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Organic Reactions under High Pressure. IV. Effect of Pressure on the Competitive Nitration of Benzene and Monosubstituted Benzenes. Dependence of the Substitutent Effect on the Pressure

Tsutomu Asano

Department of Chemistry, Faculty of Science, Kyoto University, Sakyo-ku, Kyoto

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Partial rate factors for the nitration of six monosubstituted benzenes with nitric-sulfuric acid in acetic acid at 45°C have been determined over the 1—2000 kg/cm^2 pressure range. The ρ value for this reaction changed from -7.22 (1 kg/cm^2) to -6.92 (2000 kg/cm^2). This pressure dependency of the ρ value was not expected for this type of reaction. This phenomenon is interpreted in terms of the dependence of the degree of solvation of the transition states on the substituents. An abnormal deactivation due to pressure has been observed in the case of biphenyl. This deactivation has been attributed to an increase in the deviation from the coplanarity of the two phenyl groups. The dependence of the *ortho* : *para* ratios on the pressure is also discussed.

Since the last decade, pressure effects on the rates and product distributions of organic reactions have been extensively studied, and the results have offered much useful information about the reaction mechanisms.[1] The high-pressure technique is an especially powerful tool by which to investigate the solvation and steric hindrance in transition states.

For a liquid-phase reaction, the effect of pressure on the rate constant, k, can be expressed by Eq. (1);

$$(\partial \ln k/\partial P)_T = -\Delta V^{\neq}/RT \qquad (1)$$

where $\Delta V^{\neq}$ is the volume of the activation of the reaction, that is, the difference in the partial molar volumes between the transition state and the initial state. In considering the molecular theory of activation volumes, it is convenient to follow Evans and Polanyi[2] and to split $\Delta V^{\neq}$ into two terms:

$$\Delta V^{\neq} = \Delta_1 V^{\neq} + \Delta_2 V^{\neq} \qquad (2)$$

The change in the volume of the reacting molecules when they form the transition state is represented by $\Delta_1 V^{\neq}$, while $\Delta_2 V^{\neq}$ represents the accompanying change in the volume of the surrounding solvent. The magnitude of $\Delta_2 V^{\neq}$ is mainly determined by the difference in the total charge and in its distribution in the initial and transition states.[3] As a result, reactions in which the slow step leads to the formation of ions from neutral molecules and those in which ions combine to form neutral molecules have larger $\Delta_2 V^{\neq}$ values. On the other hand, reactions in which ions participate without either increasing or decreasing the net charge of the system have smaller $\Delta_2 V^{\neq}$ values. On the basis of this electrostriction theory, Ellis *et al.*[4] considered the effect of the pressure on the ρ value of the Hammett equation and predicted as follows:

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[1] For example, see E. Whalley, "Advances in Physical Organic Chemistry," Vol. 2, ed. by V. Gold, Academic Press, London and New York (1964), p. 93.

[2] M. G. Evans and M. Polanyi, *Trans. Faraday Soc.*, **31**, 875 (1935).

[3] S. D. Hamann "Physico-Chemical Effects of Pressure," Butterworths Scientific Publications, London (1957), Chapters 8 and 9.

[4] A. J. Ellis, W. S. Fyfe, R. I. Rutherford, A. Fischer and J. Vaughan, *J. Chem. Phys.*, **31**, 176 (1959).

(A) For a reaction between an ion and a neutral molecule, pressure changes should have little effect on the value of ρ.

(B) For a reaction between ions or between neutral molecules leading to a dipolar transition state, the magnitude of ρ should be influenced by a change in the pressure.

In the case of B, the validity of the prediction was shown by examinations of the pressure effect on the dissociation constants. Fischer *et al.*[5] measured the pK values in water at 25°C of a number of substituted benzoic and phenylacetic acids over the pressure range from 1 to 3000 bars. In both series, the ρ values decreased with an increase in the pressure, as had been predicted. Imoto *et al.*[6] investigated the effect of the pressure on the rate of the saponification of ethyl benzoates in aqueous dioxane over the 1—1000 kg/cm^2 pressure range; they found that $\Delta V^{\ddagger}$ values were essentially unchanged by substituents (*p*-Cl, MeO, H). This result shoud support the above prediction of the case A.

