Ozone-mediated Nitration of Alkylbenzenes and Related Compounds with Nitrogen Dioxide

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In the presence of ozone, nitrogen dioxide exhibits a strong nitrating ability for alkylbenzenes at low temperatures, converting them into the corresponding nitro derivatives in high yield. The addition of a protonic acid as catalyst enhances considerably the ability of this nitrating system and leads to a good yield of polynitro compounds. The reaction is clean and proceeds rapidly without any accompanying side-chain substitution or aryl–aryl coupling. It shows no kinetic dependence on the concentration of substrates and, as far as can be judged from relative reactivities and isomer distributions of products, it gives the appearance of being an electrophilic aromatic process. A possible role for nitrogen trioxide has been suggested as the initial electrophilic agent for the nitration of alkylbenzenes.

Nitrogen dioxide (NO_2) is an inorganic compound, but it may be regarded as the nitro group itself from the standpoint of organic chemistry. Thus the direct attachment of nitrogen dioxide to organic molecules should lead to organic nitro compounds. This idea has been successfully applied to the industrial production of lower nitroalkanes, but in the case of nitroarenes it has failed because of the radical character and low affinity of nitrogen dioxide toward aromatic nuclei. Under forced conditions, *i.e.*, at elevated temperatures or upon irradiation, nitrogen dioxide reacts with a wide variety of arenes to produce a complicated mixture of products arising from addition, substitution and oxidative degradation.[1]†

Recently, we have observed that lower nitrogen oxides such as nitric oxide, dinitrogen trioxide and nitrogen dioxide are activated in the presence of ozone to react smoothly with a variety of arenes, giving the corresponding nitro derivatives in high yield.[2] Although the interaction between lower oxides of nitrogen and ozone has been the subject of numerous reports because of its implications to environmental problems such as ozone depletion and air pollution, no attempts have hitherto been made to apply it to organic synthesis. In the present paper we describe the reaction of a series of alkylbenzenes with nitrogen dioxide in the presence of ozone, the results of which appear to provide a new non-acidic methodology for preparative aromatic nitration as a promising pollution-free substitute for the classical, yet currently ongoing, commercial process based on nitric acid–sulfuric acid.[3]

Results and Discussion

Nitrogen dioxide is a weak electrophile of radical character. Thus, in the presence of an appropriate acid or metal catalyst, it can act as a nitrating agent for aromatic systems. In 1927 Pinck showed that aromatic compounds such as benzene and naphthalene were easily nitrated by nitrogen dioxide in conc. sulfuric acid.[4] The effective species involved therein is no doubt the nitronium ion, since Raman spectroscopic[5] and cryoscopic studies[6] of solutions of nitrogen dioxide in sulfuric acid have demonstrated the presence of this ion in the solution. Nitration with nitrogen dioxide can also be effected in the presence of aluminium trichloride,[7] boron trifluoride,[8] trifluoroacetic acid,[9] metallic palladium[10] or palladium(II) salts.[11] In the second case, nitrogen dioxide and boron trifluoride form a mixture of nitronium and nitrosonium tetrafluoroborates

which is the effective reagent,[12] while in the last case the π-complexation of an aromatic compound with palladium(II), followed by nucleophilic attack by nitrite anion, was proposed as a possible mechanism for nitration.[11] Reaction in acetic anhydride apparently involves complicated addition–elimination sequences.[13]

Highly activated aromatics such as phenols,[14] phenolic ethers[15] and *N,N*-dimethylaniline,[16] as well as polycyclic aromatic hydrocarbons,[17] can be easily nitrated with nitrogen dioxide alone. Nitration of phenols and phenolic ethers proceeds almost certainly *via* a nitrosation followed by an oxidation, often yielding a high proportion of *para*-nitro compounds.[18] Polycyclic aromatic hydrocarbons have generally been taken to react with nitrogen dioxide *via* the addition–elimination mechanism,[19] but recently the nitrosated form of dinitrogen tetraoxide was proposed as a novel attacking species.[20] For substrates less reactive than chrysene the addition of an acid catalyst is required for the nitration to proceed at reasonably fast rates.[20]

Qualitative Description of the Reaction.—When a stream of ozonized oxygen or air was introduced into a solution of an alkylbenzene in dry dichloromethane in the presence of an excess of nitrogen dioxide below 0 °C, the substrate was rapidly nitrated on the ring to afford an isomeric mixture of mononitro derivatives in good to moderate yield (Scheme 1). Table 1
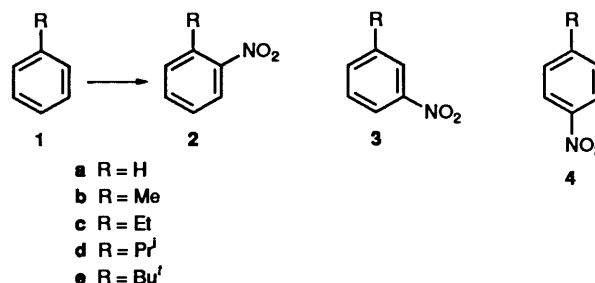
Scheme 1 *Reagents and conditions:* NO_2–O_3, CH_2Cl_2, < 0 °C, 3 h

shows the yields and isomer distributions of mononitration products obtained from four alkylbenzenes. Reaction of toluene **1b** occurred exclusively on the ring, giving a mixture of *o*-, *m*- and *p*-nitrotoluene in the proportions 57:2:41. These proportions are very close to those of the *o*:*m*:*p* proportions observed in the nitrations with mixed acid (56.5:3.1:40.4)[21] and nitric acid (56.9:2.8:40.3) in acetic acid.[21] Other alkylbenzenes also reacted smoothly to afford the corresponding

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† Caution: a mixture of liquid nitrogen dioxide and an aromatic hydrocarbon is described as being highly explosive.

