Kinetic Studies of the Sulfonation of 2-*tert*-Butylphenol with Chlorosulfonic Acid

ARNE BRÄNDSTRÖM, GERT STRANDLUND and PER-OLOF LAGERSTRÖM

AB Hässle, S-431 83 Mölndal, Sweden

The sulfonation of 2-*tert*-butylphenol with chlorosulfonic acid in dichloromethane at −30 °C has been studied. A total of 13 acids have been identified in the reaction mixture. They are derivatives of phenol, 2-*tert*-butylphenol, 4-*tert*-butylphenol and 2,4-di-*tert*-butylphenol. First-order rate constants have been obtained for most of the reactions and a two-phase reaction mechanism is discussed with respect to direct sulfonation, sulfate ester rearrangement and *ipso* sulfonation.

In ion pair extraction, sulfonic acids represent a most important source of anions. In a previous paper [1] it was reported that arylsulfonic acids with an *ortho* hydroxy group are readily extracted into an organic layer as ion pairs with different amines. We have also established principles for the estimation of extraction constants for different combinations of acids, amines and solvents. This has enabled us to separate sulfonic acids even from very complicated mixtures. HPLC methods using ion pair technique for the quantitative analysis of such mixtures have also been developed.[2] These have been used to investigate the kinetics of the sulfonation of some simple phenols. The very complicated reaction which occurs in the sulfonation of 2-*tert*-butylphenol, Scheme 1, has been a challenge to test the possibility of this analytical method more comprehensively. The numerical integration method suggested by Wideqvist [3] will furthermore enable us to investigate the kinetics of as many as possible of the reactions involved. Such an investigation should be a powerful tool to reveal the mechanism of the sulfonation of phenols.

RESULTS AND DISCUSSION

In the sulfonation of 2-*tert*-butylphenol it has been possible to identify the 13 acids which are formed in yields $> \sim 0.1$ % and also to follow their concentrations analytically. The sulfonation has been made with about 1 mol equivalent of chlorosulfonic acid and hence the products are sulfonic acids and not sulfonyl chlorides. The isolated acids are derivatives of 4 different phenols; phenol, 2-*tert*-butylphenol, 4-*tert*-butylphenol and 2,4-di-*tert*-butylphenol. The sum of the concentrations of these acids at different times is given in Table 1. The errors involved in the measurements are those expected in analytical HPLC which means a relative standard deviation of about $1-2$ % for the major components of the mixture and somewhat higher for the minor ones. The total yield is very high and slowly increases with time up to 99 %. A plot of the total yield against time indicates that this increase is about 0.1 mmol/l h^{-1}. This is probably due to slow formation of the acids from the small quantities of unreacted phenols present (*cf.* Ref. 5, Table 1a). The predominant phenol present from the beginning of the kinetic measurements onwards is 4-*tert*-butylphenol. The sulfonation of this phenol seems to be uncomplicated, giving predominantly the acids *H* and *I*. It is therefore assumed that the increase in total yield observed is due to a slow formation of *H* or *I*. This is denoted as I_x in Table 8 and H_x in Table 9.

The course of the sulfonation of 2-*tert*-butylphenol can be divided into two different phases. During the first rapid phase we have a fast attack on the phenolic hydroxy group together with migrations, eliminations and redistributions of the *tert*-butyl group with the formation of the aryl
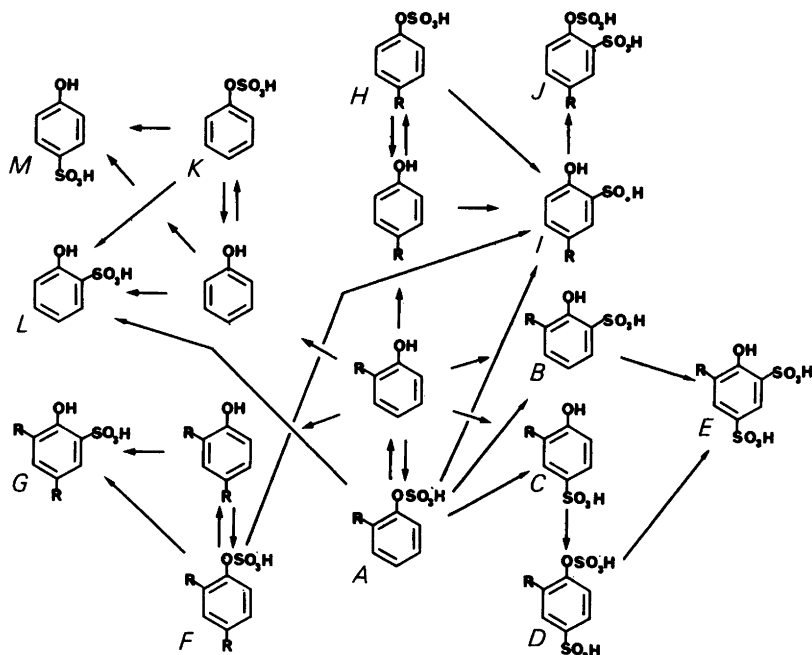
Scheme 1. R = *tert*-butyl.

hydrogen sulfates *A, F, H* and *K* (Scheme 1). At the same time there are also some ring sulfonations forming the sulfonic acids *B, C, I, G, L* and *M*.

During the second phase, which can be followed kinetically, the aryl hydrogen sulfates are converted by first-order reactions to hydroxyarylsulfonic acids.[5] During these conversions of the esters, the *tert*-butyl group in a position *ortho* to the ester group is partially eliminated or moved to the *para* position. Some sulfonations also occur with the formation of the arylsulfonic acid hydrogen sulfates *D* and *J* and the hydroxy aryldisulfonic acid *E*. In the case of *D* there also appears to be two phases. During the first phase which lasts for less than 1 h there is a fairly rapid increase in *D*. This is then followed by a second phase during which the concentration of *D* is decreased at a first-order rate. The same behaviour is also seen to a lesser extent with *K* and *J*.

