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Sulfonation of the Naphthalene Derivatives in Protic Solvent. Principles of Isomer Distribution

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The principles of formation of mono- and disulfonation products of selected derivatives of naphthalene in protic solvents were studied. The position of electrophilic substitution was compared with: localization energies (L^+) of the parent compounds; steric effect of methoxy groups; partial charges on carbon atoms in aromatic ring; dipole moment (μ) and the binding energies of the products (D). These results suggest that only steric hindrance and the binding energy of the sulfonation products of naphthalene derivatives in protic solvents may be a good prognostic index for isomer distribution substitution products.

Key words: naphthalene derivatives, sulfonation products

The mechanism of sulfonation of mono- and disubstituted methyl and methoxy derivatives of naphthalene (MN – methylnaphthalene; DMN – dimethylnaphthalene; MON – methoxynaphthalene; DMON – dimethoxynaphthalene) was studied thoroughly in anhydrous environment. The results obtained in aprotic solvents have been repeatedly compared with earlier effects of sulfonation of the same substrates in concentrated sulfuric acid. In the majority of cases, the products of mono- and disulfonation for the same substrates proved different (see Table 1). The effect of electronic and steric requirements of present substitutes on the type of obtained sulfonation products of MN, DMN, MON and DMON and their monosulfonic derivatives has been studied. In the majority of cases, it was stressed that steric hindrance, caused by preferred conformation of existing substitutes, affects the type of obtained products rather than the electronic directing effect caused by them [1–5]. The study should also establish the relation between the localization energy (calculated by Hückel molecular orbitals method) and the type of obtained sulfonation products in anhydrous solvents. Provided that allowance is made for the specific steric hindrance, the substitution patterns are in agreement with the localization energy [3,7]. The results of monosulfonation of MON and DMON derivatives in anhydrous environment were described [7,8] as generally consistent in relation to the position of sulfonic group, with results obtained with other electrophilic substitution reactions. Both reactivity and steric effect caused by the presence of substituents are greater in the case of methoxy derivatives than in similar compounds with methyl substituents [9,10]. Earlier observation of the sulfonation products of naphthalenesulfonic acids showed that introduction of the second sulfonic acid group is very rare in a substituted ring. Mesomeric deactivating effect of sulfonic acid substituent causes that the reactivity

of position C(2n) should be, thus, greater than C(1+2n) [11]. It was also found [12,13], that the methoxy groups in MONs and DMONs tend to the position in naphthalene ring plane and have conformation *cis* with a bond C(α)–C(β). They are in single-*cis* orientation with the bond that has the highest π-character. Chemical proof for the presence of a steric hindrance is isomerization of 1,3-dimethoxynaphthalene-4-sulfonic acid (1,3-DMON-4-S) to 1,3-DMON-7-S. The rearrangement results in a thermodynamically more stable compound [7]. This effect is probably due to a lower proton reactivity in dioxane as compared to nitromethane as solvent. Among literature reports there is no information on sulfonation of β,β-DMONs in the concentrated sulfuric acid. The principles of formation of mono- and disulfonation products of naphthalene derivatives in protic solvents was also not found. These studies are complementary to earlier reports on electrophilic substitution of naphthalene derivatives.

RESULTS AND DISCUSSION

Sulfonation of 2,3-, 2,6-, and 2,7-DMON in the concentrated sulfuric acid, which is the subject of this and our earlier papers [14–16], leads to the formation of mono- and disulfonic products. The reaction at room temperature gave initially products of monosulfonation: 2,3-dimethoxynaphthalene-5-sulfonic acid (2,3-DMON-5-S) and 2,3-dimethoxynaphthalene-6-sulfonic acid (2,3-DMON-6-S) in quantitative ratio 1:2; 2,6-dimethoxynaphthalene-4-sulfonic acid (2,6-DMON-4-S); 2,7-dimethoxynaphthalene-3-sulfonic acid (2,7-DMON-3-S). Further sulfonation of the obtained monosulfonic derivatives gave: 2,3-dimethoxynaphthalene-5,7-disulfonic acid (2,3-DMON-5,7-S_2); 2,6-dimethoxynaphthalene-4,7-disulfonic acid (2,6-DMON-4,7-S_2); 2,7-dimethoxynaphthalene-3,6-disulfonic acid (2,7-DMON-3,6-S_2). The products of sulfonation were different than those obtained in aprotic environment [7] (Table 1). The results of our studies are in agreement with those of other authors [1–13,17–20], on differentiation of sulfonation products in protic environment of sulfuric acid and in aprotic environments. This differentiation is both qualitative and quantitative, except for the derivative 2,3-DMON.