Table 1 Nitration of benzene and alkylbenzenes with NO_2-O_3 [a]

Substrate	Yield (%)	$o:m:p$	o/p
1a	65		
1b	51 [b]	57:2:41	1.39
1c	79 [b]	44:3:53	0.83
1d	95 [b]	23:4:73	0.32
1e	99 [b]	13:6:81	0.16

[a] Reactions were carried out using a 1:10 v/v mixture of alkylbenzene and dichloromethane for 3 h at −10 °C. [b] Combined yields of isomeric nitration products.

Table 2 Effect of additives on the yields and isomeric distributions in the nitration of toluene with NO_2-O_3 [a]

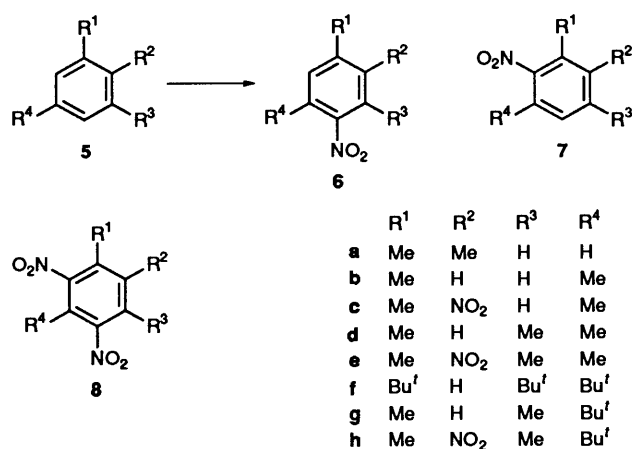| Additive	Yield (%)	$o:m:p$
None	51	57:2:41
$AlCl_3$ (1 mol equiv.)	53	50:6:44
Molecular sieves 4Å (40 weight%)	76	57:3:40
$BF_3 \cdot OEt_2$ (3.5 mol%)	78	57:3:40

[a] See footnote in Table 1.

mononitro compounds, mainly the *ortho-* and *para-*nitro isomers in accord with the ionic nature of the reaction. As expected, the *ortho/para* isomer ratios of nitroalkylbenzenes decreased as the steric bulk of alkyl groups increased.

The reaction of toluene **1b** with nitrogen dioxide was reported to give three isomeric nitrotoluenes, together with significant amounts of nitro(phenyl)methane and benzaldehyde.[22] The nitrotoluenes obtained under the irradiation conditions consisted of *ortho* (37%), *meta* (38%) and *para* isomers (25%).[23] The isomer distribution indicates that the reaction proceeded *via* a free-radical process. Nitration of alkylbenzenes with nitrogen dioxide in the presence of a perfluorinated resinsulfonic acid (Nafion-H) occurs quite slowly.[22] Under such conditions, nitration of toluene is reported to give nitrotoluenes, nitro(phenyl)methane and benzaldehyde and the isomeric composition of nitrotoluenes (*o-*, 49%; *m-*, 6%; *p-*, 45%) shows that the products are formed *via* the typical electrophilic aromatic substitution. Quite different from these reported reactions of alkylbenzenes with nitrogen dioxide in the presence or absence of a catalyst, neither side-chain substitution nor oxidation was observed in the present ozone-mediated nitration.

Reactions were mostly conducted using a mixture of substrate (5 cm³) and solvent (50 cm³) under continuous feeding of ozone at a rate of 10 mmol h⁻¹ in the presence of excess of nitrogen dioxide, unless otherwise mentioned. When the reaction was conducted using a smaller amount of substrate (10 mmol) in the same volume of solvent at below 0 °C, it was complete after 1 h. The nuclear nitration occurred so easily with the nitrogen dioxide-ozone system that abstraction of the α-hydrogen from the side-chain, leading to oxidation products, did not intervene in the reaction at all. In order to improve the yields of nitration products, the effect of several additives was investigated using toluene as a common substrate and some of the results obtained are shown in Table 2.

Molecular sieves 4Å and boron trifluoride-diethyl ether were effective as catalyst, but anhydrous aluminium trichloride did not catalyse the reaction so much. Nitrogen dioxide and gaseous boron trifluoride are known to form a stable complex $BF_3 \cdot N_2O_4$, which can act as a nitrating agent for aromatic compounds.[8] Thus, the nitration of toluene with nitrogen dioxide-ozone in the presence of boron trifluoride-diethyl ether would probably involve such a complex as an active species.