A data set like that in Table 1 does not *per se* contain sufficient data to evaluate rate constants for the different rate-determining reactions involved. If we, however, have additional information about the behaviour of analogous compounds in less complicated systems, the situation is considerably

improved. In the present case we have good information, from related reactions, about the steps by which most of the compounds are formed. We have, *e.g.*, shown that an aryl hydrogen sulfate such as *F* should be converted to a sulfonic acid *G* by a first-order process.[5] We can, therefore, use the data in Table 1 to test the hypothesis that *G* is formed from *F* by such a process. If the data are in agreement with this interpretation the concentrations of *F* and *G* thus explained can be subtracted from the original data set and the new data set obtained can be used to test another hypothesis *etc.* In such a procedure it is inevitable that the reduced data set is not as certain as the first one and that the results become less conclusive the deeper we "dig". The situation is improved by the fact that we have the possibility of "digging" from several different points. In the present case it has been possible to calculate first-order rate constants for most of the reactions given as arrows in Scheme 1. The fact that a self consistent set of reaction rate constants can be obtained for this complex reaction scheme is a good indication that it may be correct in most details.

For the reactions *H* to *I* and *F* to *G* separate measurements might have been possible. The value

Table 1. HPLC measurements from the sulfonation of 2-*tert*-butylphenol with chlorosulfonic acid.

Time/h	A/mM	B/mM	C/mM	D/mM	E/mM	F/mM	G/mM	H/mM	I/mM	J/mM	K/mM	L/mM	M/mM	Total conc. of sulfonated products/mM
0.25	18.5	11.2	8.3	1.57	0.17	3.32	1.70	30.6	3.16	0.49	15.5	0.58	0.36	95.5
0.5	16.8	11.6	7.1	3.07	0.51	3.18	1.76	30.5	3.19	0.97	16.0	0.68	0.33	95.7
1.0	15.4	11.8	6.9	3.75	0.75	3.15	1.84	30.1	3.30	1.22	16.9	0.82	0.36	96.3
1.5	13.7	12.4	7.7	3.72	1.13	2.92	1.77	30.4	3.86	1.23	16.6	1.04	0.45	96.9
2.0	11.7	12.2	8.4	3.52	1.44	2.76	2.02	29.5	4.21	1.21	16.4	1.23	0.55	95.1
3.0	9.5	13.1	8.8	3.11	2.11	2.56	2.18	30.0	5.4	1.31	15.3	1.56	0.78	95.7
5.0	6.2	13.5	9.6	2.90	2.87	2.18	2.28	29.3	6.9	1.28	15.7	2.23	1.27	96.2
7.0	3.31	13.9	11.0	2.31	3.73	1.57	2.75	28.0	9.7	1.31	14.4	3.15	1.75	96.9
12.0	1.03	13.6	12.4	1.89	5.02	1.22	2.83	26.5	12.5	1.23	12.9	4.37	2.70	98.2
25.0	–	12.8	13.1	1.15	6.3	0.43	3.34	22.8	18.5	1.00	8.6	6.3	4.66	99.0

of such experiments as an additional proof seems, however, to be low compared with the extra work involved since we can expect that medium effects will obscure the results.

The 2,4-di-*tert*-butylphenol system

This system which is the easiest to resolve contains two compounds F and G. From Table 2 we can see that the decrease in the concentration of F is first order in F with the rate constant $k_F = 0.0866$ h^{-1}. The formation of G is first order in F with the rate constant $k_{FG} = 0.0498$ h^{-1}. F is therefore also converted to another product, probably through loss of a 2-*tert*-butyl group. The 4-*tert*-butyl group is not removed as demonstrated in a separate experiment. The product formed is probably H or I. The rate for this process is first order in F with the constant 0.0368 h^{-1}. It will be discussed in connection with the 4-*tert*-butylphenol system.

The 2-*tert*-butylphenol system

The concentration of A is decreased by a reaction, first order in A, with a velocity constant $k_A = 0.240$ h^{-1} (Table 3). The sum of the concentrations of $B + C + D + E$ increases at a rate, first order in A, with a constant $k_{A(B+C)} = 0.156$ h^{-1} (Table 4). Therefore, first-order reactions with a total constant of 0.084 remain giving products belonging to the phenol and 4-*tert*-butylphenol system. It seems reasonable to assume that the proportion going to each of these systems is equal to the proportion at which each system is formed in the rapid initial step, *viz.* 1:2 (Table 1). It will also be seen that this is a stoichiometric demand. We thus have a reaction, first order in A, with a constant $k_{AL} = 0.0272$ h^{-1} leading to the phenol system and one with a constant $k_{AI} = 0.0568$ h^{-1} leading to the 4-*tert*-butylphenol system.

The concentration of C decreases somewhat at the beginning. This corresponds in time and magnitude to a rapid increase in the concentration of D. It therefore seems logical to assume that D is formed from C. From 1 h onwards the concentration of D is decreasing at a rate, first order in D, with the constant $k_D = 0.0562$ h^{-1} (Table 3). The logical reaction product of D is E. This rate is not sufficient to explain the increase in concentration of E with time. If the portion of E coming from D is named

Table 2. Kinetic studies within the 2,4-di-*tert*-butylphenol system.[a]

Time/h	F/mM	$\int_{0.25}^{t} Fdt$/mMh	F_{calc}/mM	G/mM	G_{calc}/mM	I_{Fcalc}/mM
0.25	3.32	0	3.29	1.70	1.69	0
0.5	3.18	1.54	3.16	1.76	1.76	0.06
1.0	3.15	3.12	3.02	1.84	1.84	0.11
1.5	2.92	4.64	2.89	1.77	1.92	0.17
2.0	2.76	6.05	2.77	2.02	1.99	0.22
3.0	2.56	8.71	2.54	2.18	2.12	0.32
5.0	2.18	13.44	2.13	2.28	2.36	0.49
7.0	1.57	17.16	1.81	2.75	2.54	0.63
12.0	1.22	24.10	1.21	2.83	2.89	0.89
25.0	0.43	33.95	0.36	3.34	3.38	1.25

Reaction	Rate const./h^{-1}	Standard deviation/h^{-1}	Intercept/mM	Standard error of estimate/mM
Decomposition of F	$k_F = 0.0866$	0.0032	3.29	0.105
Formation of G from F	$k_{FG} = 0.0498$	0.0030	1.69	0.10
Formation of I from F	$k_{FI} = 0.0368$			

[a] $F_{calc} = 3.29 - k_F \int_{0.25}^{t} Fdt$: $G_{calc} = 1.69 + k_{FG} \int_{0.25}^{t} Fdt$; $I_{Fcalc} = k_{FI} \int_{0.25}^{t} Fdt$; $k_{FI} = k_F - k_G$.

