NO_2^+ Nitration Mechanism of Aromatic Compounds: Electrophilic vs Charge-Transfer Process

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Received October 1, 1999

The nitration of methylnaphthalenes with NO_2BF_4 and $NOBF_4$ was examined in order to shed light on the controversial aromatic nitration mechanism, electrophilic vs charge-transfer process. The NO_2^+ nitration of 1,8-dimethylnaphthalene showed a drastic regioselectivity change depending on the reaction temperature, where ortho-regioselectivity at −78 °C and para-regioselectivity at 0 °C were considered to reflect the electrophilic and the direct or alternative charge-transfer process, respectively, because the NO^+ nitration through the same reaction intermediates as in the NO_2^+ nitration via a charge-transfer process resulted in para-regioselectivity regardless of the reaction temperature. The NO_2^+ nitration of redox potential methylnaphthalenes higher than 1,8-dimethylnaphthalene gave a similar ortho-regioselectivity enhancement to 1,8-dimethylnaphthalene at lower temperature, thus reflecting the electrophilic process. On the other hand, the NO_2^+ nitration of redox potential methylnaphthalenes lower than 1,8-dimethylnaphthalene showed para-regioselectivity similar to the NO^+ nitration, indicating the direct or alternative charge-transfer process. In the presence of strong acids where the direct charge-transfer process will be suppressed by protonation, the ortho-regioselectivity enhancement was observed in the NO_2^+ nitration of 1,8-dimethylnaphthalene, suggesting that the direct charge-transfer process could be the main process to show para-regioselectivity. These experimental results imply that the NO_2^+ nitration proceeds via not only electrophilic but also direct charge-transfer processes, which has been considered to be unlikely because of the high energy demanding process of a bond coordination change between NO_2^+ and NO_2. Theoretical studies at the MP2/6-31G(d) level predicted ortho- and para-regioselectivity for the NO_2^+ nitration via electrophilic and charge-transfer processes, respectively, and the preference of the direct charge-transfer process over the alternative one, which support the experimental conclusion

Introduction

The nitration of aromatic compounds is one of the well-known aromatic substitutions and has been studied extensively for both scientific and industrial scope.[1] The mechanism of aromatic nitration with NO_2^+ has been considered as a typical electrophilic substitution (eq 1),[2] but it was suggested that the direct charge-transfer process (eq 2) could be likely with low redox potential aromatic compounds,[3] especially in photochemical nitration.[4] However, there has been no clear evidence for the direct charge-transfer process in the NO_2^+ nitration, and the direct charge-transfer process between aromatic compounds and NO_2^+ has been reported to be unlikely recently because high energy is necessary for the bond coordination change between NO_2^+ and NO_2.[5] On the other hand, the ipso attack of NO_2^+ (eq 3)[6−9] has been reported showing ortho-regioselectivity via the 1,2-shift of the NO_2 group to the ortho- from the ipso-position of the ipso σ-complex (eq 4).[7,8] During this process, homocleavage of the $C-NO_2$ bond of the ipso σ-complex sometimes occurs and has been recognized as an alternative charge-transfer process (eq 5) to produce the radical cation with NO_2.[8,9] Despite many recent studies using various nitration reagents such as NO_2,[10] NO_2-O_3,[11] and $C(NO_2)_4$,[12] the aromatic nitration mechanism with NO_2^+

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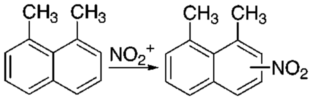
10.1021/jo991538u CCC: $19.00

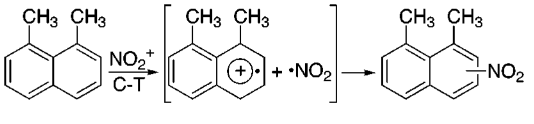
is still ambiguous due to the complexity of the reaction systems.

NO_2^+ Nitration *via* Electrophilic Process



(1)

NO_2^+ Nitration *via* Direct Charge-Transfer Process



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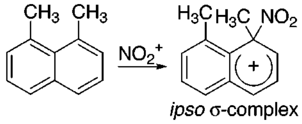

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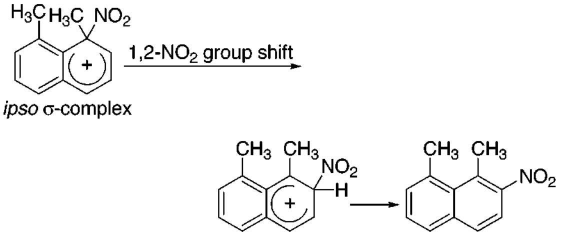