Di- and tri-alkylated benzenes **5a**, **5b**, **5d** and **5f** similarly underwent nitration (Scheme 2, Table 3). When *o*-xylene **5a** was

	R^1	R^2	R^3	R^4
a	Me	Me	H	H
b	Me	H	H	Me
c	Me	NO_2	H	Me
d	Me	H	Me	Me
e	Me	NO_2	Me	Me
f	Bu^t	H	Bu^t	Bu^t
g	Me	H	Me	Bu^t
h	Me	NO_2	Me	Bu^t

Scheme 2 *Reagents and conditions:* NO_2-O_3, CH_2Cl_2, catalyst, <0 °C

treated with nitrogen dioxide in the presence of ozone, two mononitro derivatives **6a** and **7a** were obtained in 80% combined yield, together with small amounts of dinitro isomers. The isomer ratio of the mononitration products, 3-nitro/4-nitro 0.74:1, was in accord with the electrophilic nature of the reaction. The reaction of *o*-xylene with nitric acid in the presence of Nafion-H is reported to give nitro-*o*-xylenes with a 3-nitro/4-nitro ratio of 0.82:1.[22] A similar nitration of *m*-xylene **5b** gave a mixture of 2-nitro and 4-nitro isomers **7b** and **6b** in the ratio of 0.18:1,[22] while the value of this ratio was 0.12:1 in the present case.

In the presence of Nafion-H, *p*-xylene (**5**; $R^2 = R^4 = $ Me) was nitrated with nitric acid to give nitro-*p*-xylene in 60% yield.[22] In contrast, treatment of *p*-xylene with nitrogen dioxide-ozone resulted in the formation of a complicated mixture of ring- and side-chain-substitution products. This result was not unexpected, since polymethylbenzenes with a pair of methyl groups in a *para* relationship often suffer extensive side-chain substitution *via* *ipso*-attack of an electrophile.[24]

When the aromatic ring bears two or three alkyl groups, it was easily nitrated to afford polynitro derivatives. The polynitration was facilitated by the presence of an appropriate catalyst such as boron trifluoride-diethyl ether or methanesulfonic acid (Table 4).

Further nitration of aromatic nitro compounds is usually carried out under conditions of strong acid or elevated temperature. For example, dinitrobenzenes can be obtained in 85–97% yield by the reaction of nitrobenzene with nitric acid in the presence of a large amount of trifluoromethanesulfonic acid.[*,25] A solution of nitrogen dioxide in fuming sulfuric acid is known to convert nitrobenzene into dinitrobenzene in 49–93% yield at a temperature of 60–75 °C.[4] As shown in Table 4, nitrobenzene **2a** (≡3a≡4a) could be nitrated with nitrogen dioxide-ozone in the presence of methanesulfonic acid at −10 °C to produce a mixture of three isomeric dinitrobenzenes (*o*:*m*:*p*, 8:91:1) in nearly quantitative yield. In this case, *meta*-substitution was slightly more favoured as compared with the ordinary nitration based on nitric acid.

o-Nitrotoluene **2b** reacted smoothly at 0 °C or below with nitrogen dioxide-ozone in the presence of a catalytic amount of boron trifluoride-diethyl ether, giving a 69:31 mixture of 2,4- and 2,6-dinitrotoluenes. The isomer distribution of dinitrotoluenes was rather different from those (81–89:17–10) obtained by using nitric acid.[*,25] Nitration of *o*-nitrotoluene **2b** with the $BF_3 \cdot N_2O_4$ complex is reported to form 2,4- and 2,6-

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* The acid strength of trifluoromethanesulfonic acid is 427 times as great as that of nitric acid and 14 times as great as that of sulfuric acid.[25]

Table 3 Mononitration of some di- and tri-alkylbenzenes with NO_2–O_3 [a]

Substrate	Reaction time (t/h)	Products (%)
5a	3	3-nitro 7a (34)
		4-nitro 6a (46)
		dinitro 8a (3)
5b	3	2-nitro 7b (9)
		4-nitro 6b (78)
		dinitro 6c + 8b (11)
5d	0.5	2-nitro 6d (≡7d) (98)
5f	0.5	2-nitro 6f (≡7f) (96)

[a] Reactions were carried out using a solution of substrate (10 mmol) in dichloromethane (50 cm^3) at −10 °C for 3 h.

Table 4 Nitration of nitrobenzene and nitrotoluenes, and polynitration of some di- and tri-alkylbenzenes with NO_2–O_3 [a]

Substrate	Additive [b]	Reaction time (t/h)	Product (%)
2a	A	9	o-dinitro (8)
			m-dinitro (91)
			p-dinitro (1)
2b	B	3	2,4-dinitro (48)
			2,6-dinitro (21)
4b	B	3	2,4-dinitro (59)
5b	A	9	4,6-dinitro 6c (59)
			2,4,6-trinitro 8c (9)
5d	none	1	2-nitro 6d (≡7d) (10)
			2,4-dinitro 8d (90)
5d	A	9	2-nitro 6d (≡7d) (1)
			2,4-dinitro 8d (3)
			2,4,6-trinitro 8e (96)
5f	none	3	dinitro 8f (83)
5g	A	12	2,4,6-trinitro 8h (80)

[a] See footnote in Table 3. [b] A: Methanesulphonic acid (0.5 mol equiv.) was used. B: Boron trifluoride–diethyl ether (5 mol%) was used.

Table 5 Effect of some protonic acids as additive on the yield of nitrobenzene 2a [a]

Protonic acid	Amount added (mmol)	Enhancement of yield (%) [b]
100% HNO$_3$	40	12
98% H$_2$SO$_4$	4	16
MeSO$_3$H	4	20
	40	51
CF$_3$SO$_3$H [25]	4	50

[a] Reactions were carried out at 0 °C using a mixture of benzene (50 mmol) and dichloromethane (50 cm^3). [b] Protonic acid was added 1 h after the start of reaction, and the deviations from the reaction time/product yield regression line were compared at 1 h after the addition.

dinitrotoluenes in a 61:39 ratio.[8] With nitrogen dioxide–ozone p-nitrotoluene 4b was efficiently converted into the 2,4-dinitro derivative which, however, resisted further nitration.