Table 3. Kinetic studies within the 2-*tert*-butylphenol system.[a]

Time/h	A/mM	$\int_{0.25}^{t} Adt$/mMh	A_{calc}/mM	D/mM	$\int_{0.25}^{t} Ddt$/mMh	D_{calc}/mM	E_{Dcalc}/mM
0.25	18.5	0	18.3	1.57	0	–	0
0.5	16.8	4.41	17.2	3.07	0.55	–	0.04
1.0	15.4	12.45	15.3	3.75	2.25	3.64	0.13
1.5	13.7	19.72	13.5	3.72	4.12	3.53	0.23
2.0	11.7	26.06	12.0	3.52	5.93	3.43	0.33
3.0	9.5	36.62	9.5	3.11	9.24	3.25	0.52
5.0	6.2	52.09	5.8	2.90	15.25	2.91	0.86
7.0	3.31	61.30	3.56	2.31	20.44	2.62	1.15
12.0	1.03	71.06	1.22	1.89	30.90	2.03	1.74
25.0	–	76.24	–	1.15	50.26	0.94	2.82

Reaction	Rate const./h^{-1}	Standard deviation/h^{-1}	Intercept/mM	Standard error of estimate/mM
Decomposition of A	$k_A = 0.240$	0.0034	18.25	0.287
Decomposition of D	$k_D = 0.0562$	0.0045	3.77	0.196

[a] $A_{calc} = 18.25 + k_A \int_{0.25}^{t} Adt$; $D_{calc} = 3.77 + k_D \int_{0.25}^{t} Ddt$; $E_{Dcalc} = k_D \int_{0.25}^{t} Ddt$.

Table 4. Kinetic studies within the 2-*tert*-butylphenol system.[a]

Time /h	$\int_{0.25}^{t} A\,dt$ /mMh	$B+C+D+E$ /mM	$(B+C+D+E)_{calc}$ /mM	E_{Dcalc} /mM	$C+D$ /mM	$C+D_{calc}$ /mM	$B+E$ /mM	$B+E_{calc}$ /mM
0.25	0	21.2	21.4	0	9.9	9.7	11.4	11.7
0.5	4.41	22.3	22.1	0.04	10.2	10.1	12.1	12.0
1.0	12.45	23.2	23.4	0.13	10.7	10.7	12.6	12.7
1.5	19.72	24.8	24.5	0.23	11.4	11.2	13.5	13.3
2.0	26.06	25.6	25.5	0.33	11.9	11.6	13.6	13.8
3.0	36.62	27.1	27.1	0.52	11.9	12.3	15.2	14.8
5.0	52.09	28.9	29.5	0.86	12.5	13.3	16.4	16.3
7.0	61.30	30.9	31.0	1.15	13.3	13.8	17.6	17.1
12.0	71.06	32.9	32.5	1.74	14.3	14.1	18.6	18.4
25.0	76.24	33.3	33.3	2.82	14.3	14.4	19.1	19.9

Reation	Rate const./h^{-1}	Standard deviation/h^{-1}	Intercept/mM	Standard error of estimate/mM
Formation of B and C from A	$k_{A(B+C)}=0.156$	0.0038	21.4	0.315
Formation of C from A	$k_{AC}=0.0858$	0.0059	9.72	0.495
Formation of B from A	$k_{AB}=0.0706$	0.0048	11.69	0.402

[a] $(B+C+D+E)_{calc}=21.4+k_{A(B+C)}\int_{0.25}^{t} A\,dt$; E_{Dcalc} obtained from Table 3; $(C+D)_{calc}=9.72+k_{AC}\int_{0.25}^{t} A\,dt - E_D$; $(B+E)_{calc}=11.7+k_{AB}\int_{0.25}^{t} A\,dt + E_D$.

E_D the sum of the concentrations of $C+D+E_D$ will represent the total concentrations of products coming from the reaction A to C. We can see that the increase in this sum is first order in A with the constant $k_{AC}=0.0858$ h^{-1} (Table 4). By analogy we can conclude that the rest of E comes from B probably *via* a rapidly decomposing ester. The sum of the concentrations of $B+E-E_D$ should thus represent the total concentrations of products coming from the reaction A to B. The increase in this sum is first order in A with the constant $k_{AB}=0.0706$ h^{-1}. As expected $k_{AB}+k_{AC}$ is equal to $k_{A(B+C)}$. This, together with the good agreement between found and calculated values in Table 4, indicates that this part of the reaction scheme is correct. The rate constants for the reactions B to E and C to D cannot be calculated since the reactions are sulfonations and the rate expressions will therefore contain the concentration of a sulfonating agent which is unknown.

The phenol system

As mentioned above a compound belonging to this system is formed from A with a rate constant $k_{AL}=0.0272$ h^{-1} (Table 5). Several mechanistic models for this can be discussed. The first is that L is formed directly from A. This might be by an *ipso** attack or by some other mechanism. The quantity of L formed in this way is not sufficient to explain the increase of $[L]$ with time. L must, therefore, also be formed from K. In Table 5 this possibility is tested. From the difference between the found rate constants $k_K=0.0267$ h^{-1} for the disappearance of K and $k_{KM}=0.0142$ h^{-1} for the formation of M from K, we can calculate the rate constant k_{KL} for the formation of L from K to be 0.0125 h^{-1}. The found and calculated concentra-

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* Sulfodealkylation and alkyl rearrangement are known from the sulfonation of *tert*-butyl substituted benzenes.[6]

Table 5. Kinetic studies within the phenol system. Reaction path A to L and K to $L+M$.[a]

Time/h	K/mM	$\int_{0.25}^{t} K\mathrm{d}t$/mMh	K_{calc}/mM	M/mM	M_{calc}/mM	L/mM	L_{calc}/mM
0.25	15.5	0	—	0.36	0.22	0.58	0.25
0.5	16.0	3.9	–··	0.33	0.27	0.68	0.42
1.0	16.9	12.2	16.9	0.36	0.39	0.82	0.74
1.5	16.6	20.5	16.6	0.45	0.51	1.04	1.04
2.0	16.4	28.8	16.4	0.55	0.62	1.23	1.32
3.0	15.3	44.6	15.9	0.78	0.85	1.56	1.80
5.0	15.7	75.6	15.2	1.27	1.29	2.23	2.61
7.0	14.4	105.7	14.4	1.75	1.72	3.15	3.23
12.0	12.9	173.9	12.5	2.70	2.69	4.37	4.35
25.0	8.6	311.8	8.8	4.66	4.65	6.3	6.2