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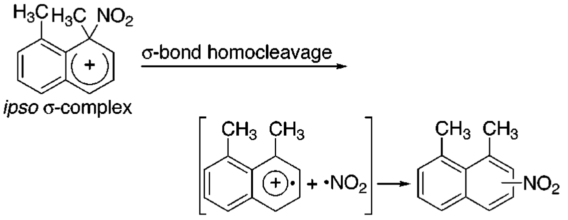
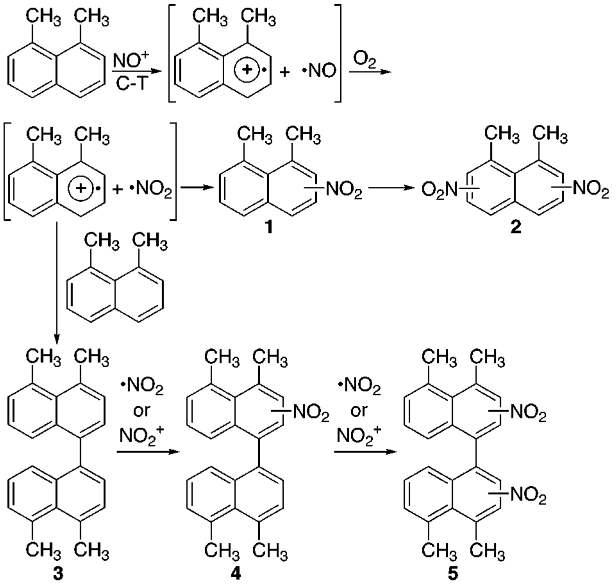
NO_2^+ Nitration *via* Alternative Charge-Transfer Process



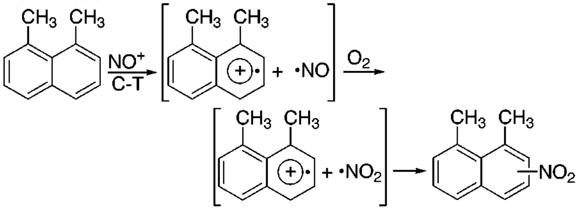
(5)

In our previous study, we found that the reaction of naphthalenes with NO^+ produces binaphthyls (**3**) via oxidation with four nitro products (**1**, **2**, **4**, and **5**) and the binaphthyl formation is prompted by strong acids (eq 6).[13] In this reaction, the NO^+ nitration (eq 7) proceeds via the same reaction intermediates, the radical cation and NO_2,[14] as in the NO_2^+ nitration via the charge-transfer processes (eqs 2 and 5). Therefore, we expected that the comparison of NO_2^+ with NO^+ nitration could shed light on the mechanism of the NO_2^+ nitration.



(6)

NO^+ Nitration



(7)

In this paper, we wish to report the results of the experimental and theoretical studies on the mechanism of the NO_2^+ nitration of aromatic compounds, namely, the direct charge-transfer process (eq 2), the ipso attack of NO_2^+ (eq 3), the 1,2-shift of the NO_2 group (eq 4), and the alternative charge-transfer process (eq 5) as shown

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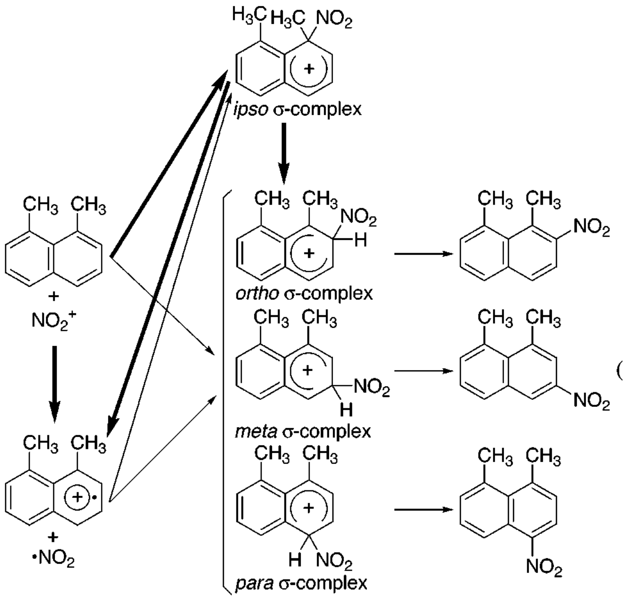
Table 1. Nitration of 1,8-Dimethylnaphthalene[a]

		products, yield (%)			
reagent	*T* (°C)	**1**	**2**	**3**	**4**
$NOBF_4$	0	31 (81:19)	0	0	5.1
$NOBF_4$	−78	8.9 (92:8)	0	6.9	1.4
NO_2BF_4	0	8.2 (78:22)	0	18	0
NO_2BF_4	−78	10 (25:75)	0	7.2	0

[a] The nitration was carried out using $NOBF_4$ (2.5 mmol) or NO_2BF_4 (2.5 mmol), 1,8-dimethylnaphthalene (2.5 mmol for $NOBF_4$ or 10 mmol for NO_2BF_4), and a mixture of CH_3CN (25 mL) with CH_2Cl_2 (25 mL) as a solvent for 1 or 2 h (for $NOBF_4$ at −78 °C) under air (for $NOBF_4$) or N_2 (for NO_2BF_4) atmosphere. Isomer ratio in parentheses is 1,8-dimethyl-4-/1,8-dimethyl-2-nitronaphthalene.

in eq 8 by the bold arrows, on the basis of the regioselectivity variation of NO_2BF_4 and $NOBF_4$ nitration under various conditions.



