Aromatic Sulfonation, $131^{[\diamondsuit]}$

Formation of Sulfonic Acids and Sulfonic Anhydrides in the Sulfur Trioxide Sulfonation of Some Dialkylbenzenes and 1,ω-Diarylalkanes

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An exploratory study has been made on the SO₃ sulfonation of a number of alkylarenes in $[D_2]$ dichloromethane as an aprotic solvent, mostly in the presence of $[D_8]1_4$ -dioxane as a reactivity moderator, in order to obtain information on sulfonic acid and sulfonic anhydride formation. 1,2-Dimethylbenzene (1) with 1.0 mol-equiv. of SO_3 yields predominantly the 4-sulfonic acid (1-4-S), whereas with 4.0 mol-equiv. of SO₃, 18 mol-% of the corresponding (intermolecular) sulfonic anhydride (1-4-SO₂)₂O is additionally formed. 1,4-Dimethylbenzene (2) with 0.8 mol-equiv. of SO_3 yields predominantly 2-2-S, whereas with 4.0 mol-equiv. of SO₃ the sulfonic anhydride $(2-2-SO_2)_2O$ and its 6-S and $6,6'-S_2$ derivatives are formed, the eventual main product being (6-S-2-2-SO₂)₂O. Reaction of 1-ethyl-4-methylbenzene (3) with 2.0 mol-equiv. of SO_3 - $[D_8]$ dioxane at $-78 \rightarrow -40$ °C leads to the predominant formation of the 2- and 3-S derivatives in a molar ratio of 26:74, with small amounts of the three corresponding intermolecular anhydrides. Upon performing the sulfonation of 3 at $0 \rightarrow 22$ °C, the relative amounts of the anhydrides are

Introduction

As an extension of previous studies on the sulfonation of ortho-^[1] and para-xylene^[2] and of a series of α, ω -diphenylalkanes^{[3][4]}, using both highly concentrated aqueous sulfuric acid and fuming sulfuric acid as reagents, we now report the results of an exploratory study on the sulfonation of a series of related alkylarenes, using SO₃ as the reagent. Previously, we observed that intramolecular arene-1,2-disulfonic anhydrides can be obtained on reaction of benzenesulfonic acids, containing a para-directing substituent in meta position, with a large excess of highly fuming sulfuric acid^[5], and that the intramolecular 3,4,5,6-tetramethylbenzene-1,2-disulfonic anhydride can be obtained in high yield upon dissolving the corresponding, more sterically crowded, 3,4,5,6-tetramethylbenzene-1,2-disulfonic acid^[6] in 93-97% H₂SO₄^[7]. Later, we showed that sulfonation of [2.2]paracyclophane with 4.0 mol-equiv. of SO₃ in dichloromethane at -60 to 20 °C^[8], as well as with 6.0 mol-equiv. of chlorosulfuric acid in dichloromethane at 0 °C^[9], affords the (intramolecular) ps-gem-disulfonic anhydride in yields

larger, and in addition the $3,5-S_2$ derivatives of the intermolecular anhydrides are formed. The absence of the isomeric $2,6-S_2$ derivative is ascribed to the buttressing effect of the 2-sulfo on the 1-ethyl group, hampering the sulfonation at C(6). Reaction of diphenylmethane (4) with 4.2 mol-equiv. of SO₃ at $-20 \rightarrow 25$ °C yields initially 4-4'-S and subsequently 4-4', 4''- S_2 . Sulfonation of 1,2-diphenylethane (5) with 4.0 mol-equiv. of SO₃ at $-78 \rightarrow 22$ °C for 4.5 h leads mainly to the cyclic dimeric disulfonic anhydride $[5-4', 4''(-SO_2)_2O]_2$ which upon hydrolysis affords 9% of 5-2',4''- and 91% of 5- $4'_{1}4''$ -S₂. However, sulfonation of **5** at $0 \rightarrow 22$ °C for ca. 0.8 h was found to lead to the formation of the intermolecular sulfonic anhydride (4'-S-5-4''-SO₂)₂O. On sulfonation of 1,2di-p-tolylethane (6) with 1.0 mol-equiv. of SO_3 , only ca. 20% of the substrate was sulfonated to give, after hydrolysis, 3% of the 2'- and 12% of the 3'-sulfonate, whereas with 4.0 molequiv. of SO₃ the initial monosulfonic acids are almost completely converted to yield the $2',3'',5''-S_3$, $3',3'',5''-S_3$, and 3',3'',5',5''-S₄.

of 87 and 97%, respectively. However, upon reaction of [2.2]paracyclophane with a large excess of 98.5% H₂SO₄ at 20 °C^[8], no ps-gem-disulfonic anhydride is formed, the main product being the ps-gem-disulfonic acid. Quite recently, intermolecular sulfonic anhydride formation was found to take place in part upon SO₃ sulfonation of benzenes and naphthalenes containing a strongly deactivating oxy substituent^{[10][11][12]}. Related product- and kinetic-type studies have been made in our laboratory on the sulfonation of chlorobenzene and 1,4-dichlorobenzene in nitromethane as solvent at 3.5-28 °C, and of 1,4-dichlorobenzene in trichlorofluoromethane at -47 to -10 °C to afford as main products chlorobenzene-4-sulfonic acid and 1,4-dichlorobenzene-2-sulfonic acid, respectively, and in addition the corresponding sulfonic anhydrides^{[13][14]}.

