Sulfonation of a Series of Bromo- and Methylphenanthrenes with Sulfur Trioxide[1]

Hans Cerfontain,* Ankie Koeberg-Telder, Khosrow Laali, and Hans J. A. Lambrechts

Laboratory for Organic Chemistry, University of Amsterdam, Nieuwe Achtergracht 129, 1018 WS Amsterdam, The Netherlands

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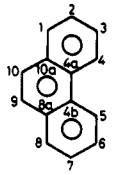
The sulfonation of a series of methylphenanthrenes (MPs) and two bromophenanthrenes with SO_3 in nitromethane has been studied at 0 °C. From the substitution pattern it is evident that steric factors play an important role. Substitution of the 4- and 5-H peri to the methyl does not occur, and that ortho to the 9-methyl is severely reduced. Provided that allowance is made for the steric factors, the positional order of substitution for monosulfonation of a given (methyl)phenanthrene is in agreement with that predicted by the localization energies, calculated by a simple Hückel MO treatment. The position of substitution of the second sulfo group is governed by two factors, viz., the positional localization energies of the starting MP (which will lead to symmetrical disulfonic acids) and the directing effect of the first (pyro)sulfonic acid group (leading to asymmetrical disulfonic acids). The latter factor is only apparent when the difference in localization energy for the positions of substitution under question of the starting MP are not too large. The formation of *di*sulfonic acids with 2,4,5,7- and 3,4,5,6-TMP when 1 equiv of SO_3 is used is ascribed to a mixing–disguised substrate selectivity, as a result of the very high reactivities of both the given TMP and its monosulfonic acid toward SO_3.

Phenanthrene (1) is an intriguing polycyclic aromatic



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hydrocarbon. X-ray studies revealed slight distortions from complete coplanarity due to steric overcrowding.[2] In fact, the distance between the 4- and 5-H is below the van der Waals distance, and the distortion in the phenanthrene molecule is attributed to this close proximity.[3] The bond order is highest for C_9–C_{10} (0.80), lowest for C_{4a}–C_{4b} (0.20), 0.40 for C_1–C_{10a}, C_2–C_3, C_4–C_{4a}, and C_{4a}–C_{10a}, and 0.60 for the remaining C–C bonds.[4] The relative positional reactivities for the electrophilic substitution of phenanthrene were examined.[5-8] In general they follow the theoretical prediction, considering the 4- and 5-positions to be unreactive due to steric hindrance for substitution. For protiodetritiation which does not suffer from any appreciable steric hindrance[9] the observed reactivity order is 9 > 1 > 4 > 3 > 2,[8] which agrees with that predicted by the localization energies L_r^+.[10] The H_2SO_4 sulfonation of phenanthrene at 60 °C is reported to give mainly the 9- and 1-sulfonic acids, as well as some 2- and 3-sulfonic acids.[5] However, at higher temperatures (120–130 °C), only the 2- and 3-isomers were obtained.[5] In nitration with nitric acid the formation of 9-nitrophenanthrene as well as 2- 4-, and a small amount of 3-nitrophenanthrene was reported.[6] A nitration study by Dewar using acetyl nitrate, however, gave the 9-, 1-, 3-, 2-, and 4-nitro derivatives in order of decreasing yield.[7] Theoretical calculations predict that in 9-bromo- and 9-chlorophenanthrene the electrophilic attack at the 10-position is favored,[11] and, indeed, nitration of 9-bromophenanthrene in HNO_3·AcOH is reported to give the 10-nitro derivative.[12] The sulfonation of 9-bromophenanthrene in 96% H_2SO_4 at 90 °C followed by catalytic hydrogenation afforded phenanthrene-2- and -3-sulfonic acids in a ratio of 1:4.[13] In benzoylation of phenanthrene in CS_2 as a solvent, only the 1-benzoyl derivative was obtained, whereas in nitrobenzene as the solvent the 3-isomer predominated, and, in addition, the 1- and 2-isomers were also formed.[14] The question of reversibility of sulfonation and acylation was then raised by Gore.[14] He suggested that "when a substituent has entered the meso position, it will cause interference to, and will therefore be twisted out of the aromatic plane by the peri hydrogen. This is the position in particular where the entering group is a bulky solvated sulfonic acid group or an aluminum chloride complexed acyl group. This out-of-plane distortion appreciably lowers the resonance stabilization, possibly below those of the isomers with the substituents at the unhindered positions, and proton catalyzed rearrangement may therefore proceed." Recently, Newman[15] showed that the rate of bromine addition to 4,5-DMP and 2,4,5,7- and 3,4,5,6-TMP[16] to form the corresponding 9,10-dibromo-9,10-dihydro derivatives is faster than that of phenanthrene itself. This rate enhancement was suggested to be due to enhanced noncoplanarity forced by the methyls at the 4- and 5-positions. An interesting study on protiodetritiation of the same 9-(tritiomethyl)phenanthrenes by Taylor[17] showed that for 2,7- and 3,6-DMP there is excellent agreement between

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the observed and the calculated rates, but for 4,5-DMP the observed rate is significantly larger than the calculated one, because of twisting of the phenanthrene framework caused by the two adjacent methyls. 3,4,5,6-TMP will be more severely distorted than the 2,4,5,7-isomer because of buttressing by the two methyls at the 3- and 6-positions. Therefore, the former isomer is expected to be more reactive than the latter. However, it is, in fact, less reactive due to inhibition of hyperconjugative stabilization of the σ complex for 9-substitution by the 3-methyl, as a result of steric hindrance by the adjacent methyl at position 4. Very recently, the sulfonation of 4,5-methanophenanthrene with both acetyl sulfate and chlorosulfuric acid was reported to yield mainly the 1-sulfonic acid, with some 3- and tiny amounts of the 2- and 9-sulfonic acids;[18] the observed reactivity order is in line with that of protiodetritiation.[19]

