Aromatic Sulphonation. Part 77.[1] Sultone and 1,3,2,4-Dioxadithian 1,1,3,3-Tetraoxide Formation in the Sulphonation of 3-Phenylpropan-1-ol

By **Ankie Koeberg-Telder, Freek van de Griendt,** and **Hans Cerfontain,*** Laboratory for Organic Chemistry, University of Amsterdam, Nieuwe Achtergracht 129, 1018 WS Amsterdam, The Netherlands

Reaction of 3-phenylpropan-1-ol (1) in concentrated sulphuric acid leads initially to the formation of mainly 3-(*p*-sulphophenyl)propyl hydrogensulphate (3a) and *ca.* 12% of the *ortho*-isomer (3b). Compound (3a) is slowly converted into the geometrically isomeric dioxadithian tetraoxides (6a) and (7a) which eventually yield (*E*)-1-(*p*-sulphophenyl)prop-1-ene-2-sulphonic acid (4a). Compound (3b) eventually yields *via* the sultone (8), a detectable and isolable intermediate and the dioxadithian tetraoxides (6b) and (7b). Reaction of (1) with SO_3 in nitromethane leads to the formation of the *para*-sulpho isomer (3a) which is slowly converted into (6a) and (7a) as stable products in the reaction system. Mechanisms for the formation of the various products in the two sulphonating systems are proposed, and the differences in mechanism discussed.

As part of a study on the sulphation and sulphonation of a series of ω-phenylalkan-1-ols in sulphuric acid we reported that 3-phenylpropan-1-ol (1) in 98.4% H_2SO_4 at 25 °C yields rapidly, probably *via* the corresponding hydrogen sulphate (2), 88 ± 2% mainly 3-(*p*-sulphophenyl)- (3a) with some 3-(*m*-sulphophenyl)- and 12 ± 2% 3-(*o*-sulphophenyl)-propyl hydrogen sulphate (3b).[2] The former compound yields in a slow reaction (*E*)-1-(*p*-sulphophenyl)prop-1-ene-2-sulphonic acid (4a) which was isolated as its dipotassium salt. Recently it was observed[3] that the sulphonation of (*E*)-1-phenylprop-1-ene (5) with dioxan–SO_3 in dioxan yields the *cis*- and *trans*-dioxadithian tetraoxides (6c) and (7c), but only a very small amount of 1-phenylprop-1-ene-2-sulphonic acid (4c), the product ratio (6c) : (7c) : (4c) being 5 : 24 : 1.

Both the presence of unassigned ^1H n.m.r. absorptions in the mixture of (1) in sulphuric acid, reminiscent of those of the main products formed in the reaction of (5) with dioxan–SO_3 in dioxan, and the difference in product formation in both reactions, prompted us to study the sulphonation of (1), both in sulphuric acid and with SO_3 in an aprotic solvent, in more detail.

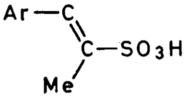
RESULTS AND DISCUSSION

Reaction with Sulphuric Acid.—The course of the reaction of 3-phenylpropan-1-ol (1) in 90.2, 95.4, and 98.4% H_2SO_4 at 25 ± 1 °C was followed by ^1H n.m.r. spectroscopy. After 20 min (1) was completely converted into the sulphonic acids (3a and b), probably *via* the intermediacy of the hydrogen sulphate (2).[2]

Upon further reaction it appeared that besides unconverted (3a and b) the following compounds were present in the reaction mixture: (i) the two geometrically isomeric dioxadithian tetraoxides (6a) and (7a), assigned on the basis of the similarity of the spectrum with (6c) and (7c) in [$^2H_8$]dioxan,[3] (ii) the sultone (8) (for characterization see Experimental section), and (iii) the unsaturated sulphonic acid (4a).[2]

The relative amounts of the components in the reaction mixtures obtained from (1) in sulphuric acid are given in Table 1 and are shown in the Figure for the reaction in 98.4% H_2SO_4 at 5 ± 2 °C. The curves indicate that the *p*- and *o*-sulphophenylpropyl hydrogensulphates (3a and b) are the primary products which are converted into (6a) and (7a), and (8) respectively. The former two compounds then yield (4a). The (6a) : (7a) product ratio is constant, indicating that there is no interconversion of the two geometrical isomers, and that the rate ratio in which they are formed is about the same as the ratio of their rates of conversion into (4a), *i.e.* $k_3/k_4 = k_6/k_7$ (see Scheme 1).

