It was also shown that under conditions of equilibration (the slowest reaction investigated) there is no destruction of **2**-OH. In this experiment a solution of an equilibrium mixture of *exo*- and *endo*-**2**-OH in 33.3% acetone containing 0.182 M $HClO_4$ and 1,1,2,2-tetrachloroethane as an internal standard was heated for >5 half-lives for equilibration. During this period relative peak areas of the alcohol and internal standard remained constant.

C. Oxygen-Exchange Experiments. Rate constants for oxygen exchange of ^{18}O-labeled *exo*- and *endo*-**2**-OH (k_{exc}) were determined as described earlier[1a] except that platinized carbon[4] was substituted for carbon black in the Unterzaucher apparatus. Samples were isolated from quenched reaction mixtures by extraction with pentane. After drying ($MgSO_4$), the pentane was removed with a spinning band column and the residual **2**-OH purified by sublimation (90 °C, 6 mm). Control experiments showed that the isolation procedure did not alter the ^{18}O content or the configurational composition of the alcohol fraction. Reactions were followed to >75% completion and good first-order behavior was observed.

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Superacid-Catalyzed Transfer Nitration of Benzene, Toluene, and Mesitylene with 9-Nitroanthracene and Pentamethylnitrobenzene. Evidence for the Reversibility of Electrophilic Aromatic Nitration in Specific Cases[1]

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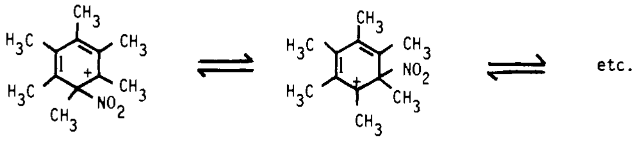
Contribution from the Hydrocarbon Research Institute, University of Southern California, University Park, Los Angeles, California 90007. *Received August 4, 1978*

Abstract: The reversibility of electrophilic aromatic nitration was proven in certain, specific cases of superacid-catalyzed transfer nitration reactions. In the reaction of benzene, toluene, and mesitylene with 9-nitroanthracene and pentamethylnitrobenzene, nitrobenzene, nitrotoluenes, and nitromesitylene were obtained in the presence of superacids. The primary kinetic hydrogen isotope effect, k_H/k_D, of 2.25 ± 0.05 in the nitration of anthracene-d_{10} with nitronium hexafluorophosphate in nitromethane solution is also in accord with the reversibility of the nitration of anthracene.

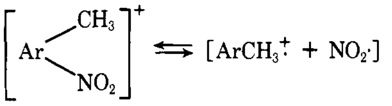
Introduction

Acid-catalyzed nitration is a typical electrophilic aromatic substitution reaction.[2,3] Nitration is generally considered to be an irreversible reaction, and nitroaromatics, in general, do not undergo rearrangement or isomerization under the reaction conditions.[4] Relative reactivities and substituent effects have been extensively studied in nitration of aromatics, assuming that the nitro compounds formed do not revert to starting materials. Otherwise, relative reactivities calculated on the basis of product ratios would become affected and require a more rigorous treatment, taking into account the reverse reaction.

Examples of acid-catalyzed migration of nitro groups have been reported.[4] The mechanisms of these migrations, however, are not always fully established and may involve, at least in some instances, radical cations (as in the case of nitramine rearrangements[5]). In the case of hexamethylnitrobenzenium ion, the intramolecular nitro group migration was directly studied by NMR spectroscopy, and the complex was also found capable of transnitrating aromatics:[6]

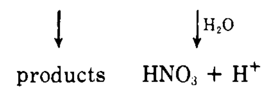


This degenerate rearrangement was subsequently also studied by Koptyug et al.[7] They showed that the rearrangement takes place through successive intramolecular 1,2 migrations of the nitro group and ruled out the possibility of an alternative pathway proceeding through the formation of a radical cation.



$$\left[\mathrm{Ar}\begin{smallmatrix}\diagup CH_3\\ \diagdown NO_2\end{smallmatrix}\right]^+ \rightleftarrows [\mathrm{ArCH_3}^{+\cdot} + \mathrm{NO_2}\cdot]$$