Reaction	Rate const./h^{-1}	Standard deviation/h^{-1}	Intercept/mM	Standard error of estimate/mM
Decomposition of K	$k_K = 0.0267$	0.0015	17.2	0.401
Formation of M from K	$k_{KM} = 0.0142$	0.0002	0.22	0.071
Formation of L from K	$k_{KL} = 0.0125$		0.25	
Formation of L from A	$k_{AL} = 0.0272$			

[a] $K_{\mathrm{calc}} = 17.2 - k_K \int_{0.25}^{t} K\mathrm{d}t$; $L_{\mathrm{calc}} = 0.25 + k_{KL} \int_{0.25}^{t} K\mathrm{d}t + k_{AL} \int_{0.25}^{t} A\mathrm{d}t$.

tions for the three components K, L and M agree very well apart from the two first values for K since K is formed in some unknown way at the start of the second slow phase.

The second model is that L and M are formed from K which is to some extent formed from A with the rate constant $k_{AK} = 0.0272$ h^{-1}. This contribution is called K_A and is equal to $k_{AK} \int_{0.25}^{t} A\mathrm{d}t$. If the concentrations of $K - K_A$ and L are then plotted against $\int_{0.25}^{t} K\mathrm{d}t$ we obtain $k_K = 0.0296$ h^{-1} and $k_{AL} = 0.0189$ h^{-1}, respectively, (Table 6). The fit between found and calculated concentrations for the three components K, L and M is not as good as in the previous example. Furthermore, the difference between $k_{KM} + k_{KL} = 0.0331$ and the found k_K is rather high which also is an indication against this mechanism.

A third model might be a conversion of A directly to L and M. The only difference between

this model and model 1 is the *ortho/para* ratio. We have made calculations with a ratio of 1:1 which is rather common under the present conditions.[2a] In Table 7 we can see that the agreement between found and calculated concentrations is almost as good as in model 1.

Finally there might be a model where A gives phenol and a sulfonating agent which is in equilibrium with K. From the mechanism given in a previous paper[5] this mechanism is kinetically almost equivalent to that in which A is converted to K. None of the discussed mechanisms can explain the slight increase in K at the beginning. A further discussion of the three mechanistic models will be given below.

The 4-*tert*-butylphenol system

As mentioned previously this system has a contribution from both A and F. The slight increase

Table 6. Kinetic studies within the phenol system. Reaction path A to K to $L+M$.[a]

Time/h	K/mM	$\int_{0.25}^{t} Kdt$/mMh	K_{Acalc}/mM	K_{calc}/mM	L/mM	L_{calc}/mM
0.25	15.5	0	0	–	0.58	0.72
0.5	16.0	3.9	0.12	–	0.68	0.80
1.0	16.9	12.2	0.34	16.3	0.82	0.95
1.5	16.6	20.5	0.53	16.2	1.04	1.11
2.0	16.4	28.8	0.71	16.2	1.23	1.27
3.0	15.3	44.6	0.99	16.0	1.56	1.57
5.0	15.7	75.6	1.41	15.5	2.23	2.15
7.0	14.4	105.7	1.66	14.9	3.15	2.72
12.0	12.9	173.9	1.93	13.1	4.37	4.0
25.0	8.6	311.8	2.07	9.2	6.3	6.6

Reaction	Rate const./h^{-1}	Standard deviation/h^{-1}	Intercept/mM	Standard error of estimate/mM
Decomposition of K	$k_K = 0.0296$	0.0019	16.3	0.509
Formation of L from K	$k_{KL} = 0.0189$	0.0008	0.72·	0.248
Formation of M from K	$k_{KM} = 0.0142$	0.0002	0.22	0.071

[a] $K_{Acalc}=k_{AL}\int_{0.25}^{t} Adt$; $K_{calc}=16.3+K_A-k_K\int_{0.25}^{t} Kdt$; $L_{calc}=0.72+k_{KL}\int_{0.25}^{t} Kdt$.

Table 7. Kinetic studies within the phenol system. Reaction path K to $L+M$ and A to $L+N$.[a]

Time /h	$\int_{0.25}^{t} Kdt$ /mMh	L_{Acalc} /mM	$L-L_{Acalc}$ /mM	L_{Kcalc} /mM	L_{calc} /mM	L /mM	M_{Acalc} /mM	$M-M_{Acalc}$ /mM	M_{Kcalc} /mM	M_{calc} /mM	M /mM
0.25	0	0	0.58	0.50	0.50	0.58	0	0.36	−0.01	−0.01	0.36
0.5	3.9	0.06	0.62	0.56	0.62	0.68	0.06	0.27	0.03	0.09	0.33
1.0	12.2	0.17	0.65	0.69	0.86	0.82	0.17	0.19	0.12	0.29	0.36
1.5	20.5	0.27	0.77	0.81	1.08	1.04	0.27	0.18	0.21	0.48	0.45
2.0	28.8	0.36	0.87	0.94	1.30	1.23	0.36	0.19	0.30	0.66	0.55
3.0	44.6	0.50	1.06	1.19	1.69	1.56	0.50	0.28	0.47	0.97	0.78
5.0	75.6	0.71	1.52	1.67	2.38	2.23	0.71	0.56	0.81	1.52	1.27
7.0	105.7	0.83	2.32	2.13	2.96	3.15	0.83	0.97	1.14	1.97	1.75
12.0	173.9	0.97	3.40	3.19	4.16	4.37	0.97	1.73	1.88	2.85	2.70
25.0	311.8	1.04	5.2	5.32	6.4	6.3	1.04	3.62	3.38	4.42	4.60

Reaction	Rate const./h^{-1}	Standard deviation/h^{-1}	Intercept/mM	Standard error of estimate/mM
Formation of L from K	$k_{KL} = 0.0155$	0.0005	0.50	0.133
Formation of M from K	$k_{KM} = 0.0109$	0.0008	−0.01	0.235

[a] $L_{Acalc}=\dfrac{k_{AL}}{2}\int_{0.25}^{t} Adt$; $L_{Kcalc}=0.50+k_{KL}\int_{0.25}^{t} Kdt$; $L_{calc}=L_{Kcalc}+L_{Acalc}$; $M_{Acalc}=\dfrac{k_{AL}}{2}\int_{0.25}^{t} Adt$; $M_{Kcalc}=-0.01+k_{KM}\int_{0.25}^{t} Kdt$; $M_{calc}=M_{Kcalc}+M_{Acalc}$; k_{AL} is obtained from Table 5 and distributed to an *ortho:para* ratio of 1:1.