$Ph[CH_2]_3OH$ (1) $Ph[CH_2]_3OSO_3H$ (2) $Ar[CH_2]_3OSO_3H$ (3)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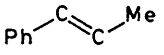
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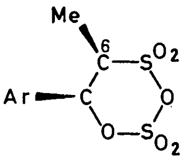
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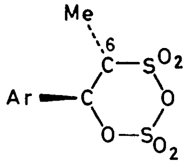
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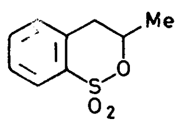
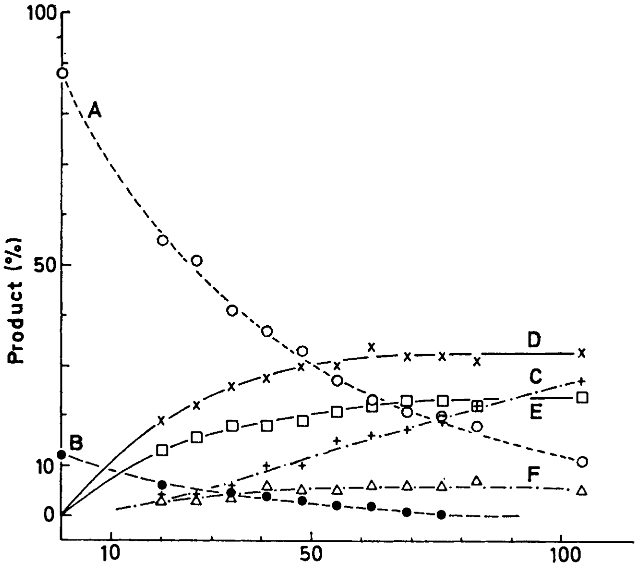

(8)

a; Ar = p-$HO_3SC_6H_4$
b; Ar = o-$HO_3SC_6H_4$
c; Ar = Ph

The final mixture obtained on reaction of (1) in sulphuric acid (*e.g.* in 98.4% H_2SO_4 at 25 °C after 21 days) contained besides (4a) compounds (6b) and (7b). These compounds have also been obtained on reaction of pure (8) with sulphuric acid, and their assignment is based on spectral similarity with (6a) and (7a).

The composition of the reaction mixture obtained from the sultone (8) in 98.4% H_2SO_4 at 25 ± 1 °C is given in Table 1. The (6b) : (7b) ratio is independent of the degree of substrate conversion; the formation of the isomeric compounds (6b) and (7b) is thus kinetically controlled. The interconversion of the various detectable products in the reaction of (1) in sulphuric acid is indicated in Scheme 1. The pseudo-first-order rate constants for the various steps are collected in Table 2.



Reaction of (1) in 98.4% H_2SO_4 at 5 ± 2 °C: A, (3a); B, (3b); C, (4a); D, (6a); E, (7a); F, (8). See note *a* of Table 1

TABLE 1

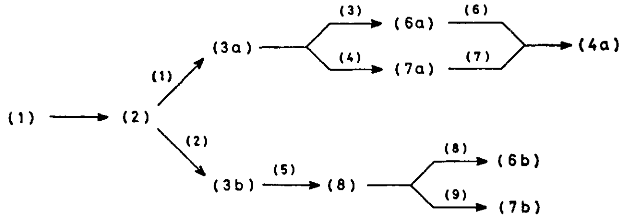
Sulphonation of 3-phenylpropan-1-ol (1) and the sultone (8)