Results and Discussion

^{1}H NMR Assignments of the Substrates. The ^{1}H NMR parameters of the phenanthrene substrates are given in Table I (supplementary material). The assignments are based on the following information. The signals of the 4- and 5-H of the phenanthrenes are the most deshielded ones. The 60-MHz proton spectra of phenanthrene, 3- and 4-MP, and 9,10-DMP and their assignments were reported,[20-23] and these (partial) assignments have been adopted. The bromine in 9-bromophenanthrene and 9-Br-10-MP will have a deshielding effect on the peri 8-H, and, therefore, the respective signals at 8.23 and 8.32 ppm were attributed to 8-H and the respective upfield signals at 7.94 and 8.15 ppm to the 1-H. A similar deshielding effect is observed for 8-H of 9-MP. For 1-MP, the methyl is expected to cause a peri steric downfield shift on the 10-H,[24] and thus the doublet at 8.00 ppm was assigned to 10-H and the 7.90-ppm doublet to 9-H. In 9-MP, because of the adjacent methyl group, the 10-H is shielded by 0.13 ppm compared to the 9,10-H_2 singlet in phenanthrene. On the basis of the same argument, the 7.42-ppm doublet of 3,4,5,6-TMP was attributed to 2,7-H_2, whereas the 7.63-ppm doublet was assigned to 1,8-H_2. A similar shielding effect is observed for the 4-H of 3-MP. For 1,8-DMP, the observed peri deshielding effect on the 9,10-H_2 is 0.22 ppm as compared to that of the 9,10-H_2 singlet in phenanthrene. For 3-MP, as the 3-methyl is expected to have a shielding effect of ca. 0.12 ppm on the 1-H in the meta position,[25] the absorption at 7.95 ppm is assigned to 8-H, whereas the absorption at 7.88 ppm is attributed to 1-H. Since the methyl group at the 3-position will have a small shielding effect on 9-H, the $^1/_2$AB absorption at 7.82 ppm is assigned to 10-H, whereas the $^1/_2$AB at 7.77 ppm is attributed to 9-H. For 4-MP, the "doublet" absorptions at 7.87 and 8.02 ppm are attributed to 1- and 8-H, respectively, in view of the chemical shifts of 7.98 and 7.73 ppm for the 1- and 8-hydrogens of phenanthrene and 4,5-DMP, respectively.

Sulfonic Acid Products and ^{1}H NMR Assignments. The aromatic substrates have been sulfonated with sulfur trioxide in nitromethane as the solvent at 0 °C. The presence of the various components in the resulting sulfonate reaction mixture has been assessed on the basis of the assignment of the several absorption signals of the ^{1}H NMR spectrum to the different hydrogens of the potassium sulfonate constituents. The assignments are compiled in Table II. The chemical shift of a specific hydrogen is the same in a given sulfonate and the parent phenanthrene, unless it is peri or ortho to a sulfonate substituent. As to the nondistorted phenanthrenes (i.e., those not methylated at the 4- and 5-positions), the sulfo substituent shift for a peri H ranges from 0.97 to 1.25 ppm, for a "normal" ortho H from 0.27 to 0.33 ppm,[26] for a cavity ortho H (i.e., the 4- and 5-Hs) from 0.18 to 0.25 ppm, for a meso ortho H from 0.45 to 0.64 ppm, and for a hydrogen with sulfo groups in both the ortho and peri positions from 1.46 to 1.71 ppm. The lower value for the cavity ortho H is due to the buttressing of that hydrogen by the sulfo group, forcing it more into the electron cloud of the other cavity hydrogen which leads to shielding. The higher value for the meso ortho H is ascribed to the shorter distance between the adjacent H and SO_3^-, due to the shorter C_9–C_{10} bond length.[4] The *o*-sulfo substituent shift for methyl is 0.21–0.28 ppm. All the sulfo substituent shifts become larger if one of the two interacting groups (or both) are buttressed by a methyl.

Sulfo Product Composition and Mass Spectra. The composition of the sulfonic acid product mixtures obtained in the aprotic kinetically controlled[27-29] sulfonation of the phenanthrenes was determined by multicomponent ^{1}H NMR analysis.[31] The results are collected in Table III.

A number of potassium sulfonate mixtures have been subjected to field-desorption mass spectrometry. This technique (Table IV, supplementary material) revealed the presence of the monosulfonates, but the di- and trisulfonates did not show any signals. In contrast, field-desorption mass spectrometric analysis of arenesulfonic *acid* mixtures showed signals for both the mono- and disulfonic acids (Table V, supplementary material). The molecular ion signal ratio of mono- and disulfonic acids appears to differ from their concentration ratio which may be related to a different desorption behavior of the ions of the two types of acid.[32]

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(26) The sulfo substituent shifts for the 2- and 4-H of potassium toluene-3-sulfonate and the 3- and 5-H of potassium *o*-xylene-4-sulfonate in [$^2H_6$]Me_2SO are 0.32, 0.28, 0.31, and 0.25 ppm, respectively.
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(29) In the homogeneous sulfonation mixture of phenanthrene (39 mg) with 1 equiv of SO_3 in CD_3NO_2 (2 mL) at 0 °C, the content of the 9-sulfonic acid [which is apparent from its 10-H singlet at 8.72 ppm ($\Delta\delta$ = 0.84 ppm)] in the reaction mixture was found by ^{1}H NMR to be independent of the reaction time (0.5–6 h). In contrast, the content of anthracene-9-sulfonic acid in the supernatant solution of the *heterogeneous* mixture obtained on sulfonation of anthracene (39 mg) with an equimolar amount of SO_3 in CD_3NO_2 (2 mL) at 0 °C was found by ^{1}H NMR to isomerize to mainly the 1-isomer with a half life of ~5 h. A similar slow isomerization of anthracene-9-sulfonic acid was observed in the sulfonation of anthracene with acetyl sulfate.[30] The proneness of anthracene-9-sulfonic acid to isomerize is apparently due to the presence of the two hydrogens peri to the sulfo group, the far more stable naphthalene-1-, phenanthrene-1-, and phenanthrene-9-sulfonic acids having only one hydrogen peri to the sulfo group.
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Table II. ^{1}H NMR Chemical Shifts (δ) and Sulfo Substituent Shifts ($\Delta\delta$)[a] of the Assigned Absorptions of Potassium Phenanthrenesulfonates in [$^2H_6$]Me_2SO[b]