In the course of acid-catalyzed nitration of aromatics, the reversibility of nitration was, however, until now not directly established. Gore[8] reported in 1957 that heating of 9-nitroanthracene with 12 N sulfuric acid in trichloroacetic acid solution for 15 min at 95 °C gave a dark solution in which, after dilution with water, an 81% yield of free nitric acid was estimated. Anthracene itself could not be isolated, but a 20% yield of anthraquinone and appreciable amounts of polymer and soluble sulfonic acids were obtained. Experiments conducted in the presence of added nitrobenzene to detect cross-nitration products failed. The system was represented as a protolytic denitration reaction:



$$\mathrm{ArNO_2} \overset{H^+}{\rightleftharpoons} [\mathrm{ArHNO_2}]^+ \rightleftharpoons \underset{\substack{\downarrow\\ \text{products}}}{\mathrm{ArH}} + \underset{\substack{\downarrow H_2O\\ HNO_3 + H^+}}{NO_2^+}$$

Oxidative degradation, however, could also account for the observed products.

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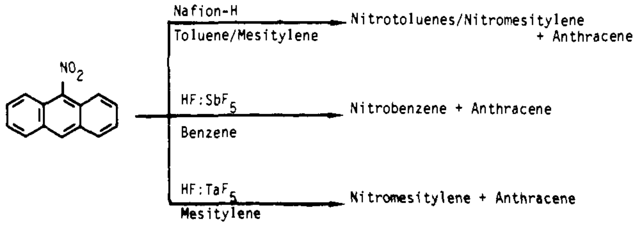
The strongest indication, so far, for the possible reversibility of aromatic nitration was obtained by Cerfontain and Telder,[9] who found a primary kinetic hydrogen isotope effect in the nitration of anthracene-*9-d*, indicative of the relative slowness of the proton transfer from the σ intermediate of the reaction.

We have now obtained the first unequivocal evidence for the reversibility of electrophilic aromatic nitration by having achieved the superacid-catalyzed transfer nitration from 9-nitroanthracene and pentamethylnitrobenzene to mesitylene and toluene and isolated the products nitromesitylene and nitrotoluene.

Results and Discussion

9-Nitroanthracene was selected for transfer nitration because the strong peri-interaction of the nitro group with the two neighboring hydrogens tilts the nitro group out of plane of the aromatic ring, thereby weakening the carbon-nitrogen bond.

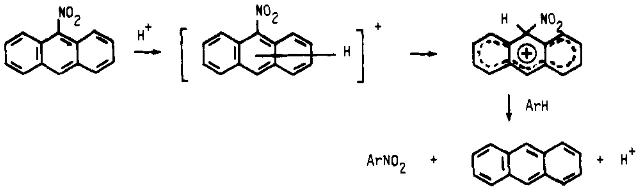
When a solution of 9-nitroanthracene in mesitylene was heated under reflux over a catalytic amount of Nafion-H[10] perfluorinated solid superacidic catalyst or with fluorotantalic acid, HF:TaF$_5$, nitromesitylene was formed (~5%), accompanied by an equivalent amount of anthracene, the product of denitration. Similarly, when toluene was treated with Nafion-H in the presence of 9-nitroanthracene, nitrotoluenes were obtained (~2%), with *p*-nitrotoluene being the major isomer (>95%). Even when a mixture of benzene and 9-nitroanthracene was treated with fluoroantimonic acid (HF:SbF$_5$, 1:1), nitrobenzene could be detected, although only in very small amounts (<1%).



Similarly, on heating a mixture of pentamethylnitrobenzene with toluene in the presence of Nafion-H, nitrotoluenes were formed, with the para isomer again being predominant.

All the transfer nitrations observed gave only low yields, ≲5%. Pentamethylnitrobenzene also gave transmethylation products, indicative of competing methyl transfer.

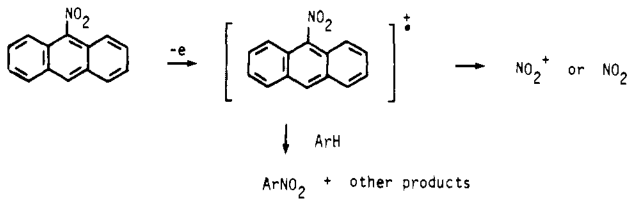
Although the yields of transfer nitration are low, one should bear in mind that protonation of nitroaromatics is generally reversible and takes place predominantly on the nitro group. Only competing and very limited ipso C-protonation leads to transfer nitration.



We propose the following mechanism for transfer nitration with 9-nitroanthracene.