Substrate	Reagent	Temp. (°C)	Reaction time (days)	Composition of reaction mixture (%)								[(6)] : [(7)]
				(3a)	(3b)	(4)	(6a)	(7a)	(6b)	(7b)	(8)	
(1)	90.2% H_2SO_4	25 ± 1	0.01	89	11							
			54	52	4	26	8	5	a	a	5	1.6
(1)	95.4% H_2SO_4	25 ± 1	0.01	87	13							
			21	12	1	53	16	11	a	a	7	1.5
(1)	98.4% H_2SO_4	5 ± 2	0.01	88	12							
			20	55	6	4	19	13	a	a	3	1.5
			27	51	4	4	22	16	a	a	3	1.4
			34	41	5	6	26	18	a	a	4	1.4
			41	37	4	10	25	18	a	a	6	1.4
			48	33	3	10	30	19	a	a	5	1.6
			55	27	2	15	30	21	a	a	5	1.4
			62	23	2	16	34	22	a	a	6	1.5
			69	21	1	17	32	23	a	a	6	1.4
			76	20	$\leqslant 0.5$	19	32	23	a	a	6	1.4
			83	18		22	31	22	a	a	7	1.4
			104	11		27	33	24	a	a	5	1.4
(1)	98.4% H_2SO_4	25 ± 1	0.01	88	12							
			2	53	6	5	18	13	a	a	5	1.4
			6	23	1	21	29	20	a	a	6	1.5
			13	9		39	27	19	a	a	6	1.4
(1)	SO_3 in CD_3NO_2	0 ± 1	0.01	>98 [b]	<2							
		−10 ± 1	21	70 ± 4			8 ± 1	22 ± 3				0.36
(8)	98.4% H_2SO_4	25 ± 1	7						43	13	44 ± 5	3.3
			14						58	19	23 ± 3	3.1
			21						66	20	14 ± 3	3.3
			49						73	22	5 ± 3	3.3

[a] These data comprise small amounts of the *ortho*-compounds (6b) and (7b). See Experimental section. [b] Containing up to *ca.* 10% of the *meta*-isomer.

The initial products from 3-(*p*-sulphophenyl)propyl hydrogensulphate (3a) are the two isomeric compounds (6a) and (7a). It is proposed (Scheme 2) that these result[4] from 1-(*p*-sulphophenyl)prop-1-ene (10a) which may be formed from (9a) by double-bond migration. The alkene (9a) in turn results from 3-(*p*-sulphophenyl)-propyl hydrogensulphate by elimination of H_2SO_4.

The eventual slow conversion of the two compounds (6a) and (7a) into (4a) is thought to proceed by the slow regeneration of 1-(*p*-sulphophenyl)prop-1-ene (10a) and the sulphonation of this alkene at position 2. Apparently the kinetically determined products of the alkene (10a) are the sulphophenyl dioxadithian tetraoxides, whereas the thermodynamically determined product is the disulphonic acid (4a), *i.e.* $k_{15} \gg k_{18}$.



SCHEME 1

The formation of the two geometrically isomeric compounds (6a) and (7a) is thought to proceed by reaction of (10a) with $H_2S_2O_7$ (which is the sulphonating entity for aromatic sulphonation in this sulphuric acid region[5]) with formation of 1-(*p*-sulphophenyl)prop-1-enium-2-pyrosulphonic acid (12) as intermediate (Scheme 2). This intermediate allows rotation around the C(5)-C(6) bond. Provided that the rotation in question is fast relative to ring closure, the ratio in which compounds (6a) and (7a) are formed will be determined by the relative stabilities of the various conformations of (12).[*]