As has been mentioned above, Ellis' prediction is based on the electrostriction theory; *i.e.*, for example, the $\Delta_2 V^{\ddagger}$ value for reactions (3) and (4) will be small because the net charge of the system does not change during the activation processes.[*1]

$$A_1 + B^+ \rightarrow \underset{\mathrm{I}}{A_1^{+\delta} \cdots B^{+\delta}} \rightarrow P_1 \qquad (3)$$

$$A_2 + B^+ \rightarrow \underset{\mathrm{II}}{A_2^{+\delta} \cdots B^{+\delta}} \rightarrow P_2 \qquad (4)$$

Hence, the difference in $\Delta V^{\ddagger}$ between reactions (3) and (4), $\delta\Delta V^{\ddagger}$,[*2] will be negligible. Therefore, it may be concluded that pressure changes have little effect on the value of ρ.[*3]

However, it should be possible to consider as follows. The solvation in the initial states will be nearly the same in both reactions because of the intervention of the common ion, B$^+$, as an attacking entity. Consequently, the difference in $\Delta_2 V^{\ddagger}$ must come from the difference in solvation between the two transition states, I and II. The situation is the same for the dissociation of benzoic acids, (5) and (6):

$$C_6H_5COOH \rightarrow C_6H_5COO^- + H^+ \qquad (5)$$

$$XC_6H_4COOH \rightarrow XC_6H_4COO^- + H^+ \qquad (6)$$

In this case, the differences in $\Delta\bar{V}^{\circ}$ values are large enough for the ρ value to change with the pressure. Since the two carboxylic acids will be solvated to quite the same extent, the difference in the $\Delta\bar{V}^{\circ}$ values is mainly due to the difference in solvation between the two carboxylate ions. Therefore, if the degrees of charge distribution in the two transition states, I and II, are considerably different, $\delta\Delta V^{\ddagger}$ will be large enough to be detected experimentally.

The nitration of monosubstituted benzenes by nitric-sulfuric acid in acetic acid seems to be a suitable model reaction for studying the influence of the pressure upon the ρ value for a reaction between an ion and a neutral molecule for the following reasons:

(1) The value of $|\rho|$ for the nitration reaction is large (*ca.* 6.0).[7]

(2) The attacking entity is undoubtedly an ionic species, an incipient nitronium ion.[8]

(3) As the competitive method is applicable, uncertainties arising from imperfect and, consequently, unequal pressure and temperature control are avoided.

In addition, the effect of the pressure on the *ortho* : *para* ratios would give new information about the steric hindrance in ionic reactions. In many instances, it is observed that $\Delta V^{\ddagger}$ becomes more negative as the reacting center becomes more sterically hindered.[9] The most plausible explanation of such a phenomenon is Gonikberg's[10] suggestion that $\Delta V^{\ddagger}$ contains a negative term, $\Delta V^{\ddagger}_{\mathrm{steric}}$, arising from the overlap of interfering atoms in the transition state.[*4] Coillet and Hamann[11] have reported, however, that the *ortho* : *para* ratios in the nitration of toluene and chlorobenzene decrease with an increase in the pressure, but the exact reason for this anomaly could not be ascertained.

This report will describe the studies in the competitive nitration of benzene and six monosubstituted benzenes by nitric-sulfuric acid in acetic

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[5] A. Fischer, B. R. Mann and J. Vaughan, *J. Chem. Soc.*, **1961**, 1093.

[6] T. Imoto, Y. Ogo and H. Oka, presented at 8th High Pressure Symposium, Kobe, Oct., 1966; Abstracts, p. 104.

