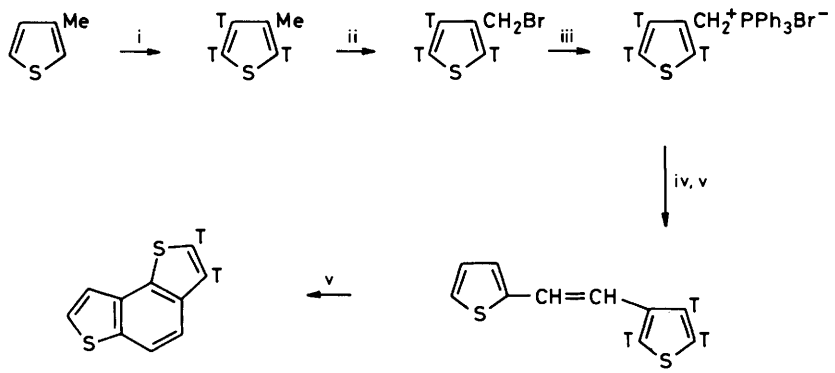
[2,4,5-^{3}H$_3$]-3-*Thienylmethyltriphenylphosphonium bromide*. Reaction of crude [2,4,5-^{3}H$_3$]-3-bromomethylthiophen and triphenylphosphine (18.4 g, 0.07 mol) in benzene (50 ml) as described above gave [2,4,5-^{3}H$_3$]-3-thienylmethyltriphenylphosphonium bromide (24 g, 81%), m.p. 315—317 °C (lit.,[16] 319 °C).

1-(3-[2,4,5-^{3}H$_3$]-*thienyl*)-2-(2-*thienyl*)*ethene*. The Wittig reaction between [2,4,5-^{3}H$_3$]-3-thienylmethyltriphenylphosphonium bromide (8 g, 0.018 mol), n-butyl-lithium (12 ml of a 1.6N solution in hexane, 0.019 mol) and thiophen-2-carbaldehyde (2.25 g, 0.02 mol) as described above gave 1-(3-[2,4,5-^{3}H$_3$]-thienyl)-2-(2-thienyl)ethene (1.4 g, 40%), m.p. 135 °C (lit.,[12] 137—137.5 °C).

Photochemical cyclization of this compound (1.3 g, 0.0068 mol) as described above gave [2,3-^{3}H$_2$]-dithieno[1,2-*b*:3,4-*b*′]-benzene (0.41 g, 32%), m.p. 38—39 °C (from hexane) (lit.,[11] 39.5—40 °C).

[4-^{3}H]-*Dithieno*[1,2-b:3,4-b′]*benzene*.—This was prepared along the lines given in Scheme 2, in this case tritium being introduced into the side chain of a derivative of 3-methylthiophen.

[α-^{3}H]-3-*Methylthiophen*. A mixture of 3-methylthiophen



Scheme 2. *Reagents:* i, CF_3CO_2H, T_2O; ii, NBS, peroxide; iii, PPh_3; iv, Bu^nLi; v, thiophen-2-carbaldehyde; vi, *hν*, I_2

(2 g, 0.061 mol), sodium hydroxide (1 g), ethanol (5 ml), and tritiated water (100 μl of 500 mCi g^{-1} specific activity) was heated under reflux during 24 h. Normal work-up gave [α-^{3}H]-3-methylthiophen (1.7 g, 85%), b.p. 114—115 °C at 760 mmHg (lit.,[15] 115.4 °C at 760 mmHg). The product was diluted with inactive 3-methylthiophen (6 g).

[α-^{3}H]-3-*Thienylmethyltriphenylphosphonium bromide*. [α-^{3}H]-3-Bromomethylthiophen was prepared from [α-^{3}H]-3-methylthiophen (4.2 g, 0.05 mol) and *N*-bromosuccinimide (8.9 g, 0.05 mol) by the method described above, and the crude product was treated with triphenylphosphine (13.1 g, 0.05 mol) as described above, to give [α-^{3}H]-3-thienylmethyltriphenylphosphonium bromide (18 g, 82% overall), m.p. 316—320 °C (lit.,[16] 319 °C).

1-([α-^{3}H]-3-*Thienyl*)-2-(2-*thienyl*)*ethene*. A Wittig reaction between [α-^{3}H]-3-thienylmethyltriphenylphosphonium bromide (16 g, 0.036 mol), n-butyl-lithium (23 ml of a 1.6N solution in hexane, 0.036 mol) and thiophen-2-carbaldehyde (4.5 g, 0.04 mol) as described above gave *trans*-1-([α-^{3}H]-3-thienyl)-2-(2-thienyl)ethene (2.1 g, 30%), m.p. 134—136 °C.

Photochemical cyclization of this product (2 g, 0.01 mol) as described above gave [4-^{3}H]-dithieno[1,2-*b*:3,4-*b*′]benzene (0.65 g, 38%), m.p. 40—40.5 °C.