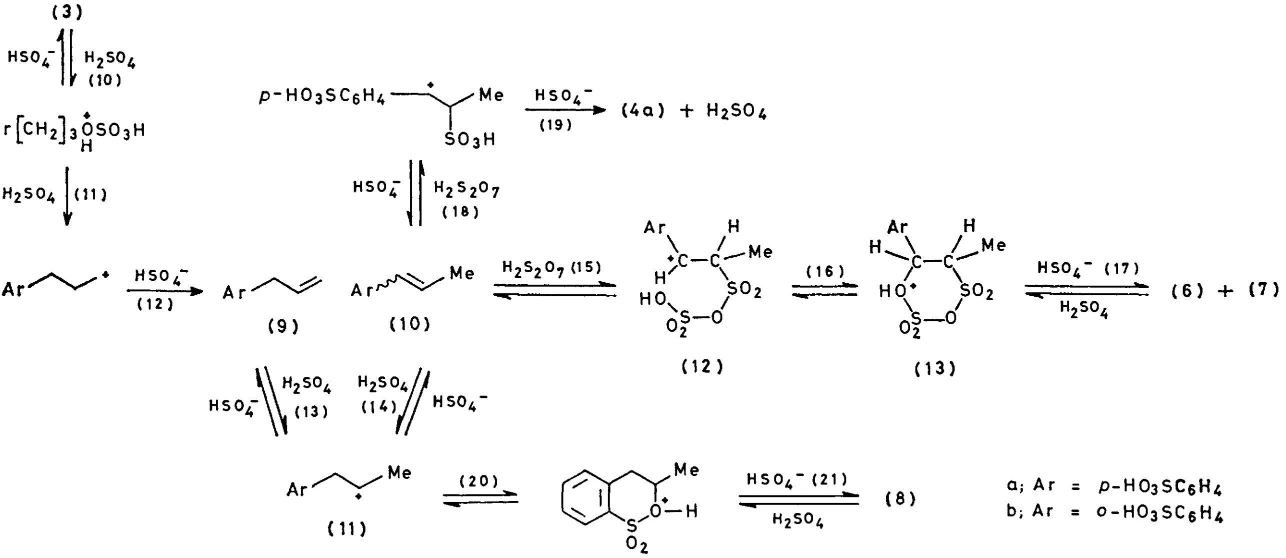
TABLE 2

Pseudo-first-order rate constants ($10^4\ k/\mathrm{ks}^{-1}$) for the reaction of (1) in sulphuric acid

H_2SO_4 (%)	Temp. (°C)	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9
90.2	25 ± 1	43 000 ± 1 000 [a]	5 000 ± 1 000 [a]	0.7 ± 0.2	0.5 ± 0.2	2.3 ± 1.6				
95.4	25 ± 1			5 ± 1	3 ± 1	15 ± 10				
98.4	5 ± 2			1.4 ± 0.4	1.0 ± 0.2	4 ± 2	0.7 ± 0.3	0.5 ± 0.2		
98.4	25 ± 1			9 ± 4	7 ± 3	40 ± 20			8 ± 2	3 ± 1

[a] A. Koeberg-Telder and H. Cerfontain, *J.C.S. Perkin II*, 1976, 1776.

With 3-(*o*-sulphophenyl)propyl hydrogen sulphate the initial product is the sultone (8). Its formation may be explained by steps (10)—(13), (20), and (21). For the *ortho*-sulpho-isomer, in contrast to the *para*-isomer, the intermediate (11) allows intramolecular alkylation by attack of C(6) on the SOH oxygen yielding the sultone (8) [steps (20) and (21)]. The eventual products are however compounds (6b) and (7b). Their formation from (8) may be explained by regeneration of the alkene (10) by the steps (—21), (—20), and (—14) and conversion of this alkene into the dioxadithian tetraoxides as outlined for the *para*-sulpho-isomer. The absence of the formation of the *o*-sulpho-derivative (4b) is ascribed to the very much lower rate of step (—16) for the *o*- compared with the *p*-sulphophenyl dioxadithian tetraoxides as a result of intramolecular hydrogen-bonding in (6b) and (7b) and the corresponding protonated species (13).



SCHEME 2

The rate constants k_3 and k_4 (see Scheme 1) both increase by a factor of *ca.* 14 upon increasing the sulphuric acid concentration from 90.2 to 98.4% H_2SO_4. Over this acid range the acidities h_0 [6] and h_0^{a} [7] (which govern *N*- and *O*-protonation respectively) increase by a factor of 39 and 6.5, respectively, and the activities of H_2SO_4 [8] and $H_2S_2O_7$ [8,9] by a factor of 3.3 and 670, respectively. These data indicate that the rate-limiting step in dioxadithian tetraoxide formation from (3a) is rather one of the protonation steps in the formation of the alkene (10a) than sulphonation of the alkene with $H_2S_2O_7$, and that the protonation step in the formation of the alkene (10a) from (3a) is determined by the acidity of the medium and not by $a_{H_2SO_4}$.

Reaction with SO_3 *in* CD_3NO_2.—The course of the reaction of (1) with SO_3 in CD_3NO_2 was followed by ^1H n.m.r. The results are in Table 1. Initially phenyl ring sulphodeprotonation is observed yielding mainly 3-(*p*-sulphophenyl)propyl hydrogensulphate (3a), some *meta*-isomer, but no *ortho*-isomer (3b) within the limits of ^1H n.m.r. detection which is 2%. Eventually (3a) is slowly converted to yield compounds (6a) and (7a) in a ratio of 0.36, and no (4) within the limits of detection which is 0.5%.