Results and Discussion

Sulfonation of 1,2-dimethylbenzene (1) (0.06 M) with 1.0 mol-equiv. of SO_3 -[D_8]1,4-dioxane in [D_2]dichloromethane as solvent at 22 °C affords mainly the 4-sulfonic acid (1-4- $S^{[15]}$) with additional small amounts of 1-3-S and 1-3,5-S₂ (see Table 1). The 1-3,5-S₂ may result from 1-3-S as well as 1-4-S, since the sulfonic acid substituent is both strongly

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Scheme 1. Formation of a renesulfonic anhydrides from a renesulfonic acids and ${\rm SO}_3$



deactivating and *meta*-directing^{[16][17]}. Upon using 4.0 molequiv. of this sulfonating reagent, the intermolecular sulfonic anhydride (1-4-SO₂)₂O is additionally obtained, which upon hydrolytic work-up and subsequent neutralization with KHCO₃ at room temperature yields again two molecules of 1-4-S^[15]. Upon mixing of 1,4-dimethylbenzene (2) (0.116 M) with 0.8 mol-equiv. of SO₃ in [D₂]dichloromethane at $-78 \rightarrow 22$ °C, a relatively rapid reaction occurs with formation of 2-2-S (see Table 2, entries 1a-1e). Subsequent addition of 10 mol-equiv. of [D₄]methanol did not lead to any change in the sulfo product composition, illustrating the absence of any preceding intermolecular sulfonic anhydride formation. The sulfonation of 2 (0.116 M) with 4.0 mol-equiv. of SO₃ at $-78 \rightarrow 22$ °C is different from the reaction with 0.8 mol-equiv. in that it leads to the formation of the sulfonic anhydride (2-2-SO₂)₂O^{[18][20]} and its 6-S- and $6,6'-S_2^{[15]}$ derivatives; eventually the main product, formed in a yield of \geq 95%, is (6-S-2-2-SO₂)₂O (see Table 2, entries 2a-2f). The reaction mixture of entry 2f was subsequently divided into two equal parts. Hydrolysis of one of these samples with D_2O and subsequent neutralization with KHCO₃ afforded a solution containing 5% of 2-2,5-disulfonate (2-2,5-S₂), 93% of 2-2,6-S₂, and 2% of (6-S-2-2-SO₂)₂O. Addition of 10 mol-equiv. of [D₄]methanol to the other sample led to methanolysis, to afford after a reaction time of 10 min a solution containing 1% of 2-2,5-S₂, 42% of 2-2,6-S₂, 2% of 5-S-2-2-SO₃CD₃, 48% of 6-S-2-2-SO₃CD₃, and 2% of unconverted (6-S-2-2-SO₂)₂O (for the mechanism of the methanolysis, see later). Upon reaction of 2 (0.116 M) with 2.0 mol-equiv. of SO₃ in $[D_2]$ dichloromethane at $0 \rightarrow 22$ °C, the sulfonation and subsequent methanolysis behaviour is intermediate between that observed employing 0.8 and 4.0 mol-equiv. of SO₃. The sulfonation mixture remained homogeneous for ca. 24 h; then some slow precipitation started to occur. ¹H-NMR analysis of the homogeneous reaction mixture after 23.0 h showed the presence of 2-2-S, (2-2-SO₂)₂O, 6-S-(2-2-SO₂)₂O, and (6-S-2-2-SO₂)₂ as the main products in yields of 29, 30, 27, and 12%, respectively (see Table 2, entries 3a-3f). After addition of 10 mol-equiv. of [D₄]methanol and a reaction time of 0.10 h, the homogeneous reaction mixture was found to contain 32% of 2-2-S, 6% of (2-2-SO₂)₂O, 2% of 2-2,5-S₂, 30% of 2-2,6-S₂, 26% of 2-2-SO₃CD₃, and 4% of $6-S-2-2-SO_3CD_3$, the respective data after 3.4 h being 36, < 2, 2, 29, 29, and 4%. These composition data show that 6-S-2-2-SO₃CD₃ is formed in low yield (4%) as compared with the disulfonic acid $2-2,6-S_2$ (30%). This observation may be explained by a specific methanolysis of the asymmetric sulfonic anhydride 6-S-(2-2-SO₂)₂O, yielding mainly $2-2-SO_3CD_3$ and $2-2,6-S_2$. Apparently, the $6-S-2-2-SO_3^$ anion is a better leaving group than the $2-2-SO_3^-$ one. A small amount of the 2-2,6-S2 may result from demethylation of 6-S-2-2-SO₃CD₃.