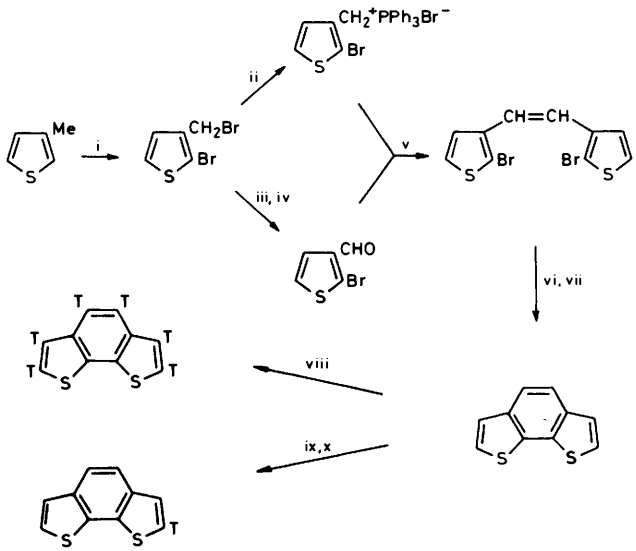
[5-^{3}H]-*Dithieno*[1,2-b:3,4-b′]*benzene*.—The route for preparation of this compound was along the lines given in Scheme 2, with in this case tritium being introduced into the side chain of a derivative of 2-methylthiophen.

1-([α-^{3}H]-2-*Thienyl*)-2-(3-*thienyl*)*ethene*. This was prepared from [α-^{3}H]-2-thienylmethyltriphenylphosphonium chloride (6 g, 0.015 mol), prepared as described above, n-butyl-lithium (11 ml of a 1.6N solution in hexane, 0.017 mol) and thiophen-3-carbaldehyde [17] (2 g, 0.031 mol) by the Wittig method described above to give *trans*-1-([α-^{3}H]-2-thienyl)-2-(3-thienyl)ethene (1.7 g, 60%), m.p. 137 °C.

Cyclization of this compound by the photochemical method gave [5-^{3}H]-dithieno[1,2-*b*:3,4-*b*′]benzene (0.52 g, 52%), m.p. 40—40.5 °C.

[7,8-$^3H_2$]-*Dithieno*[1,2-b:3,4-b′]*benzene*.—The route for preparation of this compound was along the lines given in Scheme 2, with tritium being introduced into all nuclear positions of 2-methylthiophen.

1-([3,4,5-$^3H_3$]-2-*Thienyl*)-2-(3-*thienyl*)*ethene*. [3,4,5-$^3H_3$]-2-Thienylmethyltriphenylphosphonium bromide (8.8 g, 0.02 mol), prepared as described above for the 3-isomer, was treated with thiophen-3-carbaldehyde (2.3 g, 0.02 mol) as described above to give, after work-up as before, *trans*-1-([3,4,5-$^3H_3$]-2-thienyl)-2-(3-thienyl)ethene (2 g, 50%), m.p. 134—135 °C.



Scheme 3. *Reagents:* i, NBS, peroxide; ii, PPh_3; iii, HMTA; iv, H^+; v, NaOEt, DMF; vi, Bu^nLi; vii, $CuCl_2$; viii, CF_3CO_2H, T_2O; ix, Bu^nLi; x, T_2O

Photocyclization of this compound gave [7,8-$^3H_2$]-dithieno-[1,2-*b*:3,4-*b*′]benzene (0.5 g, 30%), m.p. 39 °C (Found: C, 63.0; H, 3.3%).

[2-^{3}H]-*Dithieno*[2,1-b:3,4-b′]*benzene*.—The route for this compound is shown in Scheme 3.

2-*Bromo*-3-*bromomethylthiophen*. A mixture of *N*-bromosuccinimide (178 g, 1.0 mol) and benzoyl peroxide (1 g) was added, *via* a dropping funnel as rapidly as foaming would allow, to a boiling solution of 3-methylthiophen (49.1 g, 0.5 mol) and benzoyl peroxide (0.8 g) in AnalaR carbon tetrachloride (200 ml). The mixture was heated under reflux during 2 h, cooled to room temperature, and the succinimide removed by filtration. The solvent was removed *in vacuo*, and the residual intensely lachrymatory oil was fractionally distilled to give 2-bromo-3-bromomethylthiophen (98 g, 75%), b.p. 68—72 °C at 0.7 mmHg, n_D^{20} 1.6350 (lit.,[18] n_D^{20} 1.6363).