2,4-Dinitromesitylene 8d (≡6c≡7e) was obtained in 90% yield by the reaction of mesitylene 5d with the nitrogen dioxide–ozone system even in the absence of acid catalyst. When 0.5 mol equiv. of methanesulfonic acid was added, the reaction went further to give 2,4,6-trinitromesitylene 8e in 96% yield, along with small amounts of mono and dinitro compounds. On addition of ethanol to the reaction mixture, pure trinitromesitylene 8e precipitated as fine needles. Under similar conditions, 1-tert-butyl-3,5-dimethylbenzene 5g could be fully nitrated in a single step to give pure 2,4,6-trinitro derivative 8h (musk

xylene),[26] in 80% isolated yield, while m-xylene 5b gave dinitro 6c and trinitro derivatives 8c in the ratio 7:1 in 70% yield.

Myhre et al. reported that the attempted nitration of 2,4,6-tri-tert-butylnitrobenzene 6f (≡7f) with 90% nitric acid alone or with other electrophilic nitrating agents such as mixed acid and nitronium tetrafluoroborate led to extensive skeletal rearrangement, resulting in the formation of two isomeric dinitro-3,5-di-tert-butyltoluenes.[27] Under our conditions, however, the hydrocarbon 5f underwent smooth nuclear nitration to yield the expected dinitro compound 8f as the sole major product in 83% isolated yield.

Kinetic Approach to the Elucidation of Reaction Mechanism.—The kinetics of the reaction of benzene and alkylated derivatives with nitrogen dioxide–ozone have been studied mainly by means of gas chromatography. In the presence of excess of nitrogen dioxide, one mole of ozone and one mole of arene produced one mole of nitration product. Therefore, the stoichiometry of the present nitration may be written as follows [equation (1)]. In the presence of an

$$ArH + 2NO_2 + O_3 \longrightarrow ArNO_2 + HNO_3 + O_2 \quad (1)$$
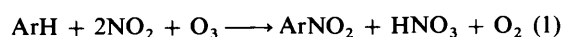
appropriate catalyst, however, the reaction became non-stoichiometric with respect to ozone and under favourable conditions the yield of nitration product increased up to 50% higher than that expected from equation (1). Protonic acids such as methanesulfonic and trifluoromethanesulfonic acids were found to be efficient as catalysts (Table 5). The nitric acid concurrently formed would probably be responsible for part of the increased yields, but molecular oxygen appears also to be involved as an additional oxidant under the conditions of these reactions.*

The gas-phase reaction between nitrogen dioxide and ozone has been known to produce dinitrogen pentaoxide via nitrogen trioxide, the trioxide being often called the nitrate radical.[28]

$$NO_2 + O_3 \longrightarrow [NO_2 \cdot O_3] \longrightarrow NO_3 + O_2 \quad (2)$$

$$NO_3 + NO_2 \longrightarrow N_2O_5 \quad (3)$$
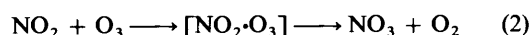
The first step [equation (2)] is a rapid rate-determining process.[29] According to the above equations (2) and (3), the electrophilic active species involved at the initial stage of the nitration should be either dinitrogen pentaoxide or nitrogen trioxide. With the progress of the reaction, however, there will be additional nitrating agents which arise from the complicated equilibria between the resulting nitrogen–oxygen compounds. Possible species include both ionic and molecular ones such as NO^+, NO_2^+, HNO_2, HNO_3, NO and N_2O_3, some of which are quite effective electrophiles under acidic conditions. Therefore, it is not easy at present to delineate the mechanistic course of this novel type of nitration, but a few prominent features are worthy of mention for a better understanding of the reaction process.

First, the reaction time/product yield profiles of the nitration of compounds 1a, 1b and 5d all ran linearly over a wide range of reaction times until the substrates were completely consumed (Fig. 1). Since the rate of introduction was kept constant both for nitrogen dioxide and ozone throughout the reaction, the linear profiles could be regarded as showing a zeroth-order reaction. All substrates examined were nitrated in the range of reaction rates 8.9–10.0 mmol h^{-1}, while the amount of ozone introduced into the reaction system was 10.0 mmol h^{-1}. The

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* In the presence of these protonic acids, the nuclear nitration of alkylbenzenes occurred slowly with nitrogen dioxide alone under an atmosphere of oxygen.
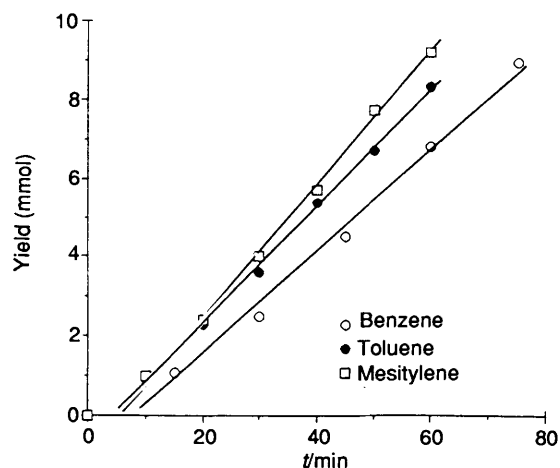
Fig. 1 Relationship between the yield of nitration product and reaction time for nitration of benzene, toluene and mesitylene. Reactions were carried out using a solution of substrate (10 mmol) in dichloromethane (50 cm³) at −10 °C.