The formation of the sulfonic anhydride $(2-2-SO_2)_2O$ from 2-2-SO₃H may proceed as shown in Scheme 1. The

SO3	Reactn	ctn Reaction mixture composition (mol %)[b]								
(mol-equiv)	time (h)	1	1-3-S	1-4-S	(1-4-SO ₂) ₂ O	1-3,5-S ₂				
1.0	0.5	58	2	36	≤2	2				
	4.0	30	3	63	≤2	2				
	96	31	3	64	-	2				
4.0	0.2	20	3	66	8	3				
	3.7	-	3	82	14	3				
	24		3	76	18	3				
	96		3	77	17	3				
	~100[c]		3	93	-	4				

Table 1. Sulfonation of 1,2-dimethylbenzene (1) (0.06 M) with SO_3 -[D_8]dioxane^[a] in CD₂Cl₂ at 22 °C

^[a] The amount of $[D_8]$ dioxane, which acts as reactivity moderator, is 1.5 mol-equiv. relative to the amount of SO₃. – ^[b] S stands for SO₃H when the solvent is CD₂Cl₂ and for SO₃⁻⁻K⁺ when it is D₂O₃. – ^[c] Reaction mixture in D₂O, after hydrolysis and neutralization.

Entry	SO3 (mol- equiv)	Reactn temp (°C)[a]	Reactn time (h)	Reaction mixture composition (mol %) ^[b]										
	• •		-	2	2 -2-S	(2-2-SO2)2O	2 -2,5-S ₂	2 -2,6-S ₂	6-S-(2-2-SO ₂) ₂ O[c]	(6-S-2-2-SO ₂) ₂ O[d]				
la	0.8	-78 → -60	0.8	38	62									
1b		$-60 \rightarrow -40$	1.0	35	65									
lc		-4 0 → -20	1.8	29	71									
1d		-20 → 0	3.6	28	72									
le		$0 \rightarrow 22$	124	26	74									
2a	4.0	-78 → -60	1.3	-	-	82	-	-	<	18>				
2b		- 60 → -40	1.5			78			<	22>				
2c		-40 → -20	2.3			59			<	41>				
2d		- 20 → 0	4.3			21			<	79>				
2e		$0 \rightarrow 22$	24.0			12			< {	38>				
2f		22	26.5			-			< 9	95>				
2g		22	27.0[e]				5[e]	93[e]		2[e]				
3a	2.0	$0 \rightarrow 22$	0.2	-	60	31	-	-	9					
3b		22	0.6		52	32			14	2				
3c		22	1.0		47	33			18	2				
3d		22	1.6		41	33			21	5				
3e		22	5.0		34	32			24	11				
3f		22	23.0		29	30			28	13				

Table 2. Sulfonation of 1,4-dimethylbenzene (2) (0.116 M) with SO_3 in CD_2Cl_2

^[a] The ¹H-NMR spectra were recorded at the latter of the two listed temperatures. - ^[b] S stands for SO₃H when the solvent is CD₂Cl₂ and for SO₃⁻K⁺ when it is D₂O. - ^[c,d] Including 1–2% of 5-S-(2-2-SO₂)₂O and [(5-S-2-2-SO₂)(6-S-2-2-SO₂)]O, respectively. - ^[e] Reaction mixture in D₂O, after hydrolysis and neutralization.

Entry	Reactn temp (°C)[a]	Reactn time (h)					Reaction mixtur	e composition	_(mol %) [b]		
		_	3	3 -2-S	3	-3-S	(3 -2-SO ₂) ₂ O	[(3 -2-SO ₂)- (3 -3'-SO ₂)]O	(3 -3-SO ₂) ₂ O	3 -3,5-8 ₂	Monosulfonic acids of ISA ^[c]
1a	-78 → -40	0.6	6	23		70	<	1	>		
1b	- 40 → - 20	1.3	1	24		70	1	2	2		
lc	$-20 \rightarrow 0$	3.5	-	24		70	1	2	3		
ld	0 → 22	48		25		71	1	1	2		
1e	22	49[d]		26		74	-	-	-		
2a	0	0.2	-	18		39	6	17	20	-	-
2b	22	0.9		<	51 -	->	<	41	>		8
2c	22	2.3		16		31	<	38	>		15
2d	22	5.2		15		28	<	35	>		22
2e	22	96[d]		25		52	-	-	-	17	6

Table 3. Sulfonation of 1-ethyl-4-methylbenzene (3) (0.116 M) with 2.0 mol-equiv. of SO₃ in CD₂Cl₂

^[a] The ¹H-NMR spectrum was taken at the latter of the two listed temperatures. - ^[b] S stands for SO₃H when the solvent is CD₂Cl₂ and for SO₃K⁺ when it is D₂O. - ^[c] ISA stands for intermolecular sulfonic anhydrides. - ^[d] Neutralized reaction mixture in D₂O.

initial step is the conversion of $2\text{-}2\text{-}SO_3H$ with SO₃ into the pyrosulfonic acid $2\text{-}2\text{-}S_2O_6H$ (step 1)^[18]. Its central oxygen atom is subsequently protonated by another molecule of $2\text{-}2\text{-}SO_3H$ to yield the ion pair $2\text{-}2\text{-}SO_2-O^+H-SO_3H$ and $2\text{-}2\text{-}SO_3^-$ (step 2). Subsequent attack of one of the three oxy-

gen atoms of the anion $2-2-SO_3^-$ on the carbon-bonded sulfur atom of the cationic species then yields a molecule of both the arenesulfonic anhydride and sulfuric acid (step 3).