The formation of compounds (6a) and (7a) from (3a) in the aprotic sulphonation system proceeds as depicted in Scheme 3 (*cf.* refs. 4 and 10) by the subsequent addition of two molecules of SO_3 to (10a) *via* the 1-(*p*-sulphophenyl)prop-1-enium-2-sulphonate (14a) and the corresponding 2-pyrosulphonate (15a) as subsequent intermediates. The large difference in the (6a) : (7a) ratio observed in the sulphuric acid and in the aprotic SO_3 sulphonations (1.5 *versus* 0.36) is related to the dif-

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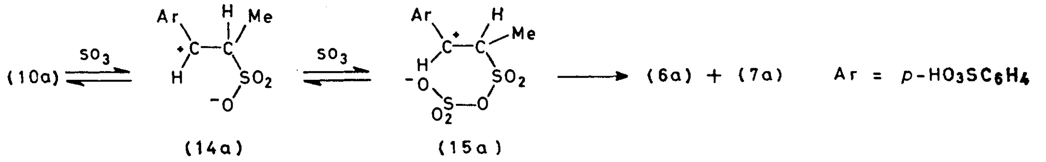
[*] If the ring closure of (12) to yield (13) is fast relative to C(5)–C(6) bond rotation, then the (6a) : (7a) ratio should reflect the ratio in which (*Z*)- and (*E*)-(10a) are formed by step (14).

ference in mechanism of formation of these dioxadithian tetraoxides. The stability of compounds (6a) and (7a) in the aprotic sulphonating system may be explained in terms of the irreversibility of the ring-closure step by which (6a) and (7a) are formed from (15a), in view of the dipolar nature of this intermediate.



SCHEME 3

EXPERIMENTAL

Sulphuric Acid Reactions.—The reactions of 3-phenylpropan-1-ol (Merck–Schuchardt) were performed by dissolving the substrate (0.10 g) in sulphuric acid (2 ml) of the desired strength. ^1H N.m.r. spectra of the sulphuric acid reaction mixtures were recorded after appropriate times. The ^1H n.m.r. data of the products (3a), (3b), and (4a) have been reported before,[2] those of the other products are given in Table 3.

Isolation and Characterization of Sultone (8).—(i) 3-Phenylpropan-1-ol (1 ml) was dissolved in 98.4% H_2SO_4 (20 ml) and left standing at 25 °C for 7 days. The mixture was then neutralized with a concentrated solution of KOH in ethanol–water (1 : 1 v/v). The precipitate (mainly K_2SO_4) was filtered off and ethanol and water were removed by rotary evaporation and freeze drying, respectively. The residue was extracted with chloroform. Removal of the chloroform then afforded the sultone (8). (ii) 3-Phenylpropan-1-ol (0.5 ml) was dissolved in 98.4% H_2SO_4 and left standing at 25 °C for 13 days. The mixture was then added under external ice-cooling to ice (10 g). The turbid mixture was extracted with chloroform. The extract was washed subsequently with sodium hydrogencarbonate solution and water. Removal of the chloroform then afforded the sultone (8). The ^1H n.m.r. data of (8) are given in Table 3. The ^{13}C n.m.r. data in $CDCl_3$ at −50 (and 37) °C are, for the aromatic region, δ 133.9 (133.9) (C–X, X ≠ H), 133.8 (133.3) (C–X, X ≠ H), 133.0 (132.5), 129.2 (128.9), 128.2 (127.8), and 124.7 (124.7) p.p.m., and for the aliphatic region, δ 80.0 (79.3) (*C*–Me), 35.5 (35.5) (CH_2), and 21.3 (21.1) (CH_3). High resolution mass spectrometry confirmed the elemental composition of (8) (Found: M^+, 198.034 7. Calc. for $C_9H_{10}SO_3$: *M*, 198.035 1), $\nu_{max.}$ ($CHCl_3$) 1 358 and 1 184 cm^{-1}, which frequencies agree with those reported for the $-SO_2-O-$ moiety in a six-membered ring.[11]

TABLE 3

^1H N.m.r. data of (1) and the products formed in the sulphonation of 3-phenylpropan-1-ol and 1-phenylprop-1-ene