These differences may be due to the rearrangement of derivatives substituted in positions most reactive into those, which are more thermodynamically stable. Such course of sulfonation of DMON derivatives in protic solvent may be confirmed by the fact that usually only one product is obtained. It may also be observed that products of sulfonation of DMON derivatives in concentrated sulfuric acid do not conform to schemes of electrophilic substitution preferences. Reactivity of particular positions in a π-electron molecule may be determined by calculation of the energy of activation for the reaction of substituent binding in the position studied. The substitution type reactions would occur at such position of the molecule, in which the localization energy – L^+ (calculated by Hückel molecular orbitals method) is smallest. Literature data on localization energy calculated by Hückel molecular orbitals method for derivatives β,β-DMON [7] were used to compare the reactivity of particular positions of electrophilic substitution in naphthalene ring eight products of reaction of these substrates with concentrated sulfuric acid. The results are presented in Table 2.

Table 1. Position of sulfonic groups in mono- and disulfonic derivatives MN, MON, DMN, DMON.

Substrate	Reaction solvent	Products of monosulfonation (%)	Products of disulfonation (%)	Reference
1,3-DMOB(**)	K	4(*)	4.6(*)	4
1-MN	N	4(95)	2.4(53); 4.6(5); 4.7(42)	3
2-MN	N	1(8); 4(15); 5(15); 6(14); 8(49)		3
1,2-DMN	N	4(98)	4.6(51); 4.7(49)	3
	K	4(*)		17
1,3-DMN	N	4(80); 5(12); 7(8)	4.6(3); 4.7(81); 5.7(16)	3
1,4-DMN	N	2(87); 6(13)	2.6(6); 2.7(92)	3
1,5-DMN	N	2(50); 3(50)	2.6(7); 2.7(88)	3
1,6-DMN	N	4(97)	2.4(91); 4.7(9)	3
	K	4(*)		17
1,7-DMN	N	4(9)	2.4(80); 4.6(18)	3
	K	4(*)		17
1,8-DMN	N	4(95)	1.4(20); 4.7(80)	3
2,3-DMN	N	1(7); 5(70); 6(21)	1.5(13); 1.6(25); 1.7(8); 5.7(54)	3
	K	6(*)		18
2,6-DMN	N	1(22); 4(74)	1.5(13); 4.7(10); 4.8(77)	3
	K	1(*)		19
	K	4(*)		20
2,7-DMN	N	1(47); 3(34); 4(19)	1.5(33); 1.6(47); 3.5(12); 3.6(8)	3
	K	3(*)		19
1-MON	N	4(>99)	2.4(58); 4.7(42)	7
2-MON	N	1(>99)	1.6(>99)	7
1,2-DMON	N	4(>99)	4.6(95); 4.7(5)	7
1,3-DMON	N	4(69); 7(18) – after 5 min.; 7(>99) – after 95 min.		7
1,4-DMON	N	2(>99)	2.6(80); 2.7(20)	7
1,5-DMON	N	4(>99)	4.8(>99)	7
1,6-DMON	N	4(>99)	2.4(91); 4.7(9)	7
1,7-DMON	N	4(>99)	2.4(8); 4.6(1); 4.8(56)	7
2,3-DMON	N	6(38)	5.7(>99)	7
	D	5(27); 6(73)		
	K	5 and 6 (in ratio 1:2)	5.7 (*)	16
2,6-DMON	N	1(>99)	1.5(>99)	7
	K	4(*)	4.7(*)	15
2,7-DMON	N	1(53); 3(47)	1.6(>99)	7
	K	3(*)	3.6(*)	14