The methanolysis of mixed arenesulfonic anhydrides is proposed to proceed by nucleophilic displacement, as deTable 4. Products of the sulfonation of 1,2-di-p-tolylethane (6) (0.058 M) with SO₃ in CD_2Cl_2 , followed by hydrolysis and neutralization

Entry	SO3 (mol- equiv)	Reactn temp (°C)	Reactn time (h)		Reaction mixture composition (mol %) ^[a,b]										
				6	6 - 2'-S	6- 3'-S	6 - 2',3"-S ₂	6- 3',3"-S2	6 - 2',3",5"-S3	6- 3',3",5"-S3	6 - 3',3",5',5"-S4				
1	1.0	-78 → 22	1.0	80	4.2 (21)	11.8 (59)	1.6 (8)	2.4 (12)							
2	1.0	$0 \rightarrow 22$	24	80	3.0 (15)	-	3.0 (15)	14 (70)							
3	4.0	-78 → 22	6.1	-	4	-	13	23	7	29	24				
4	4.0	$0 \rightarrow 22$	46	-	-	-	29	65	3	3					

^[a] S stands for $SO_3^-K^+$. - ^[b] The data between brackets refer to the sulfo product composition.

Compounds[a]	Solvent	ent δ (ppm)										
	-	3-Н	4-H	5-H	6-H	1-CH3	2-CH3					
1	CD ₂ Cl ₂	7.09	7.09			2.26						
1-3-S	CD_2Cl_2	-	7.83	7.24	7.42	2.30	2.58					
	D ₂ O	-	7.56	7.10	7.26	2.26	2.44					
1-4-S	CD ₂ Cl ₂	7.66	-	7.61	7.31	2.34	2.34					
	D ₂ O	7.44	- 1	7.39	7.17	2.17	2.17					
(1-4-SO ₂) ₂ O	CD ₂ Cl ₂	7.55	-	7.58	7.29	2.28[b]	2.34[b]					
1-3,5-S ₂	CD ₂ Cl ₂	-	8.33	-	7.90	2.44	2.64					
	D ₂ O	-	8.00	-	7.60	2.22	2.40					

Table 5. ¹H-NMR data of 1,2-dimethylbenzene (1) and its sulfonation products

^[a] S stands for SO₃H when the solvent is CD_2Cl_2 and for $SO_3^-K^+$ when it is $D_2O_2 - D_2O_2 - D_2$

picted in Scheme 2. It should be realized that the rate coefficients k_1 and k_2 for the methanolysis of mixed anhydrides are in principle different, due to the asymmetry of the sulfonic anhydride.

Upon reaction of 1-ethyl-4-methylbenzene (3) (0.116 M) with 2.0 mol-equiv. of $SO_3-[D_8]$ dioxane in dichloromethane as solvent at $-78 \rightarrow -40$ °C, the 2- and 3-sulfonic acids are formed as the main products in an initial ratio of 26:74, with additional small amounts of the (intermolecular) anhydrides (3-2-SO₂)₂O, [(3-2-SO₂)(3-3'-SO₂)]O, and (3-3-SO₂)₂O (see Table 3, entries 1a-1d). The lower rate of formation of the 2- as compared with the 3-sulfonic acid is ascribed to the larger degree of steric hindrance upon introducing a sulfo group *ortho* to the ethyl rather than the methyl substituent. On performing the sulfonation with 2.0

Scheme 2. Methanolysis of a mixed arenesulfonic anhydride

$$ArSO_{3}CD_{3} + Ar'SO_{3}D$$

$$CD_{3}OD \mid k_{1}$$

$$Ar-SO_{2}-O-SO_{2}-Ar'$$

$$CD_{3}OD \mid k_{2}$$

$$ArSO_{2}D + Ar'SO_{3}CD_{3}$$

mol-equiv. of SO₃ at $0 \rightarrow 22$ °C, the relative amounts of the three anhydrides are significantly larger and, in addition, sulfonic acid derivatives of the anhydrides are found to be present (Table 3, entries 2a-2e). In view of the dominant deactivating and *meta*-directing effect of the sulfonic acid and sulfonic anhydride substituents already present^{[16][17]}, the further sulfodehydrogenation is expected to occur exclusively *meta* to the initial sulfonic acid substituent to yield upon hydrolysis the 2,6- and 3,5-S₂ dianions^[15]. However, the former disulfonate dianion is not formed. Its absence is ascribed to a buttressing effect of the 2-sulfo on the 1-ethyl group, a result of which is that its methyl group points towards 6-H, thereby hampering sulfonation at C-6^[22].