phenanthrene substituents	shift, δ									
	1	2	3	4	5	6	7	8	9	10
2-SO_3^-	8.25 (0.27)									
9-SO_3^-								8.98 (1.00)		8.33 (0.50)
9-Br-1-SO_3^-										9.33 (1.07)
9-Br-3-SO_3^-				9.02 (0.25)						
9-Br-6-SO_3^-					9.02 (0.25)					
9-Br-10-Me-2-SO_3^-	8.48 (0.33)		8.0	8.75	8.75	8.0	8.0	8.36		
9-Br-10-Me-3-SO_3^-	8.24	8.0		9.02 (0.22)	8.75	8.0	8.0	8.36		
9-Br-10-Me-6-SO_3^-	8.24	8.0	8.0	8.75	9.02 (0.22)		8.0	8.36		
9-Br-10-Me-3,6-(SO_3^-)$_2$	8.24	8.0		9.02 (0.22)	9.02 (0.22)		8.0	8.36		
1-Me-2-SO_3^-	3.02 (0.28)									
1-Me-9-SO_3^-	2.74									8.56 (0.56)
3-Me-1-SO_3^-		8.10 (0.61)				7.60	7.60	7.93	7.88	
3-Me-2-SO_3^-			2.83 (0.23)							
3-Me-9-SO_3^-				8.66	8.79	7.60	7.60	8.92 (0.97)		8.27 (0.45)
3-Me-1,9-(SO_3^-)$_2$										9.49[c] (1.67)
3-Me-8,10-(SO_3^-)$_2$									9.40[c] (1.63)	
4-Me-3-SO_3^-				3.30 (0.20)						
4-Me-1,9-(SO_3^-)$_2$		7.98 (0.32)	7.54	3.11	8.92	7.54		8.99 (0.97)		
4-Me-8,10-(SO_3^-)$_2$			7.54	3.06	8.99	7.54			9.28 (1.46)	
9-Me-1-SO_3^-										8.99 (1.11)
9-Me-7-SO_3^-								8.37 (0.30)	2.70	
9-Me-10-SO_3^-									3.12 (0.42)	
1,8-Me_2-2,6-(SO_3^-)$_2$	3.01 (0.26)		8.03 (0.43)	8.57	8.91 (0.18)		7.78 (0.27)	2.75	8.18	8.07
1,8-Me_2-2,7-(SO_3^-)$_2$	2.99 (0.24)		8.03 (0.43)	8.76	8.76		7.78 (0.27)	2.90 (0.24)		
1,8-Me_2-3,6-(SO_3^-)$_2$	2.77	7.76 (0.25)		8.89 (0.16)	8.89 (0.16)		7.76 (0.25)	2.77		
4,5-Me_2-1-SO_3^-		8.07 (0.53)	7.35					7.68	7.57	8.65 (1.07)
4,5-Me_2-3-SO_3^-	7.70	8.09 (0.54)		2.78 (0.24)				7.70		
4,5-Me_2-9-SO_3^-										8.16 (0.58)
4,5-Me_2-1,8-(SO_3^-)$_2$		8.08 (0.54)	7.38			7.38	8.08 (0.54)		8.59 (1.01)	8.59 (1.01)
9,10-Me_2-1-SO_3^-						7.74	7.74			2.95 (0.30)[d]
9,10-Me_2-2-SO_3^-	8.43 (0.27)			8.72	8.72	7.74	7.74			
9,10-Me_2-3-SO_3^-				8.98 (0.18)	8.72					
9,10-Me_2-3,6-(SO_3^-)$_2$	8.16	7.92 (0.29)		8.98 (0.18)	8.98 (0.18)		7.92 (0.29)	8.16	2.72	2.72
2,4,5,7-Me_4-1,8-(SO_3^-)$_2$		2.90 (0.43)		2.68 (0.21)	2.68 (0.21)		2.90 (0.43)		8.97 (1.47)	8.97 (1.47)
2,4,5,7-Me_4-1,9-(SO_3^-)$_2$		2.90 (0.43)								9.14 (1.66)
2,4,5,7-Me_4-1,6,9-(SO_3^-)$_3$										9.22 (1.74)
3,4,5,6-Me_4-1-SO_3^-		8.15 (0.73)							8.75 (1.27)	
3,4,5,6-Me_4-2-SO_3^-			2.83 (0.49)							
3,4,5,6-Me_4-9-SO_3^-								8.87 (1.25)		8.12 (0.64)
3,4,5,6-Me_4-1,7-(SO_3^-)$_2$						2.87 (0.53)				
3,4,5,6-Me_4-1,8-(SO_3^-)$_2$		8.08 (0.66)	2.61[c]	2.68[c]	2.68[c]	2.61[c]	8.08 (0.66)		8.70 (1.22)	8.70 (1.22)
3,4,5,6-Me_4-1,9-(SO_3^-)$_2$										9.19 (1.71)
4,5-ethano-1,6-(SO_3^-)$_2$		8.00 (0.45)	7.41	3.23	3.66,[e] 3.69[e]		8.06 (0.51)	7.81	7.77	8.82 (0.99)
4,5-ethano-1,8-(SO_3^-)$_2$		8.01 (0.46)	7.41	3.23	3.23	7.41	8.01 (0.46)		8.80 (0.97)	8.80 (0.97)

[a] The $\Delta\delta$'s, i.e., the data given in parentheses, are only listed for positions ortho or peri to the sulfo group and, in addition, for the 4- and 5-Me of 2,4,5,7-TMP. [b] The chemical shifts were calculated on the basis of the position of the methyl proton residue of [$^2H_6$]Me_2SO which was taken to be 2.52 ppm; all the doublets and triplets resulting from ortho hydrogen coupling have J values in between 7.5 and 8.0 Hz. [c] The assignment may be reversed. [d] The sulfo substituent shift for the peri methyl in 2,7-dimethyl-1,6-methano[10]annulene-5-sulfonate in D_2O is 0.39 ppm: K. Lammertsma and H. Cerfontain, *J. Am. Chem. Soc.*, **100**, 8244 (1978). [e] These signals are triplets with J = 7 Hz, and each refers to 1 hydrogen.