Table 8. Kinetic studies within the 4-*tert*-butylphenol system. Reaction path H, A, F and X to I which is partially converted to J.[a]

Time/h	$\int_{0.25}^{t} H \, dt$ /mMh	H/mM	H_{calc} /mM	I_{Xcalc} /mM	I_{Hcalc} /mM	I_{Acalc} /mM	I_{Fcalc} /mM	$I+J$ /mM	$(I+J)_{calc}$ /mM
0.25	0	30.6	30.6	0	0	0	0	3.7	3.4
0.5	7.6	30.5	30.5	0.05	0.09	0.25	0.06	4.2	3.9
1.0	22.8	30.1	30.3	0.1	0.27	0.70	0.11	4.5	4.6
1.5	37.9	30.4	30.2	0.15	0.45	1.11	0.17	5.1	5.3
2.0	52.9	29.5	30.0	0.2	0.63	1.47	0.22	5.4	5.9
3.0	82.6	30.0	29.6	0.3	0.98	2.06	0.32	6.7	7.1
5.0	141.9	29.3	28.9	0.5	1.69	2.93	0.49	8.2	9.0
7.0	199.2	28.0	28.2	0.7	2.37	3.45	0.63	11.0	10.6
12.0	335.4	26.5	26.6	1.2	3.99	4.0	0.89	13.7	13.5
25.0	655.3	22.8	22.8	2.5	7.8	4.29	1.25	19.6	19.2

Reaction	Rate const./h^{-1}	Standard deviation/h^{-1}	Intercept/mM	Standard error of estimate/mM
Decomposition of H	$k_H = 0.0119$	0.0005	30.6	0.296
Formation of I from H	$k_{HI} = 0.0119$			
Formation of I from A	$k_{AI} = 0.0568$			
Formation of I from F	$k_{FI} = 0.0368$			

[a] $H_{calc} = 30.6 - k_H \int_{0.25}^{t} H \, dt$: I_{Xcalc} is obtained from the increase in sulfonated products (0.1 mmol/l h^{-1}): $I_{Hcalc} = k_{HI} \int_{0.25}^{t} H \, dt$: $I_{Acalc} = k_{AI} \int_{0.25}^{t} A \, dt$: $I_{Fcalc} = K_{FI} \int_{0.25}^{t} F \, dt$: $(I+J)_{calc} = 3.4^{b} + I_{Xcalc} + I_{Hcalc} + I_{Acalc} + I_{Fcalc}$: [b] Obtained from least square adaptation to found values.

in total yield observed with time is also probably due to the formation of a compound X belonging to this system. The assumption that X is a compound in this system is not critical to the discussions for the following reasons: Firstly, it is relatively small compared to the quantities coming from A. Secondly, if X is assumed instead to be a compound belonging to the 2-*tert*-butyl system, the total quantity of this system will be higher by the amount X and the contribution of A to the other systems will increase by the same amount X, *etc.* with almost the same net result as if X contributed directly to the 4-*tert*-butyl system.

By analogy with the phenol system two different mechanisms for the conversion of H will be considered.

The first model is that X, A and F form I directly and that this compound is also formed from H. J is formed from I by a sulfonating agent. The kinetics of the last process is unknown so the sum of $I + J$ is used in the calculations. The results are given in Table 8. The found and calculated concentrations agree very well and there are no systematic deviations.

The second mechanism is that X, A and F give H which then reacts to I and J. In this way we obtain $k_H = 0.0241$ h^{-1} (Table 9). The agreement between found and calculated concentrations is not as good as with this model as with model 1. There are also systematic deviations which indicate that the model is incorrect.

Table 9. Kinetic studies within the 4-*tert*-butylphenol system. Reaction path A. F and X to H to I which is partially converted to J.[a]

Time/h	$\int_{0.25}^{t} H\mathrm{d}t/\mathrm{mMh}$	H_{Acalc} /mM	H_{Fcalc} /mM	H_{Xcalc} /mM	$H-H_A-H_F-H_X$ /mM	H/mM	H_{calc} /mM	$I+J$ /mM	$(I+J)_{calc}$ /mM
0.25	0	0	0	0	30.6	30.6	29.5	3.7	4.4
0.5	7.6	0.25	0.06	0.05	30.1	30.5	29.7	4.2	4.5
1.0	22.8	0.70	0.11	0.10	29.2	30.1	29.8	4.5	5.0
1.5	37.9	1.11	0.17	0.15	29.0	30.4	29.9	5.1	5.3
2.0	52.9	1.47	0.22	0.20	27.6	29.5	30.1	5.4	5.7
3.0	82.6	2.06	0.32	0.30	27.3	30.0	30.2	6.7	6.4
5.0	141.9	2.93	0.49	0.50	25.4	29.3	29.9	8.2	7.9
7.0	199.2	3.45	0.63	0.70	23.2	28.0	29.5	11.2	9.3
12.0	335.4	4.0	0.89	1.20	20.4	26.5	27.5	13.7	12.7
25.0	655.3	4.3	1.25	2.50	14.8	22.8	21.7	19.6	20.6

Reaction	Rate const./h^{-1}	Standard deviation/h^{-1}	Intercept/mM	Standard error of estimate/mM
Decomposition of H	$k_H = 0.0241$	0.0016	29.5	0.963
Formation of I from H	$k_{HI} = 0.0248$	0.0014	4.4	0.864

[a] $H_{Acalc}=I_{Acalc}$ in Table 8; $H_{Fcalc}=I_{Fcalc}$ in Table 8; $H_{Xcalc}=I_{Xcalc}$ in Table 8; $H_{calc}=29.5+H_{Acalc}+H_{Fcalc}+H_{Xcalc}-k_H\int_{0.25}^{t} H\mathrm{d}t$; $(I+J)_{calc}=4.4+k_{HI}\int_{0.25}^{t} H\mathrm{d}t$.