The fact that the transfer nitration of toluene gives mainly *p*-nitrotoluene (>95%) indicates the bulky nature of the nitrating agent. If free nitronium ion itself were nitrating toluene, we should have observed the usual isomer distribution of nitrotoluenes (60-65% ortho, 3-4% meta, 30-35% para). The nitrating agent, thus, seems to be ipso protonated 9-nitroanthracene, which transfers nitrates before it loses a free nitronium ion. Control experiments showed that nitrotoluenes do not isomerize under the reaction conditions.

Alternatively, one can argue that under the reaction conditions, HF:SbF$_5$ or even Nafion-H is capable of oxidizing 9-nitroanthracene to its radical cation (as SbF$_5$ and SO$_3$, which can be liberated, are known oxidizing agents), which then could lose NO_2^+ or $NO_2\cdot$ to nitrate the aromatic substrate, or itself could act as a transfer nitrating agent.



We have, however, also achieved transfer nitration with HF:TaF$_5$, a nonoxidizing superacid system. Formation of nitroarenes in this system is highly improbable through the 9-nitroanthracene radical cation.

It was also thought that the use of a more nucleophilic acceptor of nitronium ion would facilitate denitration. In fact, when a mixture of 9-nitroanthracene, *n*-butyl sulfide, and HF:TaF$_5$ was heated at 200° for 24 h, anthracene was obtained in 28% isolated yield. Under similar conditions, pentamethylnitrobenzene was denitrated to give a 25% yield of pentamethylbenzene (with some acid-catalyzed disproportionation products). Nitromesitylene was not denitrated under these conditions.

We have also determined the kinetic hydrogen isotope effects of the nitration of benzene-d_6, naphthalene-d_8, and anthracene-d_{10} with nitronium hexafluorophosphate in nitromethane solution. The following results were obtained.

	k_H/k_D
benzene/benzene-d_6	0.89 ± 0.05
naphthalene/naphthalene-d_8	1.05 ± 0.05
anthracene/anthracene-d_{10}	2.25 ± 0.05

Competitive nitrations of the corresponding light and heavy hydrocarbons (C_6H_6/C_6D_6, $C_{10}H_8/C_{10}D_8$ and $C_{14}H_{10}/C_{14}D_{10}$) were carried out, and the product was analyzed by GLC/mass spectrometry.

Only the nitration of anthracene to 9-nitroanthracene shows a primary kinetic isotope effect of $k_H/k_D = 2.25 \pm 0.05$, indicative of the slowness of the proton elimination step. This effect is similar to that reported by Cerfontain[9] with nitronium tetrafluoroborate in sulfolane solution ($k_H/k_D = 2.6$), but substantially lower than the value ($k_H/k_D = 6.1$) reported[9] in acetonitrile solution, which may have been affected by other factors, including the formation of a relatively stable $CH_3C{\equiv}N^+NO_2$ complex between the solvent and NO_2^+, making it a much more selective agent. However, solutions of nitronium salts in acetonitrile are not stable, and, therefore, nitration conditions are difficult to reproduce.

No primary kinetic hydrogen isotope effect is expected in nitration of aromatics in accordance with the experimental findings. It is only in the case of sterically hindered systems, as found by Myhre,[11] that the proton elimination step is becoming, at least partially, rate determining. In the case of 9-nitroanthracene, the reversal of the nitration reaction, as observed experimentally, is in good agreement with the observed kinetic hydrogen isotope effect. The results obtained indicate that electrophilic aromatic nitration can be reversible for some nitroaromatics, such as 9-nitroanthracene and pentamethylnitrobenzene, under the specific reaction conditions used.

Experimental Section

All solvents, benzene, toluene, mesitylene, and 9-nitroanthracene, were the highest purity materials commercially available, purified by the usual methods before use. Pentamethylnitrobenzene was prepared by nitration of pentamethylbenzene with nitronium tetrafluoroborate.[12] Nafion-H was prepared by treatment of the commercial DuPont Nafion-K resin with dilute nitric acid, as described previously.[1]

General Procedure for Transfer Nitration. A solution of 9-nitroanthracene or pentamethylnitrobenzene (1 g) in the aromatic hydrocarbon (15 mL) was mixed with the acid catalyst (1 g) in a Teflon-lined, stainless steel bomb. The reaction mixture was heated to 180–190 °C for 6 h. The bomb was subsequently allowed to cool to room temperature and opened, and the products were worked up.