Table III. Sulfonation of Phenanthrenes with SO_3 in Nitromethane as Solvent at 0 °C

substrate	equiv of SO_3	sulfonic acid product distribution[a] (%)
phenanthrene	1.2	1-S (36), 2-S (6), 3-S (12), 9-S (46)
9-bromo-phenanthrene	1.2	1-S (25), 3- and/or 6-S (47)[b]
	2.2	1-S (32), 3- and/or 6-S (43)[b]
9-Br-10-MP	3.0	2-S (13), 3- and/or 6-S (25),[c] 3,6-S_2 (62)
1-MP	1.2	2-S (17), 9-S (24)
3-MP	2.2	1-S (15), 2-S (4), 9- or 10-S (62), 1,9-S_2 (5 or 10), 8,10-S_2 (10 or 5)
4-MP	3.0	3-S + 1,3-S_2 + 3,7-S_2 + 3,10-S_2 (5 + 5 + 7 + 2),[d] 1,9-S_2 (38), 8,10-S_2 (25)
9-MP	1.2	1-S (44), 2-S (<1), 3-S + 6-S (53), 7-S (1-2), 10-S (≤0.5)
1,8-DMP	3.1	2,6-S_2 (70), 2,7-S_2 (16), 3,6-S_2 (14)
4,5-DMP	1.2	1-S (40), 3-S (37), 9-S (3), 1,8-S_2 (14)
9,10-DMP	1.2	1-S (≤1), 2-S (20), 3-S (40), 3,6-S_2 (39)
	2.2	1-S (≤1), 2-S (15), 3,6-S_2 (84)
2,4,5,7-TMP	1.2	1,8-S_2 (70), 1,9-S_2 (15), 1,6,9-S_3 (15)
	2.2	1,8-S_2 (70), 1,9-S_2 (15), 1,6,9-S_3 (15)
3,4,5,6-TMP	1.2	1-S (49), 2-S (≃1), 9-S (16), 1,7-S_2 (≃1), 1,8-S_2 (30), 1,9-S_2 (≃2)
	3.0	1-S/1,8-S_2 ≃ 3:7
4,5-ethano-phenanthrene	4.0	1,6-S_2 (30), 1,8-S_2 (70)

[a] S stands for SO_3H. [b] The yield will be substantially greater for the 3- than for the 6-sulfonic acid in view of the conjugative stabilization of the σ complex for 3-substitution by the bromo substituent. [c] The yield will be greater for the 3- than for the 6-sulfonic acid, since the conjugative stabilization of the corresponding σ complex will be greater for the 9-bromo than for the 10-methyl substituent. This was concluded from the observation that 2-bromotoluene with 1 equiv of SO_3 in nitromethane at 0 °C yields 32% 4-, 63% 5-, and 5% 6-sulfonic acid. [d] Considering the directing effects of Me and SO_3H, the substitution of the 3-sulfonic acid will occur at positions 1, 7, and 10. The D_2O NMR spectrum does exhibit four low-field methyl absorptions, corresponding with sulfonic acid yields of 2%, 5%, 5%, and 7%.

From the data of Table III it appears that there is no sulfonation at the 4- and 5-positions with any of the substrates and that there is at most 1% sulfonation peri to a methyl.

Monosulfonation. The cation localization energies of phenanthrene and the methyl derivatives have been calculated by simple Hückel MO calculations by using the inductive model for the methyl substituent with $\delta\alpha_r = -0.3$; the data are in Table VI (supplementary material). The thus-predicted reactivity order for monosubstitution is given in Table VII, together with that observed experimentally, as estimated from the data in Table III. The two positional reactivity orders are in good agreement, provided that the following steric factors are recognized: (i) sulfonation peri to a methyl does not occur, as was also observed in the naphthalene[28,33] and anthracene[34] series, (ii) sulfonation at the 4- and 5-positions does not occur, as the resulting sulfonic acid would have a severely strained phenanthrene skeleton, and (iii) the sulfonation ortho to 9-methyl is sterically very severely hindered. It was established for the methylnaphthalenes that the degree of β substitution is reduced by the presence of an *o*-methyl group as result of steric repulsion between this methyl and the incoming sulfonic acid group.[28] This reduction in β substitution is larger when the *o*-methyl is located at an α- rather than a β-position. This is in line with the shorter bond length of the C_1–C_2 as compared with the C_2–C_3 bond (1.371 vs. 1.412 Å[4]). The C_9–C_{10} bond in phenanthrene is even shorter (1.350 Å[4]) than the C_1–C_2 bond of naphthalene. Accordingly, the sulfonation ortho to the 9-methyl will be severely hindered. Alternatively, the low content of 9-methylphenanthrene-10-sulfonic acid could be explained in terms of partial isomerization of the 10-sulfonic acid. This is highly unlikely, as the product formation in the SO_3 sulfonation in nitromethane is kinetically controlled (see before) and in view of the observation that *m*-xylene-2-sulfonic acid (of which the strain energy will

Table VII. Reactivity Order for Monosulfonation of Phenanthrene and Its Methyl Derivatives

substrate	reactivity order for monosulfonation positions: obsd	calcd[a]
phenanthrene	9 > 1 > 3 > 2	9 > 1 > *4* > 3 > 2
1-MP	9 > 2	9 ≃ *4* > (10) ≃ 8 > 2 ≃ *5* > 6 > 3
3-MP	9 ≫ 1 > 8 ≃ 2	*4* ≃ 9 > 10 ≃ 8 > 1 > *5* > 6 > 7
4-MP	1, 8, 9, and 10 > 3	1 ≫ 10 ≃ 9 > 8 > 3 > *5* > 6 > 7 > 2
9-MP	1 > 3 + 6 > 7 > 10	10 ≫ 1 > (8) > *5* > *4* > 3 > 6 > 7 > 2
1,8-DMP	2 ≃ 3	(9) > *4* > 2 > 3
4,5-DMP	1 > 3 > 9	1 > 9 > 3 > 2
9,10-DMP	3 > 2 ≫ 1	(1) > *4* > 3 > 2
2,4,5,7-TMP	1 > 9 > 3	1 > 9 ≃ 3
3,4,5,6-TMP	1 > 9	1 > 9 > 2

[a] The positions in parentheses and the 4- and 5-positions which are italic cannot be sulfonated because they are peri to a methyl and in view of the geometric structure of phenanthrene skeleton, respectively (see the text).