[*1] A and P are the substrate and a product respectively, B$^+$ is a common attacking entity, and the subscripts 1 and 2 denote different substituents.

[*2] $\delta\Delta V^{\ddagger} = \Delta V^{\ddagger}$ (recation (4)) $-\Delta V^{\ddagger}$ (reaction (3))

[*3] For a discussion of the substituent effect on $\Delta_1 V^{\ddagger}$ values, see Ref. 4.

[7] L. M. Stock and H. C. Brown, "Advances in Physical Organic Chemistry," Vol. 1, ed. by V. Gold, Academic Press, London and New York (1963), p. 99.

[8] G. A. Olah, S. J. Kuhn, S. H. Flood and J. C. Evans, *J. Am. Chem. Soc.*, **84**, 3687 (1962).

[9] For example, see S. D. Hamann, *Ann. Rev. Phys. Chem.*, **15**, 349 (1964).

[10] M. G. Gonikberg, "Chemical Equilibria and Reaction Rates at High Pressures," Izdatel, Akad. Nauk, SSSR, Moscow (1960), English transl. Israel Program for Scientific Translations, Jerusalem, p. 106.

[*4] There are some exceptions. See Refs. 11, 12 and 13.

[11] D. W. Coillet and S. D. Hamann, *Nature*, **200**, 166 (1963).

[12] W. J. leNoble, *J. Am. Chem. Soc.*, **85**, 1470 (1963).

[13] R. Goto, T. Asano, K. Matsumoto and A. Sera, *Rev. Phys. Chem. Japan*, **37**, 16 (1967).

TABLE 1. EFFECT OF PRESSURE ON THE COMPETITIVE NITRATION OF BENZENE AND ACTIVATED MONOSUBSTITUTED BENZENES IN ACETIC ACID AT 45°C

Toluene

P (kg/cm^2)	k_{Me}/k_H a)	o- %	m- %	p- %	f_o^{Me} b)	f_m^{Me}	f_p^{Me}
1	27.2	55.9	2.7	41.4	45.6	2.2	67.7
1000	25.0	56.4	2.8	40.9	42.2	2.1	61.2
2000	23.2	56.4	2.9	40.7	39.3	2.0	56.6

t-Butylbenzene

P (kg/cm^2)	k_{Bu}/k_H	o- %	m- %	p- %	f_o^{Bu}	f_m^{Bu}	f_p^{Bu}
1	15.2	9.7	7.4	82.9	4.4	3.4	75.6
1000	13.6	10.4	7.7	81.8	4.3	3.2	66.7
2000	12.3	11.0	8.1	80.9	4.1	3.0	59.7

Biphenyl c)

P (kg/cm^2)	k_{Ph}/k_H	o- %	p- %	f_o^{Ph}	f_p^{Ph}
1	30.3	62.2	37.8	28.2	34.3
600	26.5	62.6	37.4	24.9	29.7
1000	25.0	62.4	37.6	23.4	28.2
2000	22.7	62.1	37.9	21.1	25.8

a) Relative reactivity of toluene to benzene
b) Partial rate factor of *ortho* position to methyl group
c) It was assumed that the formed nitrobiphenyls consist of *o*- and *p*-nitrobiphenyl.

acid at 45°C over the 1—2000 kg/cm^2 pressure range; we undertook the studies in order to obtain new, detailed information about the solvation and steric hindrance in the transition states for aromatic electrophilic substitution reactions.

Experimental Results

The effects of the pressure on the competitive nitration of benzene and activated monosubstituted benzenes are summarized in Table 1.

While there are only small, but significant, changes in the isomer distribution (position selectivity), one can see rather a large change in the relative reactivity, k_X/k_H (substrate selectivity). As the pressure applied increases, the relative reactivity decreases appreciably. Although the *ortho* : *para* and *meta* : *para* ratios increase with an increase in the pressure in toluene and *t*-butylbenzene, this is not due to the increasing reactivity of the *ortho* and *meta* positions, but to the decreasing reactivity of the *para* position. In the case of biphenyl, the pressure independency of the *ortho* : *para* ratio is observed, while the relative reactivity diminishes more extensively than in alkylbenzenes.