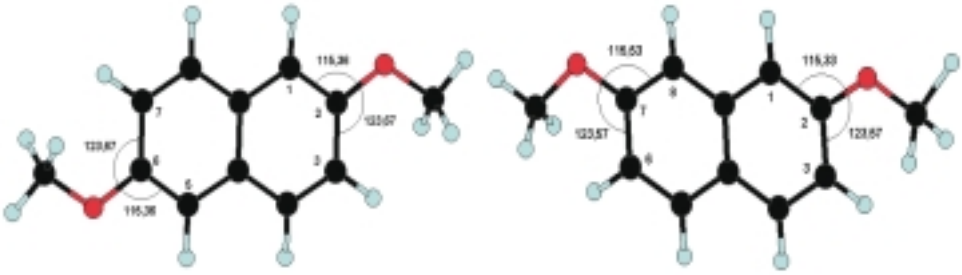
(*) – as main product; K – concentrated sulfuric acid; N – nitromethane; D – dioxane.
(**) – DMOB – dimethoxybenzene.

Table 2. Comparison of the cation-localization energies L^+ for all potential places of electrophilic substitution in derivatives β,β-DMON and products of the reaction in concentrated sulfuric acid.

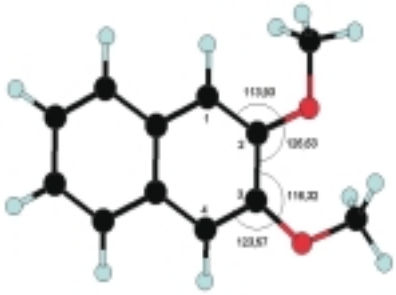
Substrate	Ring position							
	1	2	3	4	5	6	7	8
2,3-DMON	1.5972			1.5972	**1.8946**	**2.2298**	1.8946	2.2298
2,6-DMON	1.5908		1.9364	**1.8964**	1.5908		1.9364	1.8964
2,7-DMON	1.5450		**1.8466**	2.0104	2.0104	1.8466		1.5450

The mono-sulfonic derivatives obtained in protic environment are highlighted in bold print, and the lowest values of energy of location are underlined.

The positional order of substitution for the monosulfonation of given substrates is not in agreement with that predicted by the localization energies in any of the cases. Thus, we came to the conclusion that calculations of the localization energy do not give any information as to the prognostic factor in this case. For determination of steric effects in DMONs, their spatial structures were obtained. All calculations were done using the programme HyperChem®5.0, by semi-empirical method AM1 [21–22] with the exactness of 0.01 kcal/mol. Geometric optimization gives spatial structures, which confirm results on other methoxy derivatives of naphthalene obtained from ^{1}H NMR studies [7]. Methoxy groups are places in the plane of naphthalene ring, and the oxygen atom is directed towards the bond of highest π-character. The only exception here is the group 3-OCH_3 in derivatives 2,3-DMON (see Table 3.) Character of non-saturated bonds is seen in their calculated length: for the bond C(α)–C(β) – within 1.3775–1.3876 Å; for the bond C(β)–C(β) – within 1.4105–1.4381 Å. The angle between bonds O–C(β)–C(α) is smaller: 113.93°–115.65° than the angle between O–C(β)–C(β): 123.31°–126.63°.



2,6-DMON 2,7-DMON



2,3-DMON

Figure 1. Spatial structures of β,β-DMONs determined by AM1 method.

Table 3. Length of bonds formed by carbon atom combined with methoxy group in aromatic ring and angles between these bonds and the bond H_3CO–C(n) for β,β-DMONs and their monosulfonic derivatives.