Table VIII. Selected β- to α-Sulfonation Ratios with the Corresponding Differences in Localization Energies for Naphthalene, Phenanthrene, and some Methyl Derivatives[a]

substrate	substitution: positions (β/α)	ratio	no.	$L_\beta - L_\alpha$	ref
naphthalene	2/1	0.14	1	0.1811	30
2-methylnaphthalene	6/4	0.93	2	0.1415	30
	6/5	1.00	3	0.1423	30
	6/8	0.29	4	0.1712	30
1,3-dimethyl-naphthalene	7/5	0.67	5	0.1619	30
2,3-dimethyl-naphthalene	6/5	0.30	6	0.1686	30
1,2,3-trimethyl-naphthalene	6/5	≤0.10	7	0.1929	32
1,6,7-trimethyl-naphthalene	3/4	<0.01	8	0.2716	32
phenanthrene	2/1	0.17	9	0.1799	
	3/1	0.33	10	0.1357	
9-methyl-phenanthrene[b]	2/1	<0.02	11	0.2223	
	3/1	1.08	12	0.1280	
	6/1	0.12	13	0.1791	
	7/1	0.03	14	0.2066	

[a] Compared are only the sterically "unhindered" α- and β- positions, i.e., those without an adjacent methyl group. [b] In view of the localization energies, the content of the 3- and 6-sulfonic acid of 9-MP was considered to be 90 ± 5% and 10 ± 5% of their sum, respectively.

(33) H. J. A. Lambrechts and H. Cerfontain, *Tetrahedron*, 38, 1667 (1982).
(34) F. van de Griendt, C. P. Visser, and H. Cerfontain, *J. Chem. Soc., Perkin Trans. 2*, 911 (1980).

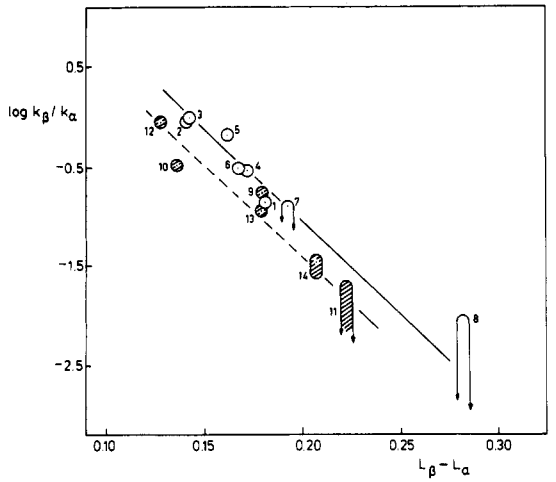


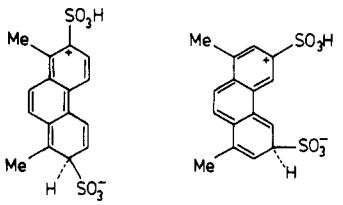
Figure 1. Correlation plot of log k_β/k_α vs. $L_\beta - L_\alpha$: ○, —, naphthalenes; ●, ---, phenanthrenes. The numbers refer to those of Table VIII.

be comparable in size to or even greater than that of 9-methylphenanthrene-10-sulfonic acid) requires a very strong acid (>75% H_2SO_4) in order to isomerize to the 4-sulfonic acid.[35]

In the naphthalene series it was established that the sulfonation at an α-position is subject to steric hindrance,[28] the primary kinetic isotope effect for the sulfonation of naphthalene at the 1-position being $k_H/k_D = 1.9$.[36] Apparently there is steric repulsion from the peri hydrogen on formation of the sulfonic acid from the preceding σ complex which lowers the rate of the proton abstraction. In Table VIII are listed the β/α ratios for the sulfonation of naphthalene, phenanthrene, and some methyl derivatives for "unhindered" positions, i.e., positions which have no methyl in the ortho and peri positions, and which are thus to a first approximation sterically comparable with those of naphthalene proper. For the naphthalenes there is a linear correlation between log (k_β/k_α) and $\Delta L_{\beta,\alpha}$.[28] The points for the phenanthrenes fall somewhat below the regression line defined by the points of the naphthalenes (Figure 1). The difference in log k_β/k_α between the regression lines for phenanthrene and naphthalene is 0.35. It is ascribed to the difference in the rates of α substitution as the result of the difference in steric hindrance, the rates of β substitution being considered sterically unaffected. Thus log $(k_\alpha{}^p/k_\alpha{}^n) = 0.35 = 2.303(\Delta S_\alpha{}^{p\ddagger} - \Delta S_\alpha{}^{n\ddagger}/RT$, where the superscripts refer to the respective hydrocarbons. Accordingly, $\Delta S_\alpha{}^{p\ddagger} - \Delta S_\alpha{}^{n\ddagger} = 0.30$ cal mol^{-1} K^{-1}.[37]

Disulfonation. The high content of phenanthrenedisulfonic acids in the sulfonic acid product mixture with the two tetramethylphenanthrenes is remarkable when 1.2 equiv of SO_3 is used (Table IV). It does not seem to be related to the strained structure of these phenanthrenes, as the 4,5-DMP behaves normally. Instead, it is ascribed to the very high reactivity of these substrates and their monosulfonic acids. For highly reactive substrates, the chemical selectivity may be disguised by the (rate of) mixing of the reactants. Recently, it was emphasized by Rys[38] that with a highly reactive substrate and with 1 equiv of reagent disubstituted products will be formed during the mixing of the reactants, as was in fact observed for, e.g., the nitration of durene[39-41] and bibenzyl.[42] As to the present study, the rate order for substitution of the three strained phenanthrenes at the 1-position (i.e., their most reactive position) is according to the localization energies: 4,5-DMP < 3,4,5,6-TMP ≪ 2,4,5,7-TMP. This order parallels that of the content of disulfonic acids. Moreover, it should be realized that the SO_3 sulfonation in nitromethane of mixtures of the far less reactive substrates benzene and toluene is kinetically not well behaved as to the substrate selectivity,[43] as result of the high rates of sulfonation. Accordingly, the high yields of disulfonic acid formed with the strained TMP's when 1.2 equiv of SO_3 is used are explained satisfactorily in terms of a mixing-disguised consecutive sulfonation step model (cf. ref 44).

The position at which the second sulfo group is introduced will be determined by the directing order of the methylphenanthrene system (cf. Table VI, supplementary material) and the electronic and steric effect of the (pyro)sulfonic acid group already present. This may be illustrated for 1,8-DMP and 3,4,5,6-TMP as typical examples. The expected position sulfodeprotonation reactivity order for 1,8-DMP is (9) > 4 > 2 > 3 (see Table VII). Substitution at the 4- and 9-position does not occur for steric reasons (the latter would be peri to methyl). The main disulfonic acid formed is the nonsymmetrical 2,6-isomer. Its preferred formation may be explained in terms of the difference in energy contents of the σ complexes for the introduction of the second sulfo group in 1,8-dimethylphenanthrene-2- and -3-sulfonic acid at positions 6 and 7. The substitution of the 2-sulfonic acid is less attractive at position 7 than at position 6, mainly in view of the repulsive interaction between the positive charges at the SO_3H sulfur and C_2 in the mesomeric structure **2**,



2 **3**

which is therefore not strongly contributing. For similar reasons, the 6-substitution of the 3-sulfonic acid is disfavored (cf. structure **3**) relative to the 7-substitution, and, in fact, the ratio of 3,6- to 2,6(= 3,7)-disulfonic acid is 14:70.