Reaction of diphenylmethane (4) (0.136 M) with 4.2 molequiv. of SO₃ and 4.6 mol-equiv. of $[D_8]$ dioxane in $[D_2]$ dichloromethane as solvent at -20 °C for 30 min was found to yield 14% of 4-4'-S and 7% of 4-4',4''-S₂. Upon further reaction at 25 °C for 2 h, the reaction mixture was found to contain 43% of 4-4'-S, 11% of 4-4',4''-S₂ and 26% of unconverted substrate. The formation of the two sulfonic acid products has been reported previously^{[4][23]}.

Upon reaction of 1,2-diphenylethane (5) (0.058 M) with 4.0 mol-equiv. of SO₃ in [D₂]dichloromethane as solvent at $-78 \rightarrow 22$ °C over a period of 4.5 h, an increasing amount of precipitate was formed, rendering the quality of the subsequent ¹H-NMR spectra increasingly poor. After removal

	CD2Cl2 / CD3OD[b]	7.73	7.22	7.16				2.57	2.33		
	D ₂ O	7.70	7.30	7.26				2.56	2.35		
(2 -2-SO ₂) ₂ O	CD_2Cl_2	7.60	7.38	7.18				2.48	2.34		
	CDCl ₃	7.70	7.36	7.20				2.56	2.37		
2-2-SO3CD3	$CD_2Cl_2 / CD_3OD^{[b]}$	7.76	7.36	7.26				2.54	2.37		
	CDCl3	7.80	7.33	7.24				2.59	2.39		
2 -2,5-S ₂	$CD_2Cl_2 / CD_3OD[b]$	7.83						2.60			
	D ₂ O	7.86						2.64			
2 -2,6-S ₂	$CD_2Cl_2 / CD_3OD[b]$	7.96						2.87	2.38		
	D ₂ O	7.97						2.90	2.43		
6-S-(2 -2-SO ₂) ₂ O	CD ₂ Cl ₂	< 7.9	- 8.2>		7.64	7.38	7.23	< 2.4 -	2.8>	2.52	2.36
5-S-2-2-SO3CD3	$CD_2Cl_2 / CD_3OD[b]$	7.83		7.86				2.60	2.65		
	D ₂ O							2.61	2.67		
6-S-2-2-SO3CD3	$CD_2Cl_2 / CD_3OD[b]$	7.96	8.09					2.86	2.43		
	D ₂ O	8.06	8.15					2.87	2.46		
(6-S-2-2-SO ₂) ₂ O	CD ₂ Cl ₂	<	8.0 - 8.3	>	<	8.0 - 8.3	>	<	2.4 -	3.0	>

Table 6. ¹H-NMR data of 1,4-dimethylbenzene (2) and its sulfonation products

6

7.27

2'

δ (ppm)

5'

6'

1-CH3

2.29

2.60

4-CH3

2.33

3'

^[a] S stands for SO₃H when the solvent is CD_2Cl_2 and for $SO_3^-K^+$ when it is $D_2O_2 - [b] CD_2Cl_2/CD_3OD$ (10:1, v/v).

Compounds ^[a]	Solvent	δ (ppm)													
		2	3	5	6	2'	3'	5'	6'	1-CH2	1-CH3	4-CH ₃	1'-CH2	1'-CH3	4'-CH3
3	CD ₂ Cl ₂	<	7.	08	>					2.59	1.20	2.30			
3 -2-S	CD_2Cl_2	-	7.70	7.43	7.34					2.98	1.26	2.34			
	D ₂ O	-	7.69	7.36	7.36					2.97	1.23	2.35			
3- 3-S	CD_2Cl_2	7.74	-	7.30	7.40					2.65	1.21	2.60			
	D ₂ O	7.73	-	7.30	7.32					2.66	1.21	2.56			
(3 -2-SO ₂) ₂ O	CD_2Cl_2	-	7.58	7.44	7.25					2.82	1.23	2.34			
{(3 -2-SO ₂)(3 -3'-SO ₂)]O	CD ₂ Cl ₂	-	7.58	7.44	7.25					2.84	1.23	2.40	2.58	1.12	2.37
(3 -3-SO ₂) ₂ O	CD_2Cl_2	7.64	-	7.22	7.42					2.70	1.18	2.48			
3-3,5-S ₂	D ₂ O	7.93	-	-						2.66	1.20	2.84			
6-S-(3-2-SO ₂) ₂ O ^[b]	CD ₂ Cl ₂	-	7.9	8.0	-	-	7.6	7.4	7.2	3.13	1.32		2.82	1.22	2.34
	D20	-			-	-	7.74	7.42	7.23	3.40	1.20	2.35	3.12	1.20	2.31
5-S-(3 -2-SO ₂) ₂ O ^[b]	CD ₂ Cl ₂	7.88	-	-	7.96					2.72	1.18	2.72			