Compound	Length of bond atoms in position C(n) [Å]							
	1–2		2–3	3–4	5–6	6–7	7–8	
2,3-DMON	1.3850		1.4347	1.3796				
2,3-DMON-5-S	1.3787		1.4372	1.3794				
2,3-DMON-6-S	1.3834		1.4381	1.3775				
2,6-DMON	1.3848		1.4211		1.3848	1.4211		
2,6-DMON-4-S	1.3876		1.4105		1.3860	1.4223		
2,7-DMON	1.3851		1.4215			1.4215	1.3851	
2,7-DMON-3-S	1.3863		1.4290			1.4253	1.3853	
Compound	**Angles between bonds (n) – position in the ring**							
	1–2–O	O–2–3	2–3–O	O–3–4	5–6–O	O–6–7	6–7–O	O–7–8
2,3-DMON	113.93	126.63	116.32	123.57				
2,3-DMON-5-S	116.42	123.96	115.50	124.22				
2,3-DMON-6-S	115.40	124.73	115.65	124.21				
2,6-DMON	115.36	123.67			115.36	123.67		
2,6-DMON-4-S	115.50	124.15			115.23	123.57		
2,7-DMON	115.33	123.57					123.57	115.33
2,7-DMON-3-S	114.77	123.31					123.49	115.39

The steric effect of these substituents may explain the lack of products of sulfonation in position C(1) in every case. This effect eliminates as well positions C(5) and C(8) for 2,3-DMON and C(1) and C(8) for 2,7-DMON, which are inaccessible for sulfonation. The principles of electrophilic substitution in aromatic compounds containing equal carbon atoms state, that electrophilic reagent attacks the carbon atom in the ring, which carries the greatest negative charge. Thus, we have determined the charges of aromatic carbon atoms of the substrates of both mono- and disulfonation described in this study. Numerical data from calculations used are presented in Table 4.

Table 4. Calculated value of electrical charge on carbon atoms of naphthalene rings in substrates for sulfonation.

Substrate	Ring position							
	1	2	3	4	5	6	7	8
2,3-DMON	–0.144			–0.178	**–0.118**	**–0.129**	–0.129	–0.115
2,3-DMON-6-S	–0.157			–0.166	0.037		–0.035	**–0.133**
2,3-DMON-5-S	–0.120			–0.222		0.014	**–0.179**	–0.026
2,6-DMON	–0.146		–0.174	**–0.093**	–0.149		–0.174	–0.093
2,6-DMON-4-S	–0.063		–0.026		–0.202		**–0.185**	–0.076
2,7-DMON	–0.167		**–0.194**	–0.075	–0.075	–0.194		–0.167
2,7-DMON-3-S	–0.174			0.040	–0.056	**–0.198**		–0.187

The reaction products obtained in concentrated sulfuric acid are highlighted in bold print, and the position of carbon atom with greatest negative charge is underlined.

As can be seen from the results of the study, correlation between the place of substitution with sulfonic acid group and position of the greatest negative charge cannot be observed (apart from 2,7-DMON derivatives). Lack of effect of substitution by sulfonic acid group in these positions can be explained by steric hindrance, caused by the presence of methoxy group, which is consistent with observations of other authors [4]. The position of the greatest negative charge is not the prognostic factor for the place of sulfonation in protic environment.

Next we have assumed that the reason of obtaining such products of sulfonation may be in this case stability of the sulfonic products formed. The stability of chemical molecules reaches the maximum in the energetic minimum for a given molecule. The minimum of the potential energy (W_p) of a given molecule is equal to the dissociation energy or binding energy (D). The values of D may be regarded directly proportional to the stability of molecules. Also, dipole moment (μ) of the molecule may be regarded an index of stability of molecule, as it shows uneven distribution of electronic properties, which enhances interactions with the environment. To explain the formation of specific sulfonation products of naphthalene derivatives by their thermodynamic stability, the parameters D and μ were investigated for all theoretically possible monosulfonic derivatives of the DMONs studied and all theoretically possible products of sulfonation of monosulfonic derivatives obtained during synthesis [14–16]. To draw more general conclusions, the study also included other products of sulfonation of aromatic derivatives in protic environment described in [3–4,7,19–20,23]. The study was based on theoretical calculations (programme HyperChem ®) after geometric optimization. The parameters determined are presented in Table 5.