Further comparisons of the different reaction models

In Scheme 1 we have suggested the reaction path for all identified products and in Table 10 we have also given the rate constants for their formation. We will now try to utilize these constants in a further discussion of the three reaction models.

The introduction of a *tert*-butyl group in the 4-position results in a slight decrease in the rate constant for the *ortho* rearrangement of a phenol ester. This can be seen from a comparison of the rate constants for the reaction F to G with that for the reaction A to B. We might therefore expect that the introduction of the same group into K should also give a reduction in the rate constant for the analogous reaction K to L. A comparison of the rate constants for the reaction K to L and H to I obtained with the different reaction models indicates that a decrease in the constants are observed in models 1 and 3 whereas an increase is observed in model 2. This is thus an additional reason to exclude model 2 from the discussion. Among the reactions concerning A, we want to discuss the loss

Table 10. Comparison of the rate constants obtained in the three reaction models.

Rate constant/h^{-1}	Model 1	Model 2	Model 3
k_A	0.240	0.240	0.240
$k_{A(B+C)}$	0.156	0.156	0.156
k_{AB}	0.0706	0.0706	0.0706
k_{AC}	0.0858	0.0858	0.0858
k_{AH}	—	0.0563	—
k_{AK}	—	0.0272	—
k_{AI}	0.0568	—	0.0568
k_{AL}	0.0272	—	0.0136
k_{AM}	—	—	0.0136
k_D	0.0562	0.0562	0.0562
k_F	0.0866	0.0866	0.0866
k_{FG}	0.0498	0.0498	0.0498
k_{FH}	—	0.0368	—
k_{FI}	0.0368	—	0.0368
k_H	0.0119	0.0241	0.0119
k_{HI}	0.0119	0.0248	0.0119
k_K	0.0267	0.0296	0.0267
k_{KL}	0.0125	0.0189	0.0155
k_{KM}	0.0142	0.0142	0.0109

of the alkyl group R and the introduction of SO_3H. These reactions may take place in two fundamentally different ways. In the first R is lost in one step and the SO_3H group is introduced in a second. In the other the SO_3H group is introduced and R is removed in a single concerted step. The intermediate in the first case is K or phenol. In a previous paper we have demonstrated that these two are in equilibrium.[5] Kinetically this is equivalent to a conversion of A to K which then gives L and M. As mentioned above we have excluded this possibility (model 2).

There thus remains the hypothesis where R is lost at the same time as SO_3H is introduced. Since the reaction is first order the most plausible mechanism is an *ipso* attack on the alkyl carrying carbon by the SO_3H group of the ester with a consequent loss of R. This explanation is also supported by the findings in our previous work [5] where an analogous direct rearrangement of a phenol ester to sulfonic acids has a high *ortho/para* ratio. According to this we should have the formation of L from A as suggested in model 1.

On these grounds, however, we cannot exclude other mechanisms such as an attack in the 4-position with the loss of R in the 2-position or by an *ipso* attack in the 2-position with the loss of R and a simultaneous transport of the SO_3H group to the 4-position resulting in the formation of M from A as suggested in model 3. This type of reaction seems in our opinion less probable, mainly because of the high *ortho/para* ratio for the intramolecular rearrangement of the phenol ester mentioned above.

A suggested mechanism for the reaction of chlorosulfonic acid with 2-tert-butylphenol

We will now use this picture to describe what we think happens when chlorosulfonic acid is added to 2-*tert*-butylphenol at a low temperature. Chlorosulfonic acid is a very strong acid which like other strong acids is capable of rearranging 2-*tert*-butylphenol to 4-*tert*-butylphenol.[7] At the same time some redistribution of the *tert*-butyl group occurs so that phenol and 2,4-di-*tert*-butylphenol are also obtained. Chlorosulfonic acid can also react with phenols giving aryl hydrogen sulfates and hydroxyarylsulfonic acids. With a phenol without bulky substituents in the *ortho* position the dominating

reaction is the formation of the aryl hydrogen sulfate. This is the case with phenol and 4-*tert*-butylphenol and over 90 % of these phenols are present as esters at the beginning of the second phase of the reaction. In the 2-*tert*-butyl substituted phenols the ester formation is hindered by the bulky group and ring sulfonation becomes an important side reaction. For the two phenols of this type present in the reaction mixture the 6-sulfonic acids are obtained in about half the quantity of the ester. If the 4-position is free, substitution also occurs there to about the same extent as in the 6-position. This *ortho/para* ratio of the direct sulfonation of the appropriate phenol would be expected for a reaction in such a concentrated solution as the present one.[5]

From the low initial yield of 2-hydroxybenzenesulfonic acid we can conclude that a sulfodealkylation does not occur to a substantial extent during the first rapid phase of the reaction. In the same step protodealkylation occurs to a considerable extent in good agreement with results found by Ris and Cerfontain.[6]

The slow second phase is in many respects different from the first rapid one. The concentration of phenols is very low and the *tert*-butyl group migration is different in the two phases. In the slow second phase it occurs to a much lesser extent and the total concentration of di-*tert*-butyl compounds decreases whereas these compounds are formed in the first rapid step. These facts are in agreement with the kinetic findings and indicate that phenols are not involved in the *tert*-butyl migrations which occur in the second slow step. A possible mechanism is that the ester A is rearranged with an *ipso* attack on the carbon atom carrying the 2-*tert*-butyl group. This group is either eliminated to give L from A, and I from F, or migrates to the 4-position with the formation of I from A. As mentioned previously, we can assume that such an *ipso* rearrangement should be first order in ester which is in good agreement with the experimental finding.

CALCULATIONS

The method of calculating velocity constants with the numerical integration method [3] for a complicated system is illustrated by the supposed reaction model 2 given in Scheme 2.

$$
\begin{array}{c}
B \\
\uparrow \\
H \leftarrow A \rightarrow K \nearrow^{L} \\
\downarrow \searrow_{M} \\
C
\end{array}
$$
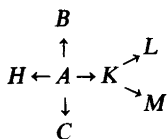
Scheme 2.