In contrast, with 3,4,5,6-TMP the main disulfonic acid is the symmetrical 1,8-isomer. The directing effect of the sulfonic acid substituent is apparently less effective with 3,4,5,6-TMP-1-SO_3H than with the 2- and 3-sulfonic acids of 1,8-DMP. The difference in localization energy for the substitution of the 1- and 2-positions of 3,4,5,6-TMP ($\Delta L_{1,2}$ = 0.2157) is far greater than that between the 2- and 3-

(35) A. Koeberg-Telder, A. J. Prinsen, and H. Cerfontain, *J. Chem. Soc.*, 1004 (1969).
(36) K. Lammertsma and H. Cerfontain, *J. Chem. Soc., Perkin Trans. 2*, 28 (1980).
(37) The lengths of the naphthalene C_1–C_{8a} (=C_8–C_{8a}) and the phenanthrene C_1–C_{10a} bonds are 1.423 Å, and the phenanthrene C_{10}–C_{10a} bond is 1.453 Å.[4] The distance between the peri carbons will thus be somewhat greater in phenanthrene than in naphthalene, and the steric hindrance for α substitution is thus expected to be less with phenanthrene than with naphthalene, as is in fact observed.
(38) P. Rys, *Acc. Chem. Res.*, **9**, 345 (1976); *Angew. Chem.*, **16**, 847 (1977).
(39) G. Illuminati and M. P. Illuminati, *J. Am. Chem. Soc.*, **75**, 2159 (1953).
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(42) P. F. Christy, J. H. Ridd, and D. N. Stear, *J. Chem. Soc. B*, 797 (1970); A. Gastaminza and J. H. Ridd, *J. Chem. Soc., Perkin Trans. 2*, 813 (1972).
(43) K. Bosscher and H. Cerfontain, *J. Chem. Soc. B*, 1524 (1968).
(44) F. Nabholz, R. J. Ott, and P. Rys, *Helv. Chim. Acta*, **60**, 2926 (1977); F. Nabholz and P. Rys, *ibid.*, **60**, 2937 (1977).

positions of 1,8-DMP ($\Delta L_{2,3}$ = 0.0783). Accordingly, the directing effect of the sulfo substituent is only apparent if the difference in localization energy between the two possible positions of substitution of the parent phenanthrene system is not too large.

A more general and detailed discussion on the problem of the kinetically controlled positional reactivity order in the sulfonation of arenemonosulfonic acids and their methyl derivatives, including those of the methylphenanthrenesulfonic acids, will be given in a forthcoming publication.[45]

Experimental Section

Starting Materials. 9-Bromophenanthrene was synthesized from phenanthrene and was also obtained from Aldrich-Europe. The reaction of 9-bromophenanthrene with *n*-BuLi followed by the addition of MeI in anhydrous ether afforded 9-MP in 60% yield as estimated by ^{1}H NMR.[46] In order to increase the yield, we repeated the methylation with this mixture to obtain 9-MP: yield 95% mp 90 °C (lit.[46] mp 90–91 °C) (after crystallization from hexane). (The use of fresh *n*-BuLi and vigorously dried ether is imperative). Bromination of 9-MP gave 9-Br-10-MP: 68% yield; mp 119–120 °C (lit.[46] mp 119.5 °C) (after recrystallization from ethanol). The subsequent reaction with *n*-BuLi and MeI similarly afforded 9,10-DMP: 62% yield; mp 144–145 °C (lit.[46] mp 143–146 °C) (after recrystallization from hexane).[46] 1-, 3-, and 4-MP were a gift generously supplied by Koninklijke/Shell Laboratories, Amsterdam. 4,5-DMP and 2,4,5,7- and 3,4,5,6-TMP were gifts from Professor M. S. Newman (The Ohio State University), 1,8-DMP was a gift from Professor M. B. Rubin (Israel Institute of Techonology, Haifa), and 4,5-ethanophenanthrene was a gift from Dr. C. Tintel (University of Leiden).

Sulfonation Procedure and Analysis. The aromatic substrate (usually 1.0 mmol) was dissolved by dry nitromethane (Aldrich Gold Label, 40 mL) under nitrogen. The required amount of SO_3 was then added with a microsyringe to 15–20 mL of nitromethane placed in a pressure-equalizing dropping funnel, and the resulting solution of the CH_3NO_2–SO_3 complex[47] was added dropwise over a 5-min period to the aromatic compound at 0 °C under nitrogen. After the addition was completed, the stirring was continued at 0 °C for 2.5 h. The reaction mixture was then quenched by addition of D_2O (3–4 mL). The bath was gradually warmed to 50 °C, in order to hydrolyze any (solid) sulfonic anhydride(s). The D_2O layer was then separated from the nitromethane and extracted with CH_2Cl_2 (dried from $CaCl_2$) in order to remove traces of residual nitromethane. The residual CH_2Cl_2 was removed by bubbling nitrogen through the D_2O solution. Then, in general, the ^{1}H NMR spectrum of the D_2O solution containing the sulfonic acids was recorded and subsequently also that of the potassium sulfonate mixture (obtained by neutralizing the sulfonic acid D_2O solution with aqueous 10% KOH, followed by removal of the water solvent) in $[^2H_6]Me_2SO$. The HDO signal was moved to somewhat higher field (between the methyl and aromatic signals) by the addition of a small drop of trifluoroacetic acid. The spectra were obtained with a Bruker WM-250 NMR spectrometer. For comparison, the spectra of the starting substrates were also recorded in $[^2H_6]Me_2SO$.

The sulfonic acid product mixtures and the potassium sulfonate product mixtures were analyzed by field-desorption mass spectrometry with a Varian MAT 711 double-focussing mass spectrometer with a combined EI/FI/FD source. The sulfonic acids dissolved in D_2O (or the potassium sulfonates in Me_2SO) were brought into the emitter (10-μm activated tungsten wire) by the dipping technique. The emitter current to desorb the sample was in the range of 15–29 mA. The results are in Tables IV and V.