(8)

Results and Discussion

Nitration Experiments. Electrophilic vs Charge-Transfer Processes. First, the regioselectivity of the 1,8-dimethylnaphthalene nitration with NO_2BF_4 and $NOBF_4$ was examined at 0 and −78 °C in $CH_3CN-CH_2Cl_2$. These results are summarized in Table 1. Remarkable ortho-regioselectivity to the methyl group of 1,8-dimethylnaphthalene appeared in the NO_2^+ nitration at −78 °C, although para-regioselectivity was observed in other experiments. The NO_2^+ nitration of toluene also showed the ortho-regioselectivity enhancement at lower temperature where the isomer ratio ortho/meta/para was 64:3:33 and 73:1:26 at 30 and −78 °C, respectively.[15]

The results of the detailed experiments for temperature dependence of the NO_2^+ nitration regioselectivity of 1,8-dimethylnaphthalene are depicted in Figure 1, where the yields of **1** were almost constant at about 10% under these conditions. As the change in NO_2^+ nitration regioselectivity was quite drastic at about 0 °C, a number of NO_2^+ nitrations were reiterated. Interestingly, para- and ortho-regioselectivities appeared at random about 0 °C, indicating that the regioselectivity was quite sensitive to reaction temperature.[16] Taking into account the similar yields for **1** around the regioselectivity change point, the high energy demanding process of bond coordination change between NO_2^+ and NO_2,[5] and the para-regioselectivity for the NO^+ nitration, the regioselectivity change seems to reflect the reaction mechanism change depending on the reaction temperature, where ortho- and para-regioselectivities in the NO_2^+ nitration of 1,8-dimethylnaphthalene are derived from the electrophilic (eq 1) and the charge-transfer processes (eqs 2 and 5), respectively.

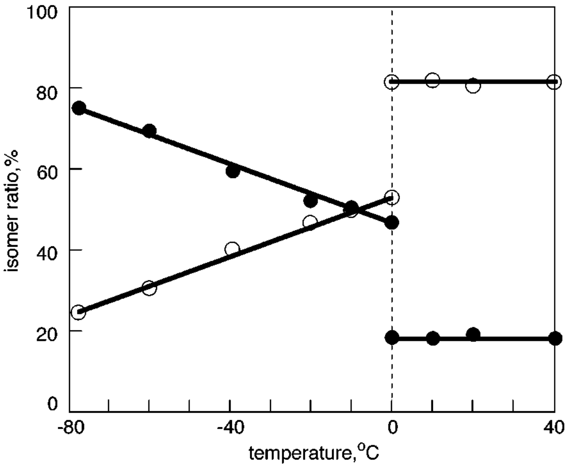


Figure 1. Temperature dependence of 1,8-dimethylnaphthalene NO_2^+ nitration isomer ratio. The nitration was carried out using NO_2BF_4 (2.5 mmol), 1,8-dimethylnaphthalene (10 mmol), and a mixture of CH_3CN (25 mL) with CH_2Cl_2 (25 mL) as a solvent for 1 h under N_2 atm. ○ and ● represent 1,8-dimethyl-4- and 1,8-dimethyl-2-nitronaphthalene, respectively.

The ortho-regioselectivity enhancement in the electrophilic NO_2^+ nitration (eq 1) has been suggested to originate via two steps that are the attack of NO_2^+ on the ipso-position to form the ipso σ-complex[6~9] (eq 3) and then the 1,2-shift of the NO_2 group to the ortho-position from the ipso-position of the ipso σ-complex to produce an ortho σ-complex resulting in ortho-regioselectivity (eq 4).[7,8] For the 1,2-shift of the NO_2 group, it has been also suggested that a part of the ipso σ-complex undergoes homocleavage of the $C-NO_2$ bond to produce the radical cation and NO_2 as an alternative charge-transfer process (eq 5) in the NO_2^+ nitration.[8,9] Para-regioselectivity for the reaction of the radical cation with NO_2 as the reaction intermediates for the direct charge-transfer process (eq 2) and the alternative one (eq 5) in the NO_2^+ nitration has been reported.[17] Therefore, we inferred that such a drastic regioselectivity change in the NO_2^+ nitration of 1,8-dimethylnaphthalene was caused by a mechanism change between the electrophilic (eq 1) and the direct charge-transfer process (eq 2) or the alternative one (eq 5).[18]

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(15) The NO_2^+ nitration of toluene was carried out according to the NO_2^+ nitration procedures. Only nitrotoluene was formed with 81 and 28% in yields at 30 and −78 °C, respectively.

(16) The NO_2^+ nitration has been known as a diffusion control reaction; therefore, the NO_2^+ nitration may proceed immediately at the diffusion surface when 1,8-dimethylnaphthalene is added to NO_2BF_4 solution with reaction heat production before formation of the homogenious solution. The local reaction heat production makes accurate reaction temperature control impossible, which may be one of the reasons for such a drastic regioselectivity change. (a) Coombes, R. G.; Moodie, R. B.; Schofield, K. *J. Chem. Soc. B* **1968**, 800. (b) Hartshorn, S. R.; Moodie, R. B.; Schofield, K.; Thompson, M. J. *J. Chem. Soc. B* **1971**, 2447.