Table 5. Calculated value of binding energy [D] and dipole moment [μ] of DMON, DMN and DMOB derivatives.

Product	D [kcal/mol]	μ	Product	D[kcal/mol]	μ
2,3-DMON-1-S	–3185.94	6,84	1,3-DMOB-2-S	–2421.14	6.60
2,3-DMON-5-S	–3190.53	2,74	**1,3-DMOB-4-S**	**–2426.97**	**7.01**
2,3-DMON-6-S	**–3191.92**	**5,90**	1,3-DMOB-5-S	–2423.91	5.07
2,3-DMON-5,1-S_2	–3547.86	3,64	1,3-DMOB-4,2-S_2	–2778.88	3.80
2,3-DMON-5,4-S_2	–3469.96	4.76	1,3-DMOB-4,5-S_2	–2775.16	6.68
2,3-DMON-5,6-S_2	–3542.72	6.03	**1,3-DMOB-4,6-S_2**	**–2785.44**	**7.28**
2,3-DMON-5,7-S_2	**–3553.36**	**4.88**	2,3-DMN-1-S	–3007.96	4.87
2,3-DMON-5,8-S_2	–3545.83	4.12	2,3-DMN-5-S	–3012.36	4.94
2,3-DMON-6,1-S_2	–3549.72	7.12	**2,3-DMN-6-S**	**–3014.85**	**5.83**
2,3-DMON-6,4-S_2	–3540.75	7.04	2,6-DMN-1-S	–3010.11	4.76
2,3-DMON-6,7-S_2	–3547.52	8.92	2,6-DMN-3-S	–3013.87	5.17
2,3-DMON-6,8-S_2	**–3553.36**	**4.88**	**2,6-DMN-4-S**	**–3012.43**	**4.78**
2,6-DMON-1-S	–3188.99	4.90	2,7-DMN-1-S	–3010.13	4.58
2,6-DMON-3-S	–3187.91	6.12	**2,7-DMN-3-S**	**–3013.83**	**5.32**
2,6-DMON-4-S	**–3189.41**	**4.76**	2,7-DMN-4-S	–3012.35	4.95
2,6-DMON-4,1-S_2	–3543.88	2.42	1,3-DMON-2-S	–3186.96	4.64
2,6-DMON-4,3-S_2	–3538.20	9.35	1,3-DMON-4-S	–3186.95	5.18
2,6-DMON-4,5-S_2	–3476.46	5.57	1,3-DMON-5-S	–3192.43	3.99
2,6-DMON-4,7-S_2	**–3551.81**	**4.02**	1,3-DMON-6-S	–3193.85	5.99
2,6-DMON-4,8-S_2	–3546.99	2.63	**1,3-DMON-7-S**	**–3195.82**	**6.51**
2,7-DMON-1-S	–3188.90	7.22	1,3-DMON-8-S	–3189.24	5.50
2,7-DMON-3-S	**–3189.0**	**5.97**	1,3-DMON-7,2-S_2	–551.04	4.76
2,7-DMON-4-S	–3189.52	2.49	1,3-DMON-7,4-S_2	–3551.40	5.97
2,7-DMON-3,1-S_2	–3547.24	7.61	**1,3-DMON-7,5-S_2**	**–3564.40**	**5.79**
2,7-DMON-3,4-S_2	–3539.60	7.45	1,3-DMON-7,6-S_2	–3548.05	10.04
2,7-DMON-3,5-S_2	–3545.90	5.60	1,3-DMON-7,8-S_2	–3542.05	7.42
2,7-DMON-3,6-S_2	**–3550.69**	**3.67**			
2,7-DMON-3,8-S_2	–3547.00	7.32			

The reaction products obtained are highlighted in bold print, and the lowest values of the binding energy and dipole moment are underlined.