All reactions are assumed to be first order and all concentrations can be followed. For the rate of formation of K we have eqn. 1.

$$d[K]/dt = k_{AK}[A] - (k_{KL} + k_{KM})[K] \qquad (1)$$

Written in integral form this gives eqn. 2.

$$[K] - [K_o] = k_{AK} \int_0^t [A]dt - (k_{KL} + k_{KM}) \int_0^t [K]dt \qquad (2)$$

The integrals are readily obtained by numerical integration, preferably by the method given in the previous paper.[5] Eqn. 2 is thus a linear equation of the "dependent" variable $K - K_o$ and the two "independent" variables are the integrals. In principle it is possible to calculate both k_{AK} and $(k_{KL} + k_{KM})$ together with K_o directly from this equation by means of the method of least squares. The simultaneous determinations of two constants and K_o are, however, much less precise than the determination of one single constant and K_o especially if the two "independent" variables are highly correlated. In the present case we have obtained the numerical values of k_{AK} from other measurements involving A. We can now calculate $k_{AK} \int_0^t [A]dt$ at all times t. Denoting this $[K_A]$ and $k_{KL} + k_{KM} = k_K$ we obtain eqn. 3.

$$[K] - [K_A] = [K_o] - k_K \int_0^t K dt \qquad (3)$$

In this we have a linear equation of the "dependent" variable $[K] - [K_A]$ and the "independent" variable $\int_0^t [K]dt$. From this k_K and K_o are readily calculated by means of the method of least squares. The determinations of k_{KL} and k_{KM} are readily performed from the integrated rate eqns. 4 and 5.

$$M - M_o = k_{KM} \int_0^t [K]dt \qquad (4)$$

$$L - L_o = k_{KL} \int_0^t [K]dt \qquad (5)$$

If the assumptions about the reaction path are correct the experimental values for $[K]$, $[L]$ and $[M]$ should fit the equations above without significant systematic deviations. The rate constant k_K for the disappearance of K should also be equal to the sum $k_{KL} + k_{LM}$ of the rate constants for all products formed from K.

The rate constants were calculated using the method of least squares minimizing the "errors" of the concentrations. The standard deviation of the velocity constant and the standard error of estimate given should only be interpreted as a measure of fit to the curve and not as a measure of the "errors" in the constants since there may also be other errors involved.

EXPERIMENTAL

The phenols used in the sulfonation reactions were purified by distillation. The purity was found to be better than 99 % in GLC analysis on a 3 % OV 17 column. The chlorosulfonic acid was purified by distillation under reduced pressure and the dichloromethane was dried over molecular sieves. The methods for the HPLC analysis are briefly described in Ref. 2a and will be published in detail.[2b] In addition to the published method a mobile phase with three different mixtures of methanol and water *viz.* 55:45, 35:65 and 10:90, respectively, was used in this case. The reference compounds $A - M$ in these measurements were tested for water content by the Karl Fischer method and the absence of sulfate and chloride ions was established by precipitation tests with $BaCl_2$ and $AgNO_3$.

NMR measurements. The structures were established by ^1H and ^{13}C NMR analysis using a Varian CFT 20 instrument at 79.54 MHz for ^1H and 20 MHz for the ^{13}C measurements. D_2O was used as solvent and 3-trimethylsilyltetradeuteriopropionate and dioxane, respectively, as internal standards. The assignments in the ^{13}C spectra were based on comparisons with calculated shift values,[8] together with the fact that carbon atoms carrying a substituent give peaks with strongly reduced intensities. The found and calculated values coincided and had a standard deviation of 1.60 ppm. The chemical shift factors for the $-OSO_3^-$ group are given in Ref. 2a. NMR data are given in Tables 11 and 12.

Sulfonation of 2-tert-butylphenol with chlorosulfonic acid. A 250 ml three-necked flask was dried

Table 11. ^{1}H NMR data of compounds $A - M$.

Compound	Chemical shift. δ
A	7.65 − 7.17 (4 H. m). 1.39 (9 H. s).
B	7.59 − 7.42 (2 H. m). 6.94 (1 H. dd. *J*. 7.7 and 0.2 Hz). 1.39 (9 H. s).
C	7.73 (1 H. d. *J* 2.3 Hz). 7.53 (1 H. dd. *J* 8.3 and 2.4 Hz). 6.91 (1H. d. *J* 8.3 Hz). 1.39 (9 H. s).
D	7.84 (1 H. m). 7.67 (2 H. m). 1.42 (9 H. s).
E	7.96 (1 H. d. *J* 2.3 Hz). 7.85 (1 H. d. *J* 2.3 Hz). 1.42 (1 H. s).
F	7.51 (1 H. d. *J* 2.5 Hz). 7.44 − 7.29 (2 H. m). 1.31 (9 H. s). 1.17 (9 H. s).
G	7.60 − 7.51 (2 H. m). 1.38 (9 H. s). 1.27 (9 H. s).
H	7.52 (2 H. d. *J* 9 Hz). 7.24 (2 H. d. *J* 9.1). 1.30 (9 H. s).
I	7.72 (1 H. d. *J* 2.5). 7.53 (1 H. dd. *J* 8.6 and 2.5). 6.95 (1 H. d. *J* 8.4). 1.29 (9 H. s).
J	7.91 (1 H. m). 7.64 (2 H. m). 1.32 (9 H. m).
K	7.39 (5 H. m).
L	7.49 − 6.85 (4 H. m).
M	7.70 (2 H. d. *J* 8.9). 6.96 (2 H. d. *J* 8.9).

Table 12. ^{13}C NMR data of compounds $A - M^a$.