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Table 2. Nitration of Naphthalene Derivatives[a]

substrate	reagent	T (°C)	products, yield (%) 1	2	3	4
naphthalene[b]	$NOBF_4$	0	28 (97:3)	0	0	2.5
	$NOBF_4$	−78	trace(98:2)	0	0	0
	NO_2BF_4	0	5.6(95:5)	0	0	0
	NO_2BF_4	−78	2.7(94:6)	0	0	0
1-methyl-naphthalene[c]	$NOBF_4$	0	31 (67:13:10:8:2)	0	3.1	48
	$NOBF_4$	−78	0.2(87:4:6:2:1)	0	2.8	0.5
	NO_2BF_4	0	7.7(54:34:6:6:0)	0	9.8	0
	NO_2BF_4	−78	8.8(48:47:3:2:0)	0	11	0.4
1,5-dimethyl-naphthalene[d]	$NOBF_4$	0	75 (89:11)	0	0	0
	$NOBF_4$	−78	3.7(94:6)	0	0	0
	NO_2BF_4	0	24 (88:12)	0	0	0
	NO_2BF_4	−78	5.6(67:33)	0	0	0
1,8-dimethyl-naphthalene[e]	$NOBF_4$	0	31 (81:19)	0	0	5.1
	$NOBF_4$	−78	8.9(92:8)	0	6.9	1.4
	NO_2BF_4	0	8.2(78:22)	0	18	0
	NO_2BF_4	−78	10 (25:75)	0	7.2	0
1,4-dimethyl-naphthalene[f]	$NOBF_4$	0	60 (90:10)	0	0	0
	$NOBF_4$	−78	3.2(97:3)	0	0	0
	NO_2BF_4	0	17 (93:7)	0	2.1	0
	NO_2BF_4	−78	5.7(97:3)	0	15	0
1,2-dimethyl-naphthalene[g]	$NOBF_4$	0	32 (86:14)	0	0	31
	$NOBF_4$	−78	2.6(88:12)	0	9.8	1.0
	NO_2BF_4	0	4.1(86:14)	0	32	2.0
	NO_2BF_4	−78	1.2(94:6)	0	25	0
1,3-dimethyl-naphthalene[h]	$NOBF_4$	0	48 (90:3:7)	0	0	31
	$NOBF_4$	−78	7.6(96:1:3)	0	18	0
	NO_2BF_4	0	14 (87:9:4)	0	9.6	0
	NO_2BF_4	−78	9.5(92:6:2)	0	6.7	0

[a] The nitration was carried out using $NOBF_4$ (2.5 mmol) or NO_2BF_4 (2.5 mmol), substrate (2.5 mmol for $NOBF_4$ or 10 mmol for NO_2BF_4), and a mixture of CH_3CN (25 mL) with CH_2Cl_2 (25 mL) as a solvent for 1 or 2 h (for $NOBF_4$ at −78 °C) under the air (for $NOBF_4$) or N_2 (for NO_2BF_4) atmosphere. [b] Isomer ratio in the parentheses is 1-nitro-/2-nitronaphthalene. [c] Isomer ratio in the parentheses is 1-methyl-4-/1-methyl-2-/1-methyl-5-/1-methyl-8-/1-methyl-3-nitronaphthalene. [d] Isomer ratio in the parentheses is 1,5-dimethyl-4-/1,5-dimethyl-2-nitronaphthalene. [e] Isomer ratio in the parentheses is 1,8-dimethyl-4-/1,8-dimethyl-2-nitronaphthalene. [f] Isomer ratio in the parentheses is 1,4-dimethyl-2-/1,4-dimethyl-5-nitronaphthalene. [g] Isomer ratio in the parentheses is 1,2-dimethyl-4-/1,2-dimethyl-8-nitronaphthalene. [h] Isomer ratio in the parentheses is 1,3-dimethyl-4-/1,3-dimethyl-2-/1,3-dimethyl-5-nitronaphthalene.

Table 3. Temperature Dependence of Nitration Regioselective Tendency[a]

substrate	nitration reagent $NOFB_4$	NO_2BF_4	redox potential[b] (V)
naphthalene	+ −	+ −	
1-methylnaphthalene	+	−	1.74
1,5-dimethylnaphthalene	+	−	1.67
1,8-dimethylnaphthalene	+	−	1.65
1,4-dimethylnaphthalene	+	+	1.63
1,2-dimethylnaphthalene	+	+	1.60
1,3-dimethylnaphthalene	+	+	1.60

[a] + and − represent para- and ortho-regioselective tendencies at lower temperature, respectively. + − represents no meaningful variation in regioselectivity by temperature. [b] Cited from ref 19. All potentials are given in V vs the Ag/AgCl electrode.

To evaluate the influence of the redox potential of the substrates on the mechanism, nitration using NO_2BF_4 and $NOBF_4$ with various methylnaphthalenes was examined at 0 and −78 °C. These results are tabulated in Table 2. In the case of NO^+ nitration, para-regioselectivity was more preferable at lower temperature in all substrates. However, the NO_2^+ nitration showed two regioselective tendencies depending on the substrates. One was that para-regioselectivity became preferable at lower temperature similar to the NO^+ nitration, and another was that ortho-regioselectivity was enhanced at lower temperature similar to the NO_2^+ nitration of 1,8-dimethylnaphthalene. Naphthalene did not show a meaningful difference in regioselectivity under these conditions.

The relationship between the regioselective tendency of nitration with redox potential of the substrates cited from the reference[19] is shown in Table 3. While the para-regioselectivity was observed in both NO_2^+ and NO^+ nitrations for the lower redox potential substrates than 1,8-dimethylnaphthalene, the ortho-regioselectivity enhancement appeared at lower temperature in the NO_2^+ nitration when substrates had a higher redox potential than 1,8-dimethylnaphthalene. As mentioned before, the ortho-regioselectivity enhancement has been considered to be derived from the ipso attack of NO_2^+ (eq 3) and then the 1,2-shift of the NO_2 group (eq 4) in the NO_2^+ nitration as the electrophilic process (eq 1).[7,8] On the other hand, it is clear that formation of the radical cation to give para-regioselectivity via both the direct charge-transfer process (eq 2) and the alternative one (eq 5) is easier with a lower redox potential substrate.[20] Again, it was implied that the NO_2^+ nitration had a dual process showing ortho- and para-regioselectivity depending on the redox potential of the substrates.