Multicomponent Analysis of Sulfo Product Mixtures. The analysis of a sulfo product mixture was based on the ^{1}H NMR spectra of the arenesulfonic acid product mixtures in D_2O (which were obtained for most of the substrates) and of the potassium arenesulfonate product mixtures in $[^2H_6]Me_2SO$. For the latter solvent the sulfo substituent shifts can be obtained, and these were in most cases decisive in the assignment of the various absorption signals. For D_2O this could not be done, because of the insolubility of the hydrocarbon substrates. The advantage of D_2O as a solvent is the far better resolution as result of sharper signals and the somewhat larger spread in the chemical shifts of the various signals (e.g., for the sulfo derivatives of 1,8-DMP the aromatic signals for $[^2H_6]Me_2SO$ and D_2O as the solvents are between 7.75 and 9.00 ppm and between 6.15 and 8.40 ppm, respectively).

In all cases but that of phenanthrene itself the composition of the sulfonate product mixture was determined by multicomponent ^{1}H NMR analysis on the basis of the specific absorptions of the various components.[31] For phenanthrene, the absorption spectrum of the sulfonate product mixture in $[^2H_6]Me_2SO$ was divided into three regions: viz., A from 7.60 to 8.10 ppm, B from 8.10 to 8.50 ppm, and C from 8.50 to 9.10 ppm. The middle region comprises *only* two sharp singlets at 8.25 and 8.33 ppm which were assigned to the 1-H of the 2-sulfonate ($\Delta\delta$ = 0.27 ppm) and the 10-H of the 9-sulfonate ($\Delta\delta$ = 0.50 ppm), respectively. For the 2- and 9-sulfonate the A/B/C hydrogen absorption ratios are 5:1:3 and 6:1:2, which allowed calculation of the contributions of these sulfonates to the A and C regions and, accordingly, of the A/C ratio of the residual absorptions. For the other two monosulfonic acids, the 1- and 3- sulfonates, the A/C hydrogen absorption ratios are 3:6 and 2:7, respectively. From these two ratios and the observed ratio of residual absorptions the amounts of the 1- and 3-sulfonates were calculated.

A typical example of the essential role of the D_2O spectrum in the product assignment is the analysis of the sulfonic acid product mixture of 1,8-DMP with 3.1 equiv of SO_3. The $[^2H_6]$-Me_2SO spectrum could, in view of the (partly) overlapping signals, be interpreted in two ways, viz., first in terms of the presence of equimolar amounts of the 2,7- and 3,6-disulfonates (both ca. 40%) and the 2-sulfonate (19%) and second in terms of the presence of mainly the 2,6-disulfonate with some of the 2,7- and 3,6-disulfonates. The D_2O spectrum clearly revealed that the latter interpretation is the correct one, since it contains as major aromatic absorptions two singlets at 7.17 and 7.97 ppm, an AB system at 6.30 and 6.63 ppm, an AB system at 7.44 and 7.51 ppm with an area ratio of 1:1:2:2 (the 2,6-disulfonic acid), three singlets of equal intensity at 6.17, 7.22, and 8.37 ppm (the 3,6-disulfonic acid), a singlet at 6.59 ppm and an AB system at 7.08 and 7.44 ppm with an area ratio of 1:2 (the 2,7-disulfonic acid).

Acknowledgment. We are indebted to Professor W. H. Laarhoven, Professor M. S. Newman, Professor M. B. Rubin, Dr. C. Tintel, and the Koninklijke/Shell Laboratories Amsterdam for gifts of phenanthrenes. We thank Professor N. M. M. Nibbering for valuable discussions, Mrs. N. E. Bruinzeel, Mrs. H. Ctvrteckova, and Mrs. C. A. M. Spruyt for recording the NMR spectra, and Mr. R. H. Fokkens and Mr. F. A. Pinkse for assistance in obtaining the FD mass spectra.

Registry No. SO_3, 7446-11-9; 9-Br-10-MP, 52979-71-2; 1-MP, 832-69-9; 3-MP, 832-71-3; 4-MP, 832-64-4; 9-MP, 883-20-5; 1,8-DMP, 7372-87-4; 4,5-DMP, 3674-69-9; 9,10-DMP, 604-83-1; 2,4,5,7-TMP, 7396-38-5; 3,4,5,6-TMP, 7343-06-8; 2-SO_3^-P K, 22172-78-7; 9-SO_3^-P K, 22172-77-6; 9-Br-1-SO_3^-P K, 82648-73-5; 9-Br-3-SO_3^-P K, 82648-74-6; 9-Br-6-SO_3^-P K, 82648-75-7; 9-Br-10-Me-2-SO_3^-P K, 82648-76-8; 9-Br-10-Me-3-SO_3^-P K, 82648-77-9; 9-Br-10-Me-6-SO_3^-P K, 82648-78-0; 9-Br-10-Me-3,6-$(SO_3^-)_2$ 2K, 82648-79-1; 1-Me-2-SO_3^-P K, 82648-80-4; 1-Me-9-SO_3^-P K, 82648-81-5; 3-Me-1-SO_3^-P K, 82648-82-6; 3-Me-2-SO_3^-P K, 82648-83-7; 3-Me-9-SO_3^-P K, 82648-84-8; 3-Me-1,9-$(SO_3^-)_2$P 2K, 82648-85-9; 3-Me-8,10-$(SO_3^-)_2$P 2K, 82648-86-0; 4-Me-3-SO_3^-P K, 82648-87-1; 4-Me-1,9-$(SO_3^-)_2$P 2K, 82648-88-2; 4-Me-8,10-$(SO_3^-)_2$P 2K, 82660-98-8; 9-Me-1-SO_3^-P K, 82648-89-3; 9-Me-7-SO_3^-P K, 82648-90-6; 9-Me-10-SO_3^-P K, 82648-91-7; 1,8-Me_2-2,6-$(SO_3^-)_2$P 2K, 82648-92-8; 1,8-Me_2-2,7-$(SO_3^-)_2$P 2K, 82648-93-9; 1,8-Me_2-3,6-$(SO_3^-)_2$P 2K, 82648-94-0; 4,5-Me_2-1-SO_3^-P K, 82648-95-1; 4,5-Me_2-3-SO_3^-P K, 82648-96-2; 4,5-Me_2-9-SO_3^-P K, 82648-97-3; 4,5-Me_2-1,8-$(SO_3^-)_2$P 2K, 82648-98-4; 9,10-Me_2-1-SO_3^-P K, 82648-99-5; 9,10-Me_2-2-SO_3^-P K, 82649-00-1; 9,10-Me_2-3-SO_3^-P K, 82649-01-2; 9,10-Me_2-3,6-$(SO_3^-)_2$P 2K, 82649-02-3; 2,4,5,7-Me_4-1,8-$(SO_3^-)_2$P 2K, 82649-03-4; 2,4,5,7-Me_4-1,9-$(SO_3^-)_2$P 2K, 82649-04-5;