Table 6 Relative rates and partial rate factors for nitration with NO_2–O_3[a]

R	k_{PhR}/k_{PhH}	f_o^R	f_m^R	f_p^R
MeO	510	1020		1020
PhO	300	170		560
Me	32	57	3	71
Et	32	47	3	96
ⁱPr	21	17	3	92
ᵗBu	23	7	3	120
F	0.13	0.070		0.68
Cl	0.055	0.076		0.18

[a] In dichloromethane at 0 °C.

Fig. 2 Relationship between the partial rate factors for nitration with NO_2–O_3 and Brown's σ^+ constants. (ρ −6.8, r 0.952)

linearity of the profiles was excellent, with the values of the correlation coefficient 0.997–0.998. The use of a five-times larger amount of substrate brought only a less than 5% variation of the slope in Fig. 1. Thus, we can conclude that the effective concentration of ozone in the reaction system is the rate determinant for the nitration. This observation contrasts with an early report that mesitylene was nitrated with nitrogen dioxide nearly 10^4-times faster than was benzene.[30] As a control, mesitylene 5d was treated with nitrogen dioxide in the absence of ozone and after 3 h nitromesitylene 6d (≡7d) was obtained in 2.5% yield. This amount corresponds to a reaction rate of 0.08 mmol h⁻¹ and so we can safely neglect the role of the nitration by nitrogen dioxide alone.

Nitration of alkylbenzenes went smoothly to completion in the presence of excess of nitrogen dioxide, but under the conditions of a slight excess of ozone the reaction was quite slow and incomplete. Interestingly, the presence of a large excess of nitrogen dioxide was found to work adversely, slowing down the reaction.

The relative reactivities of benzene 1a and the four alkylbenzenes 1b–1e were determined, along with those of two halogenobenzenes and two phenolic ethers, by using the conventional competition method. The relative rates were followed by gas chromatography until one of the two arenes underwent 10% conversion and the relative reactivities were calculated from the ratios of the initial concentrations and product concentrations. The results obtained are summarized in Table 6, together with the respective partial rate factors. Presented in Fig. 2 is a Hammett plot of the *meta* and *para* values of the partial rate factors *versus* Brown's σ^+ constants. Except for the methoxy group represented by a solid circle, this plot produced a straight line with a p-value of −6.8 and a correlation coefficient r of 0.952. From Table 6 and Fig. 2, we can easily see the general trends of common electrophilic aromatic substitution. Our mechanistic considerations based on these and other findings will be reported in a separate paper.

Dinitrogen pentaoxide is the likely agent for the present nitration, but nitrogen trioxide also provides an attractive alternative as this compound represents the initial product from the interaction of nitrogen dioxide and ozone. The trioxide is highly electron-deficient and therefore a strong oxidant (E^0 2.3 V vs. normal hydrogen electrode).[31] Although the literature contains a few references on the reaction of alkylbenzenes with nitrogen trioxide,[32] no example has been reported yet of the ring nitration of alkylbenzenes by this radical species. Baciocchi

et al. investigated the laser photolysis of cerium(IV) ammonium nitrate (CAN) in acetonitrile in the presence of aromatic compounds and confirmed the involvement of electron transfer in the side-chain-substitution process.[33] They suggested that the effective species for the side-chain oxidation was nitrogen trioxide generated in the photolysis of CAN. The reaction was very fast and was facilitated by the presence of an electron-donating group on the aromatic ring.

In order to see which one of the two primary electrophiles, dinitrogen pentaoxide and nitrogen trioxide, plays the more important role in the present nitration, we have compared the behaviours of benzyltrimethylsilane 9 toward dinitrogen pentaoxide and nitrogen dioxide–ozone. Silane 9 is known to be easily oxidized to generate the radical cation,[34] which will then release the trimethylsilyl cation to give the benzyl radical. The reaction of compound 9 with dinitrogen pentaoxide in dichloromethane at 0 °C gave, after 1 h, a 5:2-mixture of 2- and 4-nitrobenzyltrimethylsilanes 10 and 11 in 87% yield, with little side-chain-substitution products being formed. In marked contrast, the ozone-mediated reaction of compound 9 with nitrogen dioxide under similar conditions led to extensive C–Si bond cleavage, giving a complex mixture composed of benzyl nitrates, nitro(phenyl)methanes and other products. The trapping of the benzyl radical by the ambient nitrogen dioxide molecule will lead to benzyl nitrite 12 and nitro(phenyl)methane 13, and the former compound easily undergoes NO–NO_2 exchange to form the nitrate 14 in the presence of excess of nitrogen dioxide (Scheme 3). With nitrogen dioxide or ozone alone, the silane 9 remained almost intact under the conditions employed.