Direct vs Alternative Charge-Transfer Process. To evaluate the two possible processes to show para-regioselectivity by the radical cation formation (eqs 2 and 5) in the NO_2^+ nitration, the nitration of 1,8-dimethylnaphthalene was carried out using NO_2BF_4 and NO_2SbF_6 in the presence of strong acids, where strong acids will protonate 1,8-dimethylnaphthalene[21] resulting in suppression of the direct charge-transfer process (eq 2). As shown in Table 4, ortho-regioselectivity enhancement was observed even at 20 °C in the presence of CF_3SO_3H and FSO_3H regardless of the nitration reagents.[22] In the case of H_2SO_4, para-regioselectivity appeared. These results reflect the acid strength order, $FSO_3H > CF_3SO_3H > H_2SO_4$, namely, protonation ability of the acids.[23]

When the nitration of 1,8-dimethylnaphthalene using NO_2BF_4 was carried out at various CF_3SO_3H concentrations, the regioselectivity drastically changed in the

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(18) Another plausible explanation for the regioselectivity change is the formation of dicationic species such as HNO_2^{2+} as an electrophile. $HF{\cdot}BF_3$ produced during the nitration using NO_2BF_4 might be a strong enough acid to produce HNO_2^{2+}. However, in the presence of excess basic 1,8-dimethylnaphthalene to NO_2BF_4, the formation of HNO_2^{2+} seems to be unlikely. (a) Olah, G. A.; Rasul, G.; Aniszfeld, R.; Prakash, G. K. S. *J. Am. Chem. Soc.* **1992**, *114*, 5608. (b) Olah, G. A.; Wang, Q.; Orlinkov, A.; Ramaiah, P. *J. Org. Chem.* **1993**, *58*, 5017. (c) Olah, G. A.; Lin, H. C. *J. Am. Chem. Soc.* **1971**, *93*, 1259. (d) Olah, G. A. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 767. (e) Summers, N. L.; Tyrrell, J. *J. Am. Chem. Soc.* **1977**, *99*, 3960. (f) Olah, G. A.; Orlinkov, A.; Oxyzoglou, A. B.; Prakash, G. K. S. *J. Org. Chem.* **1995**, *60*, 7348. (g) Weiske, T.; Koch, W.; Schwarz, H. *J. Am. Chem. Soc.* **1993**, *115*, 6312. (h) Olah, G. A.; Germain, A.; Lin, H. C.; Forsyth, D. A. *J. Am. Chem. Soc.* **1975**, *97*, 2928.

(19) Eberson, L.; Hartshorn, M. P.; Persson, O. *J. Chem. Soc., Perkin Trans. 2* **1995**, 409.

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(22) In control experiments, the ortho-regioselectivity was about 45% over 0 °C in the presence CF_3SO_3H, which was close to the expected statistical isomer ratio for 1,8-dimethylnaphthalene.

(23) Olah, G. A.; Prakash, G. K. S.; Sommer, J. *Superacids*; Wiley-Interscience: New York, NY, 1985; Chapter 1.

Table 4. 1,8-Dimethylnaphthalene NO_2^+ Nitration in the Presence of Acids[a]

			products, yield (%)			
reagent	acid	*T* (°C)	**1**	**2**	**3**	**4**
NO_2BF_4	none	20	12 (81:19)	0	13	0
NO_2BF_4	none	−78	10 (25:75)	0	7.2	0
NO_2BF_4	CF_3SO_3H	20	7.3 (54:46)	0	40	0
NO_2BF_4	CF_3SO_3H	−78	3.4 (25:75)	0	5.9	0
NO_2BF_4	FSO_3H	20	12 (51:49)	0	19	0
NO_2BF_4	H_2SO_4	20	12 (81:19)	0	12	0
NO_2SbF_6	none	20	4.9 (82:18)	0	8.8	0
NO_2SbF_6	CF_3SO_3H	20	3.5 (53:47)	0	5.6	0
NO_2SbF_6	FSO_3H	20	5.4 (51:49)	0	11	0
NO_2SbF_6	H_2SO_4	20	4.9 (83:17)	0	9.4	0

[a] The nitration was carried out using nitration reagent (2.5 mmol), 1,8-dimethylnaphthalene (10 mmol), acid (10 mmol), and a mixture of CH_3CN (25 mL) with CH_2Cl_2 (25 mL) as a solvent for 1 h under N_2 atm. Isomer ratio in the parentheses is 1,8-dimethyl-4-/1,8-dimethyl-2-nitronaphthalene.