The results obtained indicate that mono- and disulfonic derivatives, obtained during experiments (apart from 2,7-DMON-3-S), show the lowest binding energy. The same observation was noted for DMOB, DMN and DMON derivatives obtained by other authors [3–4,7,19–20,23]. In the case of 2,7-DMON, the difference in reactivity of positions C(3) and C(4) connected with negative charge on carbon atoms is significant (–0.194 and –0.075, respectively), which shows that the position C(3) is preferred in electrophilic substitution. The angles between bonds C(1)–C(2)–O (115.33°) and O–C(2)–C(3) (123.57°) in 2,7-DMON (see Table 3) show an evident steric effect of methoxy group on substitution in C(1), and not C(3) position. This is probably the reason, why there is no effect of transformation 2,7-DMON-3-S into stable 4-S derivative.

We did not observe any correlation between the parameter μ and the tendency to form mono- and disulfonic derivatives described, obtained in concentrated sulfuric acid at room temperature. Thus, the results obtained confirm the hypothesis that steric effects and thermodynamic stability of the sulfonation products of group of aromatic compounds, formed in protic environment, expressed as binding energy, may be a good prognostic indicator for substitution effects. It is a more unequivocal sign than determinations based on the reactivity of particular positions in aromatic ring for the reaction of electrophilic substitution.

REFERENCES

1. Cerfontain H., Coenjaarts N. and Koeberg-Telder A., *Rec. Trav. Chim. Pays-Bas*., **108,** 7 (1989).
2. Ansink H. and Cerfontain H., *Phosphorus, Sulfur and Silicon,* **63**, 335 (1991).
3. Lammertsma K. and Cerfontain H., *J. Chem. Soc. Perkin Trans*., *2*, 673 (1979).
4. Cerfontain H. and Koeberg-Telder A., *Rec. Trav. Chim. Pays-Bas*., **107**, 543 (1988).
5. Kresge A., Chang Y. and Hakka L., *J. Am. Chem. Soc*., **93**, 6167 (1971).
6. Paul M. and Long F., *Chem. Rev*., **57**, 1 (1957).
7. Ansink H., Graaf E., Zelvelder E. and Cerfontain H., *Rec. Trav. Chim. Pays-Bas*., **111**, 499 (1992).
8. Font J., Messeguer A.,Serratosa F., Sala P. and Villarosa L., *An. Quim*., **72**, 247 (1976); *C.A*. **86**; 55193w (1977).
9. Nishino H., Tsunoda K. and Kurosawa K., *Bull. Chem. Soc. Jpn*., **62**, 545 (1989).
10. Ferlin M., Chiarelotto G. and Malesani G., *Heterocycl. Chem*., **26**, 245 (1989).
11. Cerfontain H., *J. Org. Chem*., **47**, 4680 (1982).
12. Seita J., Sandstrom J. and Drakenberg T., *Org. Magn. Res*., **11**, 239 (1978).
13. Herndon W., *J. Am. Chem. Soc*., **96**, 7605 (1974).
14. Cisak A. and Kusztal D., *Polish J. Chem*., **71**, 40 (1997).
15. Cisak A., Kusztal D. and Brzezińska E., *Acta. Polon. Pharm*., **57**, 299 (2000).
16. Cisak A., Kusztal D. and Brzezińska E., *J. Chem. Soc., Perkin Trans., 2*, 538 (2001).
17. Kruber O. and Schade W., *Chem. Ber.*, **69**, 1722 (1936).
18. Haworth R. and Bloom F., *J. Chem. Soc*., 2248 (1932).
19. Weissgerber R. and Kruber O., *Chem. Ber.*, **52**, 346 (1919).
20. Fieser L., *J. Am. Chem. Soc*., **55**, 4977 (1933).
21. Dewar M., Zoebisch E., Healy E. and Stewart J., *J. Am. Chem. Soc*., **107**, 3902 (1985).
22. Leach A., *„Molecular Modelling. Principles and Applications"* Addison Wesley Longman Ltd., 90–104 (1998).
23. Coulsen E., *J. Chem. Soc*., 1305 (1938).