Table 7. ¹H-NMR data of 1-ethyl-4-methylbenzene (3) and its sulfonation products

^[a] S stands for SO₃H when the solvent is CD_2Cl_2 and for SO₃-K⁺ when it is D_2O_2 . – ^[b] The presence of relatively small amounts of [(5-S-3-3-SO₂)(3-2'-SO₂)]O cannot be excluded.

of the precipitate, the main product of the homogeneous solution, in [D₂]dichloromethane as solvent, shows an AB system with chemical shifts at $\delta = 7.08$ and $\delta = 7.61$, which is ascribed to the cyclic dimer $[5-4',4"(-SO_2)_2O]_2^{[29]}$ (the various sulfonation products of 5 are shown in Scheme 3). On dissolving the precipitate in D₂O and subsequent neutralization with aqueous KHCO₃, the resulting solution was shown by ¹H-NMR spectroscopy to contain 9% of 5-2',4"and 91% of 5-4',4"-disulfonate. The reaction mixture of 1,2diphenylethane (0.058 M) with 4.0 mol-equiv. of SO_3 in $[D_2]$ dichloromethane as solvent at $0 \rightarrow 22$ °C remained homogeneous over a period of 0.8 h. Its ¹H-NMR spectrum was again indicative of sulfonic anhydride formation. The main product shows two AB systems of equal intensity, one consisting of two sharp doublets at $\delta = 7.92$ and 7.36 and the other of two broadened doublets at $\delta = 7.63$ and 7.18, which are assigned to the intermolecular sulfonic anhydride $(4'-S-5-4''-SO_2)_2O_2O_2$. After 3 days, the reaction mixture was

1'-CH3

4'-CH3

Compounds^[a]

2

2-2-S

Solvent

CD₂Cl₂

CD₂Cl₂

2

7.05

3

7.69

5

7.36

Compounds ^[a]	Solvent						δ (μ	opm)					
		1-CH2	2-CH2	2'-H	3'-Н	4'-H	5'-H	6'-H	2"-Н	3"-Н	4"-H	5"-H	6"-H
4	CD ₂ Cl ₂	3.95		<	7.1 - 7.4	>		<u> </u>					
4 -4'-S[b]	CD ₂ Cl ₂	4.07		7.41	7.90	-			<	7.3 - 7.5	>		
4 -4',4"-S2[b]	CD_2Cl_2	4.17		7.39	7.87								
	D_2O	4.12		7.40	7.73								
5	CDCl3	< 3.	07>	7.39	<	7.34	>						
5-4'-S	D ₂ O	< 3.	02>	7.36	7.71				<	7.2 - 7.4	>		
5-2',4"-S2	CD ₂ Cl ₂	3.34	3.16	-	8.12	~7.4	7.53	7.43	~7.4	7.95		7.95	~7.4
	D_2O	3.33	3.08	-	7.88	~7.4	7.58	7.43	7.39	7.70		7.70	7.39
5-4',4"-S ₂	D_2O	3.05		7.36	7.72	-							
(5- 4'-S-4"-SO ₂) ₂ O	CD ₂ Cl ₂	3.13	2.83	7.36	7.92	-			7.18	7.63			
[5-4',4"(-SO ₂) ₂ O] ₂	CD ₂ Cl ₂	3.1		7.08	7.61								
or 5-4',4"(-SO2)2O													
5-2'-S-4',4"(-SO ₂) ₂ O	D ₂ O	3.41	3.10	-	8.30	-	7.83	7.44	7.44	7.75			
5-2',2",4',4"-84	D ₂ O	3.68		-	8.48	-	8.05	7.65					
5-2',2"-S ₂ -4',4"(-SO ₂) ₂ O	D ₂ O	3.47		-	8.31	-	7.87	7.53					

Table 8. ¹H-NMR data of diphenylmethane (4), 1,2-diphenylethane (5) and their sulfonation products

^[a] S stands for SO₃H when the solvent is CD_2Cl_2 and for $SO_3^-K^+$ when it is $D_2O_2 - [b]$ For reasons of consistency, the positions of the phenyl groups have been numbered similarly to those of 1,2-diphenylethane.

dissolved in D₂O and neutralized with aqueous KHCO₃ to yield a solution containing 41% of 5-4',4"-S₂, 41% of 5-2',4',4"-S₃, 10% of 5-2',2",4',4"-S₄, and probably 8% of 2',2"-S₂-5-4',4"-(SO₂)₂O.