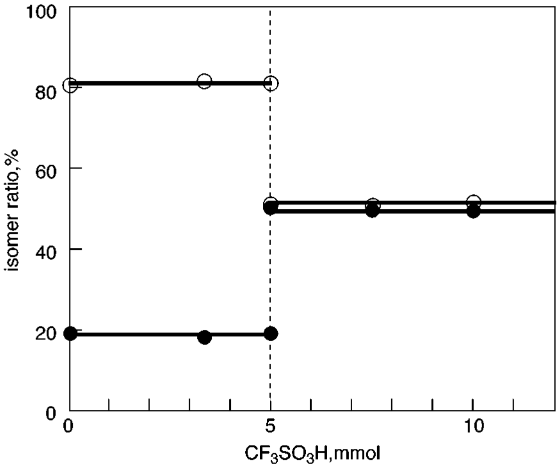

Figure 2. Acid dependence of 1,8-dimethylnaphthalene NO_2^+ nitration isomer ratio. The nitration was carried out using NO_2BF_4 (2.5 mmol), 1,8-dimethylnaphthalene (10 mmol), and a mixture of CH_3CN (25 mL) with CH_2Cl_2 (25 mL) as a solvent for 1 h under N_2 atm at 20 °C. ○ and ● represent 1,8-dimethyl-4- and 1,8-dimethyl-2-nitronaphthalene, respectively.

presence of 5 mmol CF_3SO_3H as shown in Figure 2. The yields were almost constant at about 9%. The proton H^+ seems to neither suppress the alternative charge-transfer process (eq 5) because of the charge repulsion with the ipso σ-complex nor influence the regioselectivity via the direct charge-transfer process (eq 2) that is considered to proceed via an inner-sphere mechanism taking into account the high energy demanding process of bond coordination change between NO_2^+ and NO_2[3b,5,24] and the unhindered donor nature of 1,8-dimethylnaphthalene.[25] Therefore, we concluded that the protonation of 1,8-dimethylnaphthalene by strong acids suppressed the direct charge-transfer process (eq 2), resulting in an ortho-regioselectivity enhancement, which suggested that the direct charge-transfer process (eq 2) could be the main process showing para-regioselectivity.[26]

The remaining point to discuss is the influence of the solvent-cage on the NO_2^+ nitration via the alternative charge-transfer process (eq 5). If collapse of the radical cation with NO_2 formed from the ipso σ-complex of 1,8-dimethylnaphthalene via alternative charge-transfer process (eq 5) proceeds immediately in a solvent-cage, the ortho-regioselectivity is expected to be similar to the intracomplex formylation[27] because the formed NO_2 should be close to the ortho-position. This possibility cannot be excluded although this process is meaningless in view of the synthetic scope.[28]

Experimental Conclusions. The results of the nitration experiments suggest that the NO_2^+ nitration of 1,8-dimethylnaphthalene proceeds via not only electrophilic (eq 1) but also direct charge-transfer processes (eq 2) depending on the reaction conditions, although the direct charge-transfer process has been considered to be unlikely because of the high energy demanding process of a bond coordination change between NO_2^+ and NO_2. The direct charge-transfer process (eq 2) seems to be favorable with low redox potential substrates; however, the possibility of the alternative charge-transfer process (eq 5) cannot be excluded.

Theoretical Studies

In the nitration experiments, it is suggested that the direct charge-transfer process (eq 2), the ipso attack of NO_2^+ (eq 3), and the 1,2-shift of the NO_2 group (eq 4) are likely processes in the NO_2^+ nitration of 1,8-dimethylnaphthalene, except for the alternative charge-transfer process (eq 5). To evaluate these results, the energy profile of four σ-complexes (ortho, meta, para, and ipso) and the radical cation of 1,8-dimethylnaphthalene with NO_2 were calculated at the MP2/6-31G(d)//HF/6-31G(d) level of theory with the zero-point energy corrections of the HF level, using the Gaussian 94 ab initio program package.[29] The calculation results for the energy profile and the spin density are summarized in Schemes 1−3, where the total energy for 1,8-dimethylnaphthalene with NO_2^+ is the standard energy potential.

Evaluation of Equation 2 (Scheme 1). The spin density of the 1,8-dimethylnaphthalene radical cation

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(24) Boughriet, A.; Wartel, M. *J. Chem. Soc., Chem. Commun.* **1989**, 809.

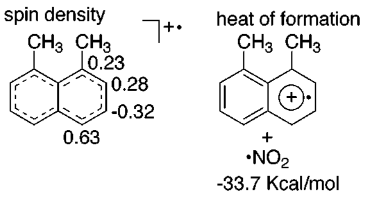
(25) Hubig, S. M.; Rathore, R.; Kochi, J. K. *J. Am. Chem. Soc.* **1999**, *121*, 617.

(26) The appearance of CF_3SO_3H influence on the regioselectivity under the conditions where CF_3SO_3H was less than 1,8-dimethylnaphthalene seemed to be derived from that $HF{\cdot}BF_3$ formed locally at the diffusion surface of added 1,8-dimethylnaphthalene also protonated 1,8-dimethylnaphthalene reflecting the nature of the diffusion control NO_2^+ nitration.[16] The addition of 1,8-dimethylnaphthalene (10 mmol) to a mixture of NO_2BF_4(2.5 mmol) with CF_3SO_3H (3 mmol) at 20 °C gave **1** with 16% ortho-regioselectivity as shown in Figure 2. However, when NO_2BF_4(2.5 mmol) was added to a mixture of 1,8-dimethylnaphthalene (10 mmol) with CF_3SO_3H (3 mmol) at 20 °C, 35% ortho-regioselectivity was observed. On the basis of the diffusion concept, the local H^+ concentration at the diffusion (reaction) surface of added NO_2BF_4 corresponding to the latter condition might be higher than that at the diffusion surface of the added 1,8-dimethylnaphthalene corresponding to the former condition because the local concentration of free 1,8-dimethylnaphthalene to quench H^+ at the diffusion surface under the latter condition should be lower than under the former condition during the NO_2^+ nitration. These results reflect the fact that the NO_2^+ nitration is a typical diffusion control reaction.[16] The reaction procedure was similar to the NO_2^+ nitration procedures. NO_2BF_4 (2.5 mmol) was added to a mixture of 1,8-dimethylnaphthalene (10 mmol), CF_3SO_3H (3 mmol), dry CH_3CN (25 mL), and dry $CHCl_3$ (25 mL). The product yields for **1**, **2**, **3**, **4**, and **5** were 3.2, 2.9, 47, trace, and 0%, respectively. In control experiments, the NO_2^+ nitration of **1** to give **2** did not show substrate-selectivity according to this NO_2^+ nitration procedure although the NO_2^+ nitration of **1** with the general procedures showed substrate−selectivity to 2-nitro-1,8-dimethylnaphthalene. Therefore, the obtained regioselectivity reflects the original regioselectivity in **1**.