TABLE 2. EFFECT OF PRESSURE ON THE COMPETITIVE NITRATION OF BENZENE AND DEACTIVATED MONOSUBSTITUTED BENZENES IN ACETIC ACID AT 45°C

Fluorobenzene

P (kg/cm^2)	k_F/k_H	o- %	m- %	p- %	f_o^F	$f_m^F\times10^3$	f_p^F
1	0.142	9.23	0.210	90.6	0.0392	0.89	0.769
1000	0.140	9.32	0.239	90.5	0.0391	1.00	0.758
2000	0.140	9.26	0.268	90.5	0.0390	1.13	0.761

Chlorobenzene

P (kg/cm^2)	k_{Cl}/k_H	o- %	m- %	p- %	f_o^{Cl}	$f_m^{Cl}\times10^3$	f_p^{Cl}
1	0.0400	23.1	0.669	76.2	0.0277	0.80	0.183
1000	0.0409	23.6	0.768	75.7	0.0290	0.94	0.186
2000	0.0409	23.6	0.844	75.6	0.0289	1.03	0.185

Bromobenzene

P (kg/cm^2)	k_{Br}/k_H	o- %	m- %	p- %	f_o^{Br}	$f_m^{Br}\times10^3$	f_p^{Br}
1	0.0337	27.3	0.91	71.8	0.0277	0.92	0.145
1000	0.0354	27.8	1.03	71.2	0.0295	1.09	0.151
2000	0.0365	28.0	1.12	70.8	0.0306	1.23	0.155

TABLE 3. REACTION CONSTANT ρ AND CORRELATION COEFFICIENT r FOR THE NITRATION BY MIXED ACID IN ACETIC ACID AT 45°C

P (kg/cm^2)	1	1000	2000
ρ	−7.22	−7.05	−6.92
r	0.988	0.989	0.986

On the contrary, chlorobenzene and bromobenzene show an increasing relative reactivity with an increase in the pressure. The results are shown in Table 2. In all three cases in Table 2, the increase in f_m is striking; bromobenzene and chlorobenzene reveal an apparent increase in the *ortho* : *para* ratio with the pressure, as is also observed in alkylbenzenes.

The partial rate factors in Tables 1 and 2 are plotted against Brown-Okamoto's σ^+ value to give a straight line. The ρ values calculated by the method of least squares and the correlation coefficients, r, are listed in Table 3. (The values of biphenyl were not included in the calculations. This will be discussed below.) The correlation of these plots is not excellent, but it may be concluded that the ρ value increases appreciably with an increase in the pressure.

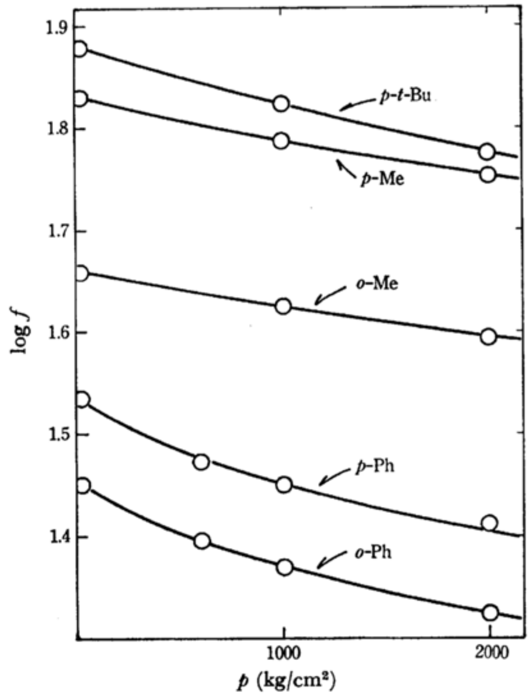


Fig. 1. log f-p curves for the nitration of activated monosubstituted benzenes.