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2,4,5,7-Me_4-1,6,9-$(SO_3^-)_3P$ 3K, 82649-05-6; 3,4,5,6-Me_4-1-SO_3^-P K, 82649-06-7; 3,4,5,6-Me_4-2-SO_3^-P K, 82649-07-8; 3,4,5,6-Me_4-9-SO_3^-P K, 82649-08-9; 3,4,5,6-Me_4-1,7-$(SO_3^-)_2P$ 2K, 82649-09-0; 3,4,5,6-Me_4-1,8-$(SO_3^-)_2P$ 2K, 82649-10-3; 3,4,5,6-Me_4-1,9-$(SO_3^-)_2P$ 2K, 82649-11-4; 4,5-ethano-1,6-$(SO_3^-)_2P$ 2K, 82649-12-5; 4,5-ethano-1,8-$(SO_3^-)_2P$ 2K, 82649-13-6; phenanthrene, 85-01-8; 9-bromophenanthrene, 573-17-1; 4,5-ethanophenanthrene, 6628-98-4; 2-methylnaphthalene, 91-57-6; 1,3-dimethylnaphthalene, 575-41-7; 2,3-dimethylnaphthalene, 581-40-8; 1,2,3-trimethylnaphthalene, 879-12-9; 1,6,7-trimethylnaphthalene, 2245-38-7; naphthalene, 91-20-3; anthracene, 120-12-7; anthracene-9-sulfonic acid, 22582-76-9.

Supplementary Material Available: Table I, listing the ^1H NMR parameters of the phenanthrene substrates, Tables IV and V, listing the mass spectral data of the potassium sulfonate mixtures and of the arenesulfonic acid mixtures, respectively, and Table VI, listing the cation localization energies of the phenanthrenes, obtained by simple Hückel calculation with $\delta\alpha_r = -0.3$ (4 pages). Ordering information is given on any current masthead page.

N-Unsubstituted β-Lactams from β-Hydroxy-α-amino Acids. Facile Preparation of Intermediates for Isocephalosporins[1]

Ajay K. Bose, M. S. Manhas,* J. E. Vincent, K. Gala, and I. F. Fernandez

Department of Chemistry and Chemical Engineering, Stevens Institute of Technology, Hoboken, New Jersey 07030

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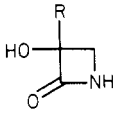
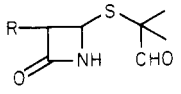
A facile method has been devised for the synthesis of N-unsubstituted β-lactams. The *cis*-azido β-lactam (**13**) obtained by the reaction of azidoacetyl chloride and the Schiff base (**10**), derived from cinnamaldehyde and a threonine ester, is subjected to controlled oxidation with Jones reagent: the threonine moiety is thereby oxidized to a β-keto ester (**19**), which exists primarily in its enolic form. The use of an excess of the oxidizing agent results in the removal of the threonine moiety and the formation of an N-unsubstituted β-lactam (**22**). Such β-lactams are known key intermediates for the synthesis of isocephalosporins and other β-lactam antibiotics.

N-Unsubstituted β-lactams were first synthesized in the laboratory many years before they were discovered in nature. The first naturally occurring member of this series to be reported in the literature was Wildfire toxin (**1**),[2]



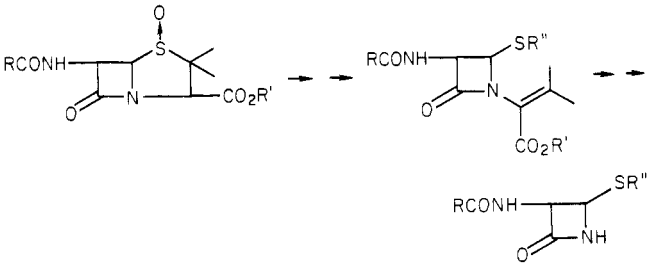
1, R = $CH_2CH_2CH(NH_2)CONHCH(COOH)CH(CH_3)OH$
2, R = $CHClCH_2CH(CO_2H)NHCOCH(CH_3)NH_2$



3a

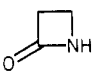
which is a peptide derivative. This β-lactam is produced by the bacterium, *Pseudomonas tabaci*, that causes the "wildfire disease" of tobacco leaves. Another peptide-bearing monocyclic β-lactam (**2**) was isolated from an unidentified *Streptomyces* species 372A.[3]

Sheehan and Brandt[4] cleaved the thiazolidine ring of penicillin and prepared N-unsubstituted β-lactams of type (**3a**). Since then many N-unsubstituted β-lactams (**3b**) have been prepared by the degradation of penicillin sulfoxide via *N*-vinyl β-lactams. Various laboratories have developed their own favorite method for removing the *N*-vinyl group to obtain N-unsubstituted β-lactams.[5]



3b

A number of synthetic approaches to N-unsubstituted β-lactams have been described; all but one[6] of them involve the removal of the N-substituent by some reaction that will not lead to the scission of the β-lactam ring. The one exception is the method first described by Breckpot[7] for the cyclization of β-amino esters directly to N-unsubstituted β-lactams under the influence of an organometallic reagent, such as a hindered Grignard agent[8] or diisobutylaluminum hydride.[9] The parent β-lactam (**4**) was first prepared by this method by Holley and Holley.[10]



4

(1) Part 65 in the series "Studies on Lactams". For part 64, see A. K. Bose, M. S. Manhas, J. M. van der Veen, S. G. Amin, I. F. Fernandez, K. Gala, R. Gruska, J. C. Kapur, M. S. Khajavi, J. Kreder, L. Mukkavilli, B. Ram, M. Sugiura, and J. E. Vincent, *Tetrahedron*, **37**, 2321 (1981).
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