The above findings are highly suggestive of the important role of nitrogen trioxide as the effective electrophile in the nitration of electron-rich substrates, such as alkylated benzenes and phenolic ethers. With less electron-rich or electron-deficient
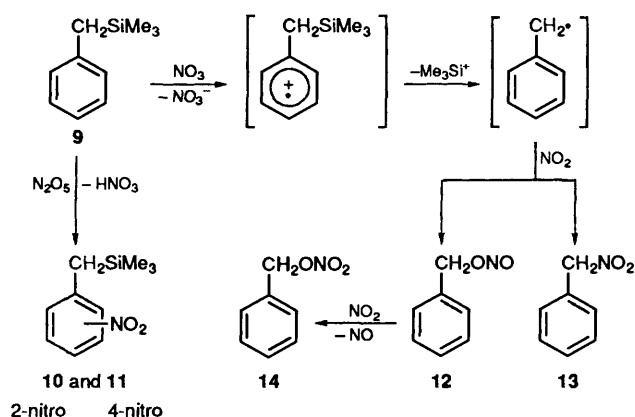
Scheme 3

substrates, however, the oxidative electron transfer would become a less favourable process for arenes, and nitrogen trioxide would react preferentially with nitrogen dioxide to form dinitrogen pentaoxide. Under these circumstances, the nitration is expected to follow the conventional ionic or molecular process well established for dinitrogen pentaoxide.[35]
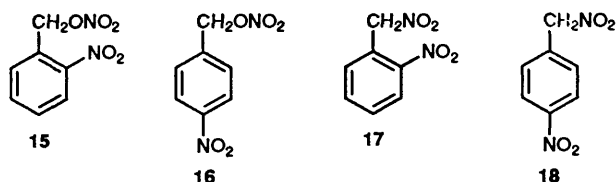
Experimental

General Experimental Details.—IR spectra were recorded on an FT-IR DR 8000/8100 IR spectrophotometer for pure liquid films or KBr pellets. ^{1}H NMR spectra were obtained with a Varian Gemini-200 spectrometer for CDCl$_3$ solutions, with SiMe$_4$ as internal standard. J Values are given in Hz. Mass spectra were recorded on a Shimadzu GCMS QP-2000A spectrometer at an ionization potential of 70 eV. GLC analyses were performed on a Shimadzu GC 14A gas chromatograph, using a CBP1-M25-025 column [25 m × 0.2 mm (i.d.)]. Merck precoated silica gel sheets 60F-254 were used for TLC. Silica gel column chromatography was performed with Wakogel 200 (100–200 mesh) support with hexane–ethyl acetate (5–10:1) as eluent. All m.p.s were determined on a Yanagimoto hot-stage apparatus and are uncorrected. Products were identified by IR, ^{1}H NMR, MS and elemental analysis, or by direct comparison with authentic specimens.

Reagents and Solvents.—All reagents and solvents were reagent-grade commercial samples. Anhydrous dichloromethane was distilled from calcium hydride. Benzene and liquid alkylbenzenes were distilled and solid alkylbenzenes were recrystallized from ethanol–hexane prior to use. Nitrogen dioxide [99% pure; major impurity nitrogen monoxide (NO), plus small amounts of nitrogen] was used as obtained in liquid form from Sumitomo Seika Co. Ltd. Dinitrogen pentaoxide was prepared by the literature procedure.[36] A Nippon Ozone Co. Ltd., type ON-1-2 apparatus was used for the generation of ozone. The machine produced ozone at a rate of 10 mmol h^{-1} under the following conditions: oxygen flow 10 dm^3 h^{-1}; applied voltage 80 V. Calibration of the ozone generator was by iodometric titration. Oxygen gas was dried by passage through a silica gel-packed tube before entering the ozone generator, because moisture was found to have a deleterious effect on the efficiency of the machine.

Nitration of Benzene **1a**.—In a three-necked 50 cm^3 flask fitted with two gas inlet tubes and a vent which permits waste gas to escape was placed a solution of benzene **1a** (10 mmol) in freshly distilled dichloromethane (50 cm^3). The mixture was cooled to -10 °C externally by an ice–salt-bath, while a stream of ozonized oxygen was introduced through the gas inlet tube, which should dip below the surface of the liquid in the flask, and a stream of nitrogen dioxide was slowly introduced from another inlet tube which opened just over the surface of the liquid mixture. Throughout the reaction, both ozonized oxygen and nitrogen dioxide were fed continuously at a low flow rate. It was necessary to carry out the reaction in the presence of an excess of nitrogen dioxide, otherwise the nitration was quite slow and incomplete. Within 1 h the reaction ran to completion at the mononitration stage (**2a≡3a≡4a**) and was quenched by the addition of aq. sodium hydrogen carbonate. The organic phase was separated, washed with water, and dried over sodium sulfate. Removal of the solvent under reduced pressure left nitrobenzene **2a** (≡**3a≡4a**) in nearly quantitative yield.

Nitration of Alkylbenzenes.—To a stirred solution of an alkylbenzene (5 cm^3) in dry dichloromethane (50 cm^3) at 0 °C or below were slowly introduced streams of ozonized oxygen and nitrogen dioxide as described above. The mixture soon turned dark brown. After 1 h the reaction was quenched with aq. sodium hydrogen carbonate. The organic layer was separated and worked up as usual to obtain nitro compounds as an oily or solid residue. The product compositions were determined by GLC or GC-MS.