		δ (p.p.m.) (multiplicity, *J*/Hz)					
		Aromatic			Aliphatic		
Compound	Solvent	2′-H	3′-H	Total	Ar$CH_{(2)}$	C(2)$H_{(2)}$	CH_2O or Me
(1a)	CD_3NO_2			6.93 (s)	2.38 (t, 7.9)	1.54 (m)	3.30 (t, 6.5)
(3a)	CD_3NO_2	7.57	7.32 (AB, 8.0)		2.72 (t, 7.0)	1.98 (m)	4.34 (t, 6.0)
(6c)	[$^2H_8$]dioxan			7.3—7.9 (m)	6.76 (d, 1.5)	4.6 (m) *	1.53 (d, 7.0)
(7c)	[$^2H_8$]dioxan			7.3—7.9 (m)	6.08 (d, 11.0)	4.59 (dq, 11.0, 7.0) *	1.46 (d, 7.0)
(6a)	98.4% H_2SO_4	8.57	8.23 (AB, 8.5)		6.85 (d, 2.0)	4.32 (m) *	2.03 (d, 7.0)
	CD_3NO_2	7.92	7.59 (AB, 8.5)		6.41 (d, 1.2)	4.0—4.3 (m) *	1.21 (d, 7.0)
(6b)	98.4% H_2SO_4			7.9—8.6 (m)	7.07 (d, 0.5)	4.68 (m) *	1.81 (d, 6.8)
(7a)	98.4% H_2SO_4	8.57	8.23 (AB, 8.5)		6.45 (d, 8.0)	4.59 (m) *	1.84 (d, 7.0)
	CD_3NO_2	7.92	7.59 (AB, 8.5)		5.80 (d, 10.5)	4.0—4.3 (m) *	1.19 (d, 7.0)
(7b)	98.4% H_2SO_4			7.9—8.6 (m)	6.74 (d, 4.0)	4.68 (m) *	2.22 (d, 7.8)
(8)	98.4% H_2SO_4			7.8—8.4 (m)	3.7 (m)	5.86 (m)	2.15 (d, 6.2)
	$(CD_3)_2SO$			7.7—8.3 (m)	3.54 (d, 6.5)	5.58 (m)	1.89 (d, 6.2)
	$CDCl_3$			7.7—8.4 (m)	3.66 (d, 10) 3.59 (d, 4.5)	5.78 (m)	2.13 (d, 6.2)

* Refers to C(6).

Reaction with SO_3 *in Nitromethane.*—To a solution of 3-phenylpropan-1-ol (0.95 mmol) in CD_3NO_2 (2 ml) at 0 °C was added SO_3 (3.27 mmol) and the ^1H n.m.r. spectrum recorded after 20 min. The mixture was then stored for 21 days at −10 °C and the ^1H n.m.r. spectrum recorded again. The ^1H n.m.r. data of the sulphonic acids and the dioxadithian tetraoxides are in Table 3.

Product Analysis.—The composition of the reaction mixtures both in sulphuric acid and in CD_3NO_2 were determined by multi-component ^1H n.m.r. analysis on the basis of the specific absorptions of the various components.[12] As to the analysis of the product mixtures obtained from (1) in sulphuric acid the presence of compounds (6b) and (7b) has been neglected in view of the limitations of the multi-component analysis for these products which are only present together in *ca.* 5% yield and which have no observable specific absorptions relative to those of the other main products.

Determination of Rate Constants.—The pseudo-first-order rate constants listed in Table 2 were determined from a plot of log *a versus* time (where *a* is the concentration of the reacting substrate) and the ratio of the resulting products, if more than one compound is formed (as for k_1—k_5, k_8, and k_9). The other two rate constants were calculated using the equation $d[(4)]/dt = \{k_6[(6a)] + k_7[(6b)]\}t$ for a reaction period of 69—104 days, such (see Results and Discussion section) that $k_6/k_7 = k_3/k_4$.

Spectrometers.—^1H N.m.r. spectra were recorded with a Varian HA-100 spectrometer; the chemical shifts are relative to external neat tetramethylsilane (capillary). ^{13}C N.m.r. spectra were obtained using a Varian XL-100 spectrometer equipped with a variable temperature probe, in 5 mm tubes at 25.2 MHz, with proton-noise decoupling. Chemical shifts are relative to internal $CDCl_3$ and are converted into the tetramethylsilane scale.

The field desorption (f.d.) and the 70 eV electron impact (e.i.) mass spectra were recorded on a Varian MAT 711 double focusing mass spectrometer equipped with a combined e.l.–f.i.–f.d. source. The samples (DMSO solutions) were loaded with the dipping technique. Emission controlled f.d. was used at a threshold of 4 nA. The e.i. measurements were obtained with a direct insertion probe at 50 °C and the exact mass measurements were performed with a resolution of 10.000 (10% valley definition).

I.r. spectra ($CHCl_3$) were recorded on a Perkin-Elmer 177 spectrometer.

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