When Nafion-H was used as a catalyst, the reaction mixture was filtered, and the solid catalyst washed with chloroform (3 × 10 mL). The filtrate was concentrated and the products were analyzed by gas chromatography.

When HF:SbF$_5$ and HF:TaF$_5$ were used as catalysts, the reaction mixture was quenched with 10% aqueous sodium bicarbonate and extracted with chloroform (100 mL). The chloroform extract was dried over anhydrous sodium sulfate, concentrated, and analyzed by gas chromatography.

Protolytic Denitration of 9-Nitroanthracene with HF:TaF$_5$ in the Presence of *n*-Butyl Sulfide. A mixture of 9-nitroanthracene (5 mL), *n*-butyl sulfide (15 mL), and HF:TaF$_5$ (10 mL) was heated in a stainless steel bomb at 160° for 16 h. The reaction mixture was cooled to room temperature, extracted with benzene, and washed with 10% aqueous sodium bicarbonate solution and brine. The extract was dried over anhydrous sodium sulfate and evaporated to dryness. The residue was sublimed to give 250 mg (28%) of anthracene.

Analysis of Products. All reaction products were analyzed by gas–liquid chromatography, using a Varian Model 3700 gas chromatograph equipped with hydrogen flame ionization detector and using a 9 ft × 1/8 in. stainless steel column packed with 1.75% butanediol succinate on Chromosorb W (80–100 mesh). Nitro compounds were identified by comparison of retention times with those of authentic samples on the same column.

Determination of Kinetic Hydrogen Isotope Effects. Competitive Nitration of Benzene/Benzene-*d*$_6$, Naphthalene/Naphthalene-*d*$_8$, and Anthracene/Anthracene-*d*$_{10}$. A mixture of benzene (or naphthalene) (20 mmol) and benzene-*d*$_6$ (or naphthalene-*d*$_8$) (20 mmol) was dissolved in nitromethane (75 mL), and a solution of nitronium hexafluorophosphate (0.96 g, 5 mmol) in nitromethane (10 mL) was added with vigorous stirring, while maintaining the reaction mixture at 25 °C. In the case of anthracene/anthracene-*d*$_{10}$, 2.5 mmol of each was dissolved in nitromethane (200 mL), and nitrated with nitronium hexafluorophosphate (0.29 g, 1.5 mmol) dissolved in nitromethane (10 mL).

After 30 min, the reaction mixture was quenched with 10% aqueous sodium bicarbonate and extracted with ether (100 mL). The ethereal extract was washed with brine and dried over anhydrous sodium sulfate. The dried extract was concentrated and the product ratios were determined by GLC–mass spectrometry on a DuPont 21-094 mass spectrometer coupled to a Varian Associates Aerograph Model 2700 gas chromatograph.

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Effect of Acid Concentration on the Partitioning of the Tetrahedral Intermediate in the Hydrolysis of Thioacetanilide[1]

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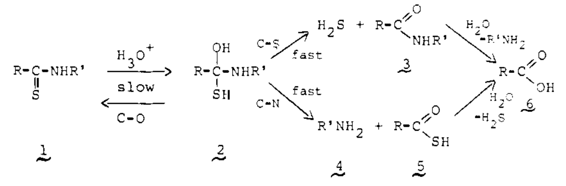
Contribution from the Department of Chemistry, McGill University, Montreal, Quebec, Canada H3A 2K6. *Received August 11, 1978*

Abstract: In dilute sulfuric acid, the hydrolysis of thioacetanilide to acetic acid, hydrogen sulfide, and aniline takes place chiefly by C–S cleavage of the tetrahedral intermediate to give hydrogen sulfide and acetanilide as intermediates. As the concentration of sulfuric acid is raised from 1.1 to 36%, hydrolysis via C–N cleavage to give aniline and thioacetic acid as intermediates becomes progressively more important, and is the exclusive pathway in 48% acid. The results may be explained by postulating that C–S cleavage involves the neutral, and C–N cleavage the amino-protonated, tetrahedral intermediate.

Introduction

The acid-catalyzed hydrolysis of a thioamide (e.g., **1**) most probably involves the rate-determining formation of a tetrahedral intermediate **2**,[2,3] which can then undergo fast C–O cleavage to give starting material, C–S cleavage to give hydrogen sulfide and amide (**3**), or C–N cleavage to give ammonia or amine (**4**) and thio acid (**5**),[2,4] as shown in Scheme I. The amide and the thio acid are then hydrolyzed to car-

Scheme I



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