Scheme 3. Sulfonation products of 1,2-diphenylethane



The sulfonation of 1,2-di-*p*-tolylethane (6) in $[D_2]$ dichloromethane was studied using 1.0 and 4.0 mol-equiv. of SO₃ over temperature ranges of both $-78 \rightarrow 22$ and $0 \rightarrow 22$ °C. The results are collected in Table 4. With 1.0 molequiv. of SO₃, only ca. 20% of the substrate is sulfonated to yield, after subsequent hydrolysis and neutralization, 3% of the 2'- and 12% of the 3'-S, and relatively small amounts of the 2',3"- and the 3',3"-S₂ derivatives (Table 4, entries 1 and 2). Upon using 4.0 mol-equiv. of SO₃, the substrate **6** and the mono- and disulfonic acids are almost fully converted to yield, after hydrolysis and neutralization, the 2',3",5"-S₃, 3',3",5"-S₃, and 3',3",5',S"-S₄ polyanionic derivatives (entries 3 and 4). From the data of entries 2 and 4, it was calculated that the initial ratios of sulfonation of **6** at the 2'- and 3'-positions are 16:84 and 17:83, respectively. This ratio is smaller than the corresponding ratio observed for the sulfonation of 1-ethyl-4-methylbenzene (**3**), which is 26:74 (see above). Apparently, the steric hindrance is significantly larger for sulfonation *ortho* to the phenylethyl than to the ethyl group.

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Experimental Section

General: The ¹H-NMR spectra were recorded with Bruker AC-200, WM-250, and AMX-300 spectrometers. – Materials: The high-purity aromatic hydrocarbon substrates were obtained commercially. – Sulfonation procedures and analysis: These were analogous to those described previously^{[8][30][31]}.

NMR Analysis: The ¹H-NMR spectra were recorded of the various types of reaction mixtures, applying the NOE^[32] technique, as appropriate. The structural assignments of the components of the reaction mixtures were made on basis of the observed ¹H-NMR chemical shifts, absorption area ratios and coupling constants in combination with the ¹H-NMR shielding parameters of the SO₃H, SO₃⁻, SO₃Me, and SO₂-O-SO₂ substituents^{[33][34]}. The ¹H-NMR assignments are compiled in Tables 5–9. The product compositions of the various reaction mixtures were determined by multicomponent ¹H-NMR analysis^[33]. For the sulfonation of diphenylmethane,

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Table 9. ¹H-NMR data of 1,2-di-*p*-tolylethane (6) and its sulfonation products

Compound ^[a]	Solvent		δ (ppm)											
		1-CH2	2-CH2	2'-H	3'-H	4'-CH3	5'-H	6'-H	2"-H	3"-H	4"-CH3	5"-H	6"-H	
6	CD ₂ Cl ₂	2.86		< 7.	08>	2.31								
6 -2'-S	D_2O	3.25	2.96	-	7.72	2.33	<	7.0 -	7.4	>	2.30	< 7.0 -	7.4>	
6-3'-5	D20	2.88	2.88	7.67	-	2.53	<	7.0 -	7.4	>	2.25	< 7.0 -	7.4>	
6-2',3"-S2	CD ₂ Cl ₂	3.25	2.94	-	7.87	2.38	< 7.0	- 7.4>	7.79	-	2.62	< 7.0 -	7.4>	
	D ₂ O	3.29	2.96	-	7.72	2.33	< 7.0	- 7.4>	7.70	-	2.57	< 7.0 -	7.4>	
6-3',3"-S2	D ₂ O	2.96		7.70	-	2.54	< 7.0	- 7.4>		-				
[6 -3',3"(-SO ₂) ₂ O] ₂	CD_2Cl_2	2.86		7.08	-	2.66	7.40	7.47		-				
6- 2',3",5"-S ₃	D ₂ O	3.41	2.94	-	7.72	2.41	< 7.0	7.4>	7.86	-	2.86	-	7.86	
6 -3',3",5'-S ₃	D ₂ O	2.99	2.99	7.70	-	2.54	-	7.0 - 7.4	7.87	-	2.85		7.87	
6-3',3",5',5"-S4	D_2O	3.04		7.99	-	2.87	-			-		-		

^[a] S stands for SO₃H in CD₂Cl₂ and for SO₃⁻K⁺ in D₂O as solvent; $(-SO_2)_2O$ stands for $-SO_2OSO_2-$.

the reaction mixture composition of 4, 4-4-S and 4-4,4'-S₂ in [D₂]dichloromethane was calculated from the relative areas of methylene singlets at $\delta = 3.95$, 4.07 and 4.17, respectively.