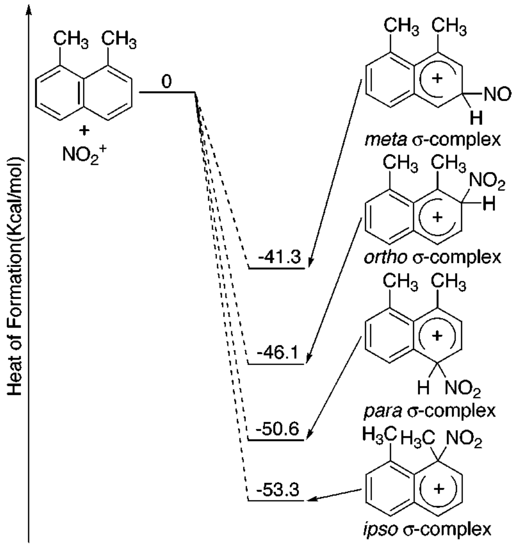
(27) (a) Tanaka, M.; Fujiwara, M.; Xu, Q.; Souma, Y.; Ando, H.; Laali, K. K. *J. Am. Chem. Soc.* **1997**, *119*, 5100. (b) Tanaka, M.; Fujiwara, M.; Xu, Q.; Ando, H.; Raeker, T. J. *J. Org. Chem.* **1998**, *63*, 4408. In the intracomplex formylation, regioslectivity is depending on the structure of σ-complex as a reaction precursor.

(28) Todres, Z. V. *Tetrahedron* **1985**, *41*, 2771.

Scheme 1



Scheme 2

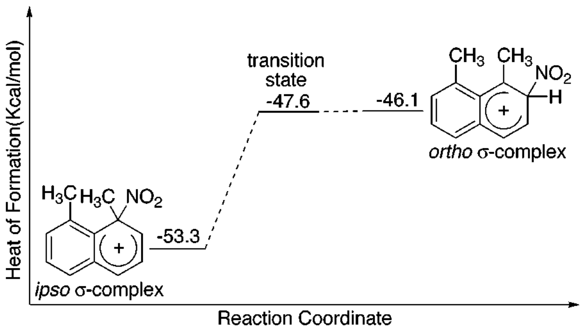


was the highest at the para-position, thus predicting para-regioselectivity for the NO_2^+ nitration via the charge-transfer processes (eqs 2 and 5) as reported before.[17] Unfortunately, it was impossible to evaluate the energy barrier for the direct charge-transfer process (eq 2) between 1,8-dimethylnaphthalene with NO_2^+ and the radical cation with NO_2.

Evaluation of Equation 3 (Scheme 2). The calculation predicted that the collapse of 1,8-dimethylnaphthalene with NO_2^+ proceeded without the transition energy barrier similar to the collapse of benzene with CH_3^+.[30] The ipso σ-complex formation (−53.3 kcal/mol) was the most favorable among the four σ-complexes,[31] implying that the ipso attack of NO_2^+ (eq 3) is a probable process. On the other hand, the formation of the ortho σ-complex (−46.1 kcal/mol) was not preferable compared with the para σ-complex formation (−50.6 kcal/mol).

Evaluation of Equation 4 (Scheme 3). The calculation of the energy profile for the 1,2-shift of the NO_2 group to the ortho- from the ipso-position of the ipso σ-complex (eq 4) was also performed. The transition state energy during this process was −47.6 kcal/mol, which was lower than the energy for the ortho σ-complex (−46.1 kcal/mol) by the effect of electron correlation; therefore, the 1,2-shift of the NO_2 group (eq 4) with a 7.2 kcal/mol transition state energy barrier was recognized to be the likely process.

Scheme 3



Evaluation of Equation 5 (Schemes 1 and 2). The energy difference between the radical cation with NO_2 (−33.7 kcal/mol, Scheme 1) and the ipso σ-complex (−53.3 kcal/mol, Scheme 2) was 19.6 kcal/mol. Although the radical cation formation via the alternative charge-transfer process in the NO_2^+ nitration (eq 5) has been reported with several aromatic compounds,[8,9] the calculation result indicates that the 1,2-shift of the NO_2 group (eq 4) is the more favorable process than the alternative charge-transfer process (eq 5) on the basis of the comparison of the transition state energy barrier for the former process (7.2 kcal/mol) with that for the latter process (at least 19.6 kcal/mol) in the case of the ipso σ-complex from 1,8-dimethylnaphthalene. This result supports the fact that the direct charge-transfer process (eq 2) could be the main process to give para-regioselectivity and the alternative charge-transfer process (eq 5), which have potential to show not only para- but also ortho-regioselectivity with a solvent cage-effect, is unlikely in the NO_2^+ nitration in accordance with the experimental results.