Polynitration of Alkylbenzenes.—Into a stirred solution of an alkylbenzene (10 mmol) and an appropriate catalyst (0.5 mol equiv. of methanesulfonic acid or 5 mol% of boron trifluoride–diethyl ether) in dry dichloromethane (50 cm^3) kept between -10 and 0 °C by an ice–salt-bath, were slowly introduced ozonized oxygen and nitrogen dioxide. The progress of the reaction was monitored by TLC. After an appropriate time the reaction mixture was worked up as described above to give the corresponding di- and/or tri-nitration products as an oily mass or a solid residue. GLC analyses of the crude product mixtures suggested that nitration proceeded nearly quantitatively and that losses occurred mainly on work-up. Spectral data and m.p.s of several less common products are shown below.

2,4-Dinitro-m-xylene **8b**: m.p. 84–86 °C (lit.,[37] 82 °C); v_{max}(neat)/cm^{-1} 2938, 1520, 1461, 1342, 875, 833 and 745; δ_H(200 MHz) 2.38 (3 H, s), 2.43 (3 H, s), 7.37 (1 H, d, J 8.42) and 7.94 (1 H, d, J 8.42); m/z 196 (M$^+$, 47.5), 179 (99.8), 133 (56.0), 104 (72.1), 103 (90.9), 91 (86.8), 78 (83.1) and 77 (100).

4,6-Dinitro-m-xylene **6c**: m.p. 94–95 °C (lit.,[37] 93 °C); v_{max}(KBr)/cm^{-1} 2940, 1626, 1518, 1461, 1385, 1340, 916, 840 and 744; δ_H(200 MHz) 2.69 (6 H, s), 7.38 (1 H, s) and 8.71 (1 H, s); m/z 196 (M$^+$, 31.2), 179 (91.7), 162 (27.1), 104 (45.9), 103 (45.4), 91 (68.8), 78 (87.6), 77 (100), 65 (54.1) and 63 (50.5).

2,4,6-Trinitro-m-xylene **8c**: m.p. 184–185 °C (lit.,[37] 177 °C); v_{max}(KBr)/cm^{-1} 3110, 1615, 1597, 1538, 1456, 1393, 1377, 1352, 1005, 905, 872, 745, 727, 675, 656 and 627; δ_H(200 MHz) 2.56 (6 H, s) and 8.65 (1 H, s); m/z 241 (M$^+$, 4.5), 224 (57.2), 149 (66.1), 148 (20.7), 103 (69.5), 90 (33.8), 89 (31.1), 77 (52.3), 76 (38.9), 75 (29.0), 63 (48.9), 53 (33.4), 51 (100) and 50 (33.9).

2,4-Dinitromesitylene **8d**: m.p. 84–85 °C (lit.,[38] 86 °C); v_{max}(KBr)/cm^{-1} 2942, 1615, 1537, 1471, 1389, 1368, 1040, 881, 863, 834, 772, 696 and 688; δ_H(200 MHz) 2.22 (3 H, s), 2.33 (6 H, s) and 7.27 (1 H, s); m/z 210 (M$^+$, 48.2), 193 (100), 118 (33.5), 91 (73.9), 77 (50.0) and 65 (41.7).

2,4,6-Trinitromesitylene **8e**: m.p. 230–232 °C (lit.,[39] 232–233 °C); v_{max}(KBr)/cm^{-1} 2886, 1550, 1402, 1356, 1030, 872, 733, 687 and 625; δ_H(200 MHz) 2.28 (9 H, s); m/z 255 (M$^+$, 30.9), 238 (37.8), 208 (25.8), 193 (51.2), 162 (22.6), 118 (24.6), 117 (74.3),

115 (26.2), 104 (50.4), 103 (29.5), 91 (45.5), 90 (36.4), 89 (47.3), 78 (39.8), 77 (84.3), 65 (96.8), 63 (69.8), 53 (62.3) and 51 (100).

5-*tert*-Butyl-2,4,6-trinitro-*m*-xylene **8h**: m.p. 113–114 °C (lit.,[26] 114 °C); v_{max}(KBr)/cm^{-1} 2858, 1561, 1473, 1392, 1376, 1345, 1211, 1167, 1031, 951, 889, 860 and 784; δ_H(200 MHz) 1.47 (9 H, s) and 2.18 (6 H, s); *m/z* 297 (M$^+$, 20.6) and 282 (100).

1,3,5-Tri-*tert*-butyl-2,4-dinitrobenzene **8f**: m.p. 293–295 °C (lit.,[27] 293–295 °C); v_{max}(neat)/cm^{-1} 2971, 1578, 1542, 1472, 1449, 1402, 1372, 1242, 1217, 1117, 932, 884, 833, 766 and 625; δ_H(200 MHz) 1.39 (18 H, s), 1.45 (9 H, s) and 7.72 (1 H, s); *m/z* 336 (M$^+$, 18.2), 321 (34.1) and 57 (100).

Nitration of Benzyltrimethylsilane **9**.—(a) *With dinitrogen pentaoxide.* To a solution of benzyltrimethylsilane **9** (5 mmol) in dry dichloromethane (50 cm^3) cooled to 0 °C was added a solution of dinitrogen pentaoxide (5 mmol) in the same solvent (9 cm^3). After 1 h the reaction was quenched by the addition of aq. sodium hydrogen carbonate and the organic phase was separated, washed with brine, and dried over sodium sulfate. Evaporation of the solvent gave an oil, which was chromatographed on silica gel to give trimethyl-(2-nitrobenzyl)-silane **10** (0.67 g, 64%) and its 4-nitro isomer **11** (0.24 g, 23%).