Compound	Chemical shift. δ							
	C-1	C-2	C-3	C-4	C-5	C-6	C-α	C-CH$_3$
A	150.8	141.0	(127.8)	(125.5)	(127.6)	120.2	35.2	30.7
B	128.3	152.7	139.2	131.2	120.3	125.8	35.4	29.7
C	134.5	(125.2)	137.6	158.2	117.1	(125.4)	34.9	29.4
D	153.6	142.2	(125.3)	139.4	(125.6)	120.5	35.1	29.9
E	128.2	155.5	140.5	128.2	134.1	123.4	35.6	29.3
F	(147.9)	140.4	124.6	(149.5)	124.6	120.2	35.2 / 34.9	31.8 / 30.6
G	127.6	150.3	139.0	128.4	143.3	122.0	35.6 / 34.6	31.2 / 29.6
H	(149.5)	121.6	127.2	(150.0)	127.2	121.6	34.5	31.3
I	127.5	151.0	117.5	131.2	144.1	124.6	34.1	31.1
J	146.8	133.4	125.9	148.9	130.3	120.4	34.6	31.1
K	151.8	122.1	130.4	126.9	130.4	122.1		
L	128.3	153.5	117.1	134.1	120.8	128.3		
M	135.2	128.3	116.2	159.0	116.2	128.3		

^{a} Similar values in parentheses may be interchanged.

at 120 °C overnight and then filled with argon whilst cooling. Then 16.5 g (0.11 mol) of 2-*tert*-butylphenol was added, dissolved in 83.5 ml dried dichloromethane and cooled below − 35 °C during magnetic stirring. Next. 14.2 g (0.121 mol) of chlorosulfonic acid. dissolved in 10 ml dried dichloromethane in a dropping funnel, was added at such a rate that the temperature never exceeded − 35 °C. After

about 10 min when the addition was completed. the reaction flask was placed in a cryostat at − 30 °C. The volume of the mixture at this temperature was determined to be 110 ml in a separate experiment. As soon as the mixture had reached − 30 °C (after about 5 min) a 10 ml sample was taken out with a cooled pipette and immediately poured into an ice-cooled solution of 19 ml 1 M KOH and 15 ml

water. The pH .was adjusted to 6.5 within less than 1 min. The organic layer was separated and the aqueous layer extracted with 2×25 ml dichloromethane. The combined organic layers were washed with a 5 ml portion of water to compensate for incomplete separation The combined aqueous layers were adjusted to pH 7, diluted to 100 ml in a volumetric flask and kept in a refrigerator overnight until HPLC analysis was performed. Nine other 10 ml samples were taken out at different times and treated in the same way (Table 1).

The organic layers were analyzed by GLC and found to contain phenol, 2-*tert*-butylphenol, 4-*tert*-butylphenol and 2,4-di-*tert*-butylphenol. The total amount of phenols in each sample varied between 2.1 and 6.3 mg (about 0.1 − 0.4 per cent of the total quantity taken). The main product was 4-*tert*-butylphenol but the deviation in the measured concentrations was too large to make it possible to draw any conclusions about the variations in concentration for each phenol.

Sulfonation of 2,4-di-tert-butylphenol with chlorosulfonic acid. 2,4-Di-*tert*-butylphenol, 10.3 g (0.05 mol) was sulfonated with 6.3 g (0.054 mol) chlorosulfonic acid in a procedure similar to that of 2-*tert*-butylphenol After 2 h at − 30 °C the temperature was allowed to rise to room temperature over 4 h. A sample of the reaction mixture was worked up according to the method described and analyzed by HPLC. The main products were sulfonic acid *I*, 49 %, and *G*, 42 %. Products such as *C* and *M*, which could have been formed by a loss of the 4-*tert*-butyl group and sulfonation at the same position, were formed in amounts of less than 0.2 %

Preparation of the reference compounds B, C, I and E. The appropriate *tert*-butylphenol, 15 g (0.1 mol) was dissolved in 100 ml dichloromethane and added dropwise during magnetic stirring at − 20 °C. The mixture was allowed to stand for about 2 h while the temperature rose to room temperature. Fifty ml of ice-water was then added with magnetic, stirring and the organic layer was separated. Next the sulfonic acid with an *ortho*-hydroxy group was extracted from the acid water layer as an ion pair with an appropriate aminium ion. The choice of amine and solvent was made in accordance with the principles given in Ref. 1. In this case *N,N*-dimethylaniline and dichloromethane were used. A 0.5 M solution of potassium hydroxide was added to the organic layer until pH 6.5 was reached. The organic layer was separated and the aqueous layer was washed twice with dichloromethane in order to extract the liberated amine. The aqueous layer was then evaporated under reduced pressure and the residue was crystallized from methanol or ethanol until no sulfate or chloride ions could be detected. The yield of *I* was 82 %. The yield of *B* was considerably lower because of several side reactions.

The sulfonic acid with a *para*-hydroxy group and the disulfonic acid *E* were left in the primary acid water layer. These acids were extracted with dichloromethane in the form of ion pairs with tripropylamine. The organic layer was neutralized to pH 9.2 with 0.5 potassium hydroxide solution and the work-up procedure was analogous to *I*. *C* and *E* were separated by recrystallization from ethanol.

Preparation of the compounds L *and* M. These substances were prepared by the same procedure as above. The work-up procedure for *M* was, however, performed in a different way. After the *ortho*-sulfonic acid *L* had been extracted as an ion pair, the acid water layer contained mainly *M*. This acid was too hydrophilic to be separated from the sulfuric acid by extraction as an ion pair using conventional methods and therefore the water layer was neutralized and evaporated to dryness. The crystalline mixture was then treated with methanol in a soxhlet extractor in order to separate the sulfonate from the inorganic salts. After recrystallizations from a methanol-water mixture a pure sample of *M* was obtained.

Preparation of compound G. The synthesis of this compound was performed according to Ref. 9.

Preparation of the sulfuric acid esters A, F, H *and* K. A general procedure is given in Ref. 10.

Preparation of the sulfuric acid esters J *and* D. The potassium salt of sulfonic acid *C* or *I*, 2.9 g (11 mmol) was dissolved in 40 ml dry pyridine. Chlorosulfonic acid, 1.4 g (13 mmol) was added dropwise during magnetic stirring and the temperature was kept at about 5 °C during the addition and then raised to to 55 °C for 4 h. The reaction mixture was then cooled and poured into 30 ml 1 M potassium hydroxide. The pH was adjusted to 7.5 and the pyridine was extracted with four 50 ml portions of tetrachloromethane. The remaining water layer was evaporated to dryness and treated four times with 15 ml boiling methanol. Ethanol was then added and the organic salts were filtered off. Cooling and crystallization yielded 1.9 g ester.

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