2-*Bromo*-3-*thienylmethyltriphenylphosphonium bromide*. 2-Bromo-3-bromomethylthiophen (25.6 g, 0.1 mol) was added to a stirred solution of triphenylphosphine (26.2 g, 0.1 mol) in dry benzene (50 ml) under nitrogen at room temperature, and the mixture was stirred during 60 h. The brown sticky precipitate was removed by filtration, washed twice with benzene, and three times with ether. The required compound

was obtained by recrystallisation from ethanol. Concentration of the mother liquor to about half the original volume yielded a second crop of material. The yield was 33 g (64%), m.p. 238—240 °C (lit.,[16] 240 °C).

2-Bromothiophen-3-carbaldehyde. This was prepared in 19% yield from 2-bromo-3-bromomethylthiophen according to the literature method.[18] After recrystallisation from light petroleum (b.p. 80—100 °C) the product had m.p. 34 °C (lit.,[18] 34 °C). Another batch of material was also prepared by the higher-yield (60%) route starting from thiophen-3-carbaldehyde ethylene acetal; [18] the product also melted at 34 °C.

1,2-Bis-(2-bromo-3-thienyl)ethene. Sodium ethoxide (1.4 g, 0.02 mol), suspended in dry dimethylformamide (8 ml), was added to a stirred solution of 2-bromo-3-thienylmethyltriphenylphosphonium bromide (8.4 g, 0.016 mol) in dry dimethylformamide (20 ml) at 0 °C. After 30 min a solution of 2-bromothiophen-3-carbaldehyde (2.35 g, 0.016 mol) in dry dimethylformamide (12 ml) was added. The mixture was stirred overnight, poured onto ice, acidified, and worked up in the usual way to give an oil which was worked into a dry powder with silica gel. This powder was packed onto a silica column, and eluted with hexane. Removal of the solvent gave an oil estimated by g.l.c. (1 ft column packed with 5% OV101 absorbed onto 100—120 mesh Chromosorb G, operated at 230 °C) to consist of a mixture of *ca.* 65% *cis*- and 35% *trans*-ethene. The oil was taken up in hexane and allowed to stand for several days which precipitated some of the *trans*-isomer, the filtrate being estimated to contain 80% of the *cis*-isomer; this was used for the photocyclization without further purification. The total yield of both isomers was 4.2 g (75%).

A solution of the *cis–trans* mixture of ethenes (2.8 g, 0.008 mol) in dry THF (25 mol) was added to a stirred solution of n-butyl-lithium (12 ml of a 1.6N solution in hexane, 0.019 mol) under nitrogen at −78 °C, the temperature being maintained during 30 min. Anhydrous copper(II) chloride (2.8 g, 0.021 mol) was added, the temperature being maintained at −78 °C during a further 4 h, then allowed to rise to room temperature during 14 h. The mixture was poured into a solution of sodium cyanide (50 ml of 17% w/v) and the organic layer was separated. The aqueous layers were ether-extracted twice and the combined organic layers washed twice with 10% sodium cyanide solution. After work-up the residue was chromatographed over alumina (activity grade 1) with pentane–benzene as eluant, to give dithieno[2,1-*b*:3,4-*b*′]benzene, (60%), m.p. 44 °C (lit.,[14] 45—46 °C), τ ($CDCl_3$) 2.56 (2 H, d, *J* 5.4 Hz, 3- and 6-H), 2.49 (2 H, d, *J* 5.3 Hz, 2- and 7-H), and 2.26 (2 H, s, 4- and 5-H).

Treatment of the above product with n-butyl-lithium at room temperature followed by hydrolysis with tritiated water and normal work-up gave [2-^{3}H]-dithieno[2,1-*b*:3,4-*b*′]-benzene.

[2,3,4,5,6,7-$^3H_6$]-Dithieno[2,1-b:3,4-b′]benzene. As shown in Scheme 3 the route to this compound only differs from the above in the last step whereby the parent hydrocarbon was tritiated by equilibriating it with a mixture of tritiated water and trifluoroacetic acid at 70 °C during 30 h, followed by normal work-up.

Kinetic Studies.—The general method has been described previously.[19] For compound (I) the 2- and 4-positions were individually labelled and gave excellent first-order kinetics. The 1,2-detritiated isomer gave the expected curved kinetic plot which could be resolved into the two first-order components, one of which gave the same rate coefficient as the separately prepared 2-isomer. For compound (II) the 4- and 5-positions were individually labelled and gave excellent first-order kinetics. The 2- and 3-positions were labelled together and the curved plot dissected into the two first-order components and we made the assumption that the faster rate was due to exchange at the α-position. Likewise the data for the other pair of α- and β-positions, *viz.* positions 7 and 8, were treated in the same way. For compound (III) the 2-position was individually labelled and hence gave the usual first-order plot. The fully tritiated compound gave three rate coefficients of widely differing values, one of which was already known and very fast. Hence the remaining plot after a short reaction time could be dissected again into two first-order components and we have made the assumption that the slowest exchange takes place in the benzenoid ring, as was shown unambiguously to be the case with compounds (I) and (II).

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