Trimethyl(2-nitrobenzyl)silane **10**: oil; v_{max}(neat)/cm^{-1} 2957, 1609, 1522, 1345, 1250, 1150 and 851; δ_H(200 MHz) −0.01 (9 H, s), 2.57 (2 H, s), 7.12–7.23 (2 H, m), 7.46 (1 H, dd, *J* 1.43 and 7.53) and 7.92 (1 H, dd, *J* 1.42 and 8.18); *m/z* 194 (19.7), 149 (15.0), 120 (25.7), 92 (36.6), 75 (66.1) and 73 (100) (Found: C, 57.7; H, 7.4; N, 6.5. C$_{10}$H$_{15}$NO$_2$Si requires C, 57.40; H, 7.22; N, 6.69%).

Trimethyl(4-nitrobenzyl)silane **11**: oil; v_{max}(neat)/cm^{-1} 2957, 1597, 1518, 1345, 1250, 1210, 1148, 1109 and 855; δ_H(200 MHz) 0.00 (9 H, s), 2.22 (2 H, s), 7.10 (2 H, d, *J* 9.07) and 8.11 (2 H, d, *J* 8.79); *m/z* 209 (M$^+$, 8.2), 194 (12.1) and 73 (100) (Found: C, 57.6; H, 7.5; N, 6.7%).

(b) *With nitrogen dioxide–ozone.* A solution of the silane **9** (5 mmol) in dry dichloromethane (50 cm^3) was kept at 0 °C in an ice-bath, while streams of nitrogen dioxide and ozonized oxygen were slowly introduced from separate inlet tubes. After 1.5 h the reaction was quenched by the addition of aq. sodium hydrogen carbonate, and the organic phase was separated and worked up as usual. The oily product mixture was chromatographed on silica gel with a mixture of hexane and ethyl acetate (5:1) as eluent, to give nitrobenzyl nitrates (0.18 g, 18%) as the early eluates and (nitrophenyl)nitromethanes (0.14 g, 15%) as the late eluates. From the former eluates 2-nitrobenzyl nitrate **15** and its 4-nitro isomer **16** could be isolated by repeated chromatography.

2-Nitrobenzyl nitrate **15**: m.p. 25.5–26.5 °C; v_{max}(neat)/cm^{-1} 1645, 1582, 1530, 1345, 1281, 847, 789 and 731; δ_H(200 MHz) 5.90 (2 H, s), 7.58–7.73 (3 H, m) and 8.20 (1 H, d, *J* 8.14); *m/z* 152 (11.2), 136 (14.4), 121 (11.3), 104 (100), 77 (79.2) and 51 (84.2) (Found: C, 42.75; H, 2.95; N, 14.0. C$_7$H$_6$N$_2$O$_5$ requires C, 42.43; H, 3.05; N, 14.14%).

4-Nitrobenzyl nitrate **16**: m.p. 67–68 °C (lit.,[40] 66–68 °C); v_{max}(KBr)/cm^{-1} 1650, 1526, 1429, 1354, 1300, 1281, 864, 849, 741 and 698; δ_H(200 MHz) 5.54 (2 H, s), 7.60 (2 H, d, *J* 8.79) and 8.27 (2 H, d, *J* 8.75); *m/z* 198 (M$^+$, 5.1), 152 (65.1), 151 (54.6), 150 (39.8), 136 (30.8) 122 (41.6), 106 (34.4), 92 (29.0), 78 (81.6), 77 (100), 76 (68.2) and 75 (44.9).

From the latter eluates 2- and 4-nitrophenylnitromethanes **17** and **18** were similarly isolated; both were solids.

Nitro(2-nitrophenyl)methane **17**: m.p. 66–67 °C; v_{max}(KBr)/cm^{-1} 1615, 1560, 1532, 1429, 1375, 1348, 833, 791 and 714; δ_H(200 MHz) 5.82 (2 H, s), 7.48–7.76 (3 H, m) and 8.24 (1 H, d, *J* 9.04); *m/z* 136 (70.2), 89 (22.7) and 78 (100) (Found: C, 46.3; H, 3.3; N, 15.6. C$_7$H$_6$N$_2$O$_4$ requires C, 46.16; H, 3.32; N, 15.38%).

Nitro(4-nitrophenyl)methane **18**: m.p. 89–91 °C; v_{max}(KBr)/cm^{-1} 1563, 1530, 1350, 1266, 739 and 706; δ_H(200 MHz)

5.56 (2 H, s), 7.48 (2 H, d, *J* 8.79) and 8.31 (2 H, d, *J* 8.79); *m/z* 136 (100), 90 (39.2), 89 (43.4) and 78 (41.8) (Found: C, 46.5; H, 3.3; N, 15.3%).

Kinetic Measurements.—The rates of nitration of alkylbenzenes were followed by gas chromatography. All reactions were carried out under the same conditions as used for benzene and their courses were usually followed up to 90% completion. In a typical example, a solution of mesitylene **5d** (1.20 g, 10 mmol) and cyclododecane (0.1 g) (as an internal standard) in freshly distilled dichloromethane (50 cm^3) was employed for the kinetic study of nitration. The amount of nitromesitylene formed was measured at intervals of 10 min. The absolute rate was derived from the least-squares evaluation of the slope of the change of yield with time.

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