- [1] A. J. Prinsen, H. Cerfontain, Recl. Trav. Chim. Pays-Bas 1969, 88, 833-844
- [2] A. W. Kaandorp, H. Cerfontain, Recl. Trav. Chim. Pays-Bas 1969, 88, 725-727
- [3] H. Cerfontain, Z. R. H. Schaasberg-Nienhuis, J. Chem. Soc., Perkin Trans. 2 1974, 536-542.
- ^[4] H. Cerfontain, Z. R. H. Schaasberg-Nienhuis, T. A. Kortekaas, J. Chem. Soc., Perkin Trans. 2 1979, 844-850
- ^[5] A. Koeberg-Telder, C. Ris, H. Cerfontain, J. Chem. Soc., Perkin Trans. 2 1974, 98-101.
- ^[6] J. D. Schagen, P. Seignette, C. H. Stam, Cryst. Struct. Commun. 1982, 11, 1643-1645
- [7] A. Koeberg-Telder, H. Cerfontain, Recl. Trav. Chim. Pays-Bas 1982, 101, 41-47.
- ^[8] H. C. A. van Lindert, A. Koeberg-Telder, H. Cerfontain, Recl. Trav. Chim. Pays-Bas 1992, 111, 379-388
- [9] H. C. A. van Lindert, J. A. van Doorn, B. H. Bakker, H. Cerfontain, Recl. Trav. Chim. Pays-Bas 1996, 115, 167–178. ^[10] H. R. W. Ansink, H. Cerfontain, Recl. Trav. Chim. Pays-Bas
- 1992, 111, 215-221
- ^[11] H. R. W. Ansink, E. Zelvelder, H. Cerfontain, *Recl. Trav. Chim. Pays-Bas* **1993**, *112*, 210–215.
- [12] H. R. W. Ansink, E. Zelvelder, H. Cerfontain, *Recl. Trav. Chim. Pays-Bas* 1993, *112*, 216–225.
- ^[13] J. K. Bosscher, H. Cerfontain, Recl. Trav. Chim. Pays-Bas 1968,
- 87, 873–887. ^[14] J. K. Bosscher, H. Cerfontain, *Tetrahedron* **1968**, *24*, 6543-6555.
- ^[15] S stands for SO₃H when the solvent is CD_2Cl_2 , and for $SO_3^ K^+$ when it is D_2O .
- [16] H. Cerfontain, J. Org. Chem. 1982, 47, 4680-4688.
 [17] H. Cerfontain, Recl. Trav. Chim. Pays-Bas 1985, 104, 153-165. ^[18] Robinson and Silberberg have suggested that SO₃ at low molar concentration in methanesulfonic acid reacts to give initially methanepyrosulfonic acid (CH₃S₂O₆H), which will further react with methanesulfonic acid to give methanesulfonic anhydride $(CH_3SO_2)_2O^{[19]}$.

- ^[19] E. A. Robinson, V. Silberberg, Can. J. Chem. 1966, 44, 1437-1444.
- ^[20] 1,4-Dimethylbenzene-2-sulfonic anhydride [(2-2-SO₂)₂O] can easily be isolated from the sulfonation mixtures, resulting from the arene and SO₃ in dichloromethane, by the addition of water, since arenesulfonic acids are highly soluble in water, whereas the arenesulfonic anhydrides are quite insoluble^{[8][21]}
- ^[21] N. H. Christensen, Acta Chem. Scand. 1964, 18, 954-966.
- [22] A. J. Prinsen, A. Koeberg-Telder, H. Cerfontain, *Tetrahedron* 1970, 26, 1953–1960.
- ^[23] Diphenylmethane (4) with chlorosulfuric acid in chloroform yields 82% 4-4-S^[24]. This acid is also formed using SO₃-[D₈]dioxane as the reagent in 1,2-dichloroethane^[25]. With an excess of chlorosulfuric acid^[26] and with both 85 wt-% aqueous sulfuric acid at 140 °C^[27] and 60% oleum in the cold^[28], the 4,4'disulfonated product of diphenylmethane was obtained.
- ^[24] E. Wedekind, D. Schenk, Ber. Dtsch. Chem. Ges. 1911, 44, 198 - 202
- ^[25] F. G. Bordwell, G. W. Crosby, J. Am. Chem. Soc. 1956, 78, 5367-5371.
- ^[26] C. S. Marvel, P. D. Ceasar, J. Am. Chem. Soc. 1951, 73, 1097-1099.
- ^[27] J. Feldmann, Helv. Chim. Acta 1931, 14, 751-764
- ^[28] V. S. Etlis, G. A. Razuvaev, Dokl. Akad. Nauk. SSSR, 1956, 111, 842-844; Chem. Abstr. 1957, 51, 9607c.
- ^[29] The formation of the monomeric intramolecular sulfonic anhydride $5-4',4"(-SO_2)_2O$ is far less likely than that of the cyclic double intermolecular anhydride $[5-4',4"-(SO_2)_2O]_2$, since studies with Catalin-Stuart-type molecular models have clearly shown that the former anhydride - in contrast to the latter one would be highly strained
- ^[30] H. Cerfontain, A. Koeberg-Telder, R. H. Mitchell, N. Khalifa, M. Tashiro, *Recl. Trav. Chim. Pays-Bas* 1996, *115*, 293-301.
- [31] H. Cerfontain, B. H. Bakker, A. Koeberg-Telder, O. Wilmes, Liebigs Ann. 1997, 49-53
- ^[32] K. Nagayama, A. Kumar, K. Wuthrich, R. R. Ernst, J. Magn. *Reson.* **1980**, *49*, 321–334. ^[33] H. Cerfontain, A. Koeberg-Telder, C. Kruk, C. Ris, *Anal.*
- Chem. **1974**, 46, 569–574.
- ^[34] H. R. W. Ansink, E. J. de Graaf, E. Zelvelder, H. Cerfontain, Can. J. Chem. 1993, 71, 210-215.

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