Theoretical Conclusions. In the case of 1,8-dimethylnaphthalene, the calculation predicted that the ipso attack of NO_2^+ (eq 3) and the 1,2-shift of the NO_2 group (eq 4) are the likely processes, but the alternative charge-transfer process (eq 5) is unlikely in the NO_2^+ nitration.

Conclusions

The results of both the experimental and theoretical studies suggest that the NO_2^+ nitration of 1,8-dimethylnaphthalene proceeds via not only an electrophilic (eq 1) but also a direct charge-transfer process (eq 2), which has been considered to be unlikely because of the high energy demanding process of the bond coordination change between NO_2^+ and NO_2. The probability of the direct charge-transfer process in the NO_2^+ nitration (eq 2) implies that the coordination of an electrophile with an aromatic compound can play a critical role in determining the reaction process between the electrophilic and direct charge-transfer processes via an inner-sphere mechanism, and the direct charge-transfer process seems to be possible for some aromatic substitutions that have been considered to proceed via an electrophilic process such as the diazonium coupling reaction.[32]

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(30) Miklis, P. C.; Ditchfield, R.; Spencer, T. A. *J. Am. Chem. Soc.* **1998**, *120*, 10482.

(31) When the calculation was carried out at the HF/6-31G(d) level, which is known to have less precision than MP2/6-31G(d) level, the heat of formation energy for σ-complexes were −66.9, −65.3, −59.8, and −69.0 kcal/mol for ipso, ortho, meta, and para σ-complexes, respectively, indicating that para σ-complex formation was the most favorable. Such a discrepancy is sometimes caused by to calculation precision.

Experimental Section

All materials were of the highest available purity and used without further purification. The products and their isomers were identified by NMR (^{1}H, ^{13}C NMR, H−H, C−H COSY, NOESY, and COLOC) with mass spectra after separation using GPC. The yields were determined by GC with the internal standard method, and the isomer distributions were determined by GC and NMR.

The formation of coupling products, **3**, **4**, and **5** (eq 4) in the NO_2^+ nitration can be evidence for the charge-transfer process, but it is known that commercially available NO_2BF_4 always contains $NOBF_4$, causing the coupling reaction as an impurity. Azide is known as a NO^+ scavenger;[33] however, to obtain a clear regioselectivity variation to compare the NO_2^+ with the NO^+ nitration as much as possible, the NO_2^+ nitration was conducted without azide. Therefore, the formation of coupling products was not discussed in this study. Furthermore, the conditions under which dinitro compounds **2** were not formed were adopted in order to avoid complexity in the products analysis. The formation of **5** was not detected in any experiments, and the meta nitro product in **1** was not found in the case of 1,8-dimethylnaphthalene.

NO_2^+ Nitration Procedures. NO_2BF_4 (2.5 mmol) (with the required amount of acid in some cases) was placed in a three-necked flask (300 mL) containing a mixture of dry CH_3CN (25 mL) and dry CH_2Cl_2 (15 mL) (25 mL of dry CH_3CN and 25 mL of dry CH_2Cl_2 for liquid substrates such as 1-methylnaphthalene, 1,2-, and 1,3-dimethylnaphthalene). The mixture was degassed three times to exclude the NO^+ nitration,[13] and then a substrate (10 mmol) was added to the mixture with vigorous stirring in N_2 under temperature control. When the substrate was a solid, the solution of the substrate dissolved in CH_2Cl_2 (10 mL) was added to the mixture. After 1 h, the reaction mixture was poured into ice−water and extracted with $CHCl_3$. The product yields and structures were determined according to general procedures.

NO^+ Nitration Procedures. $NOBF_4$ (2.5 mmol) was placed in a three-necked flask (300 mL) containing a mixture of dry CH_3CN (25 mL) and dry CH_2Cl_2 (15 mL) (25 mL of dry CH_3CN and 25 mL of dry CH_2Cl_2 for liquid substrates such as 1-methylnaphthalene, 1,2-, and 1,3-dimethylnaphthalene). A substrate (2.5 mmol) was added to the mixture with vigorous stirring in air under temperature control. When the substrate was a solid, the solution of the substrate dissolved in CH_2Cl_2 (10 mL) was added to the mixture. After 1 h (2h in the case of at −78 °C), the reaction mixture was poured into ice−water and extracted with $CHCl_3$. The product yields and structures were determined according to general procedures.

Calculation Procedures. All the molecular orbital calculations were carried out with the GAUSSIAN 94 ab initio program package.[29] The geometrical optimization for all the present molecules was performed with the HF level of theory and 6-31G(d) basis set. On the basis of the optimized geometries, the single-point calculations of the energies were carried out at the PM2 (frozen core)/6-31G(d) level with the zero-point energy (ZPE) corrections of the HF level. All the optimized geometries corresponding to a local minimum point have real frequencies, except for a transition state with one imaginary frequency. A Silicon Graphics Origin 2000 R10000 workstation was used for calculations in this study.

Acknowledgment. We thank Prof. Inoue (Osaka University) for his significant advice on this work.

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