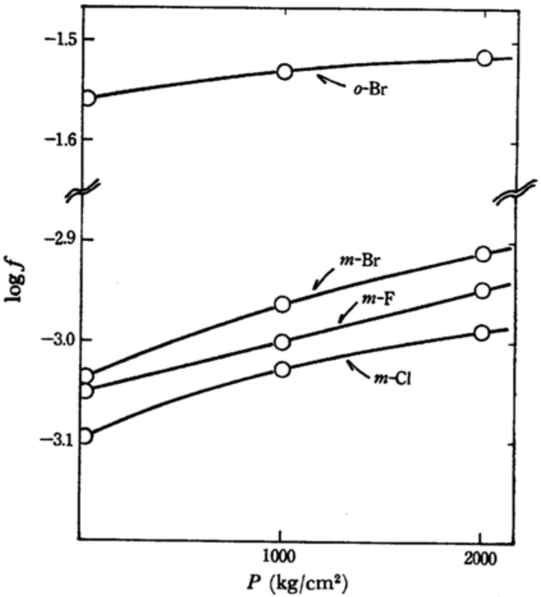


Fig. 2. log f-p curves for the nitration of halobenzenes.

TABLE 4. $\delta\Delta V_1^\ddagger$ OR $\delta\Delta\bar{V}_{1000}^\ddagger$ VALUES FOR THE NITRATION BY MIXED ACID IN ACETIC ACID AT 45°C (ml/mol)[a)]

Substituent	o-	m-	p-
Methyl	2.1	1.2*	3.2
t-Butyl	0.6*	1.6*	3.5
Fluoro	0.1*	−3.1	0.4*
Chloro	−1.2*	−5.0	−0.5*
Bromo	−2.0	−5.2	−1.1*
Phenyl	6.2		6.6

*: $\delta\Delta\bar{V}_{1000}^\ddagger$ values

a) The error is estimated at most 0.5 ml/mol.

Fischer *et al.*[5)] have pointed out that the magnitude of $\Delta V^\ddagger$ values could be an indication of anticipating whether or not ρ depends on the pressure. This can be interpreted as follows. Assuming that σ^+ is not a function of the pressure, one can obtain Eq. (9) from Eqs. (7) and (8):

$$\Delta V^\ddagger = -\boldsymbol{R}T(\partial \ln k/\partial P)_T \tag{7}$$

$$\log f = \rho\sigma^+ \tag{8}$$

$$\begin{aligned}\delta\Delta V^\ddagger &= -\boldsymbol{R}T(\partial \ln f/\partial P)_T \\ &= -2.3\boldsymbol{R}T\sigma^+(\partial\rho/\partial P)_T \end{aligned} \tag{9}$$

Thus, if σ^+ is independent of the pressure and if ρ varies with the pressure, then the plot of $\delta\Delta V^\ddagger$ at a constant pressure and temperature against σ^+ should give a linear line, including the point of origin. Figures 1 and 2 show the dependence of $\log f$ on the pressure. From the slopes of the curves at zero pressure, the $\delta\Delta V^\ddagger{}_1$[*5] values were calculated; they are listed in Table 4, together with the values of $\delta\Delta\bar{V}_{1000}^\ddagger$[*6] for the other positions.[*7]

[*5] $\delta\Delta V^\ddagger$ values at 1 atm.

[*6] $\delta\Delta\bar{V}_{1000}^\ddagger = -RT(\ln f_{1000} - \ln f_1)1/1000$. The numerals indicate the pressure.

[*7] The values of $\delta\Delta\bar{V}_{1000}^\ddagger$ are adopted instead of $\delta\Delta V^\ddagger{}_1$ for the *meta* positions of alkylbenzenes and the *para* positions of halobenzenes because the changes in the reactivity of these positions with the pressure are relatively small; hence, $\delta\Delta V^\ddagger$ should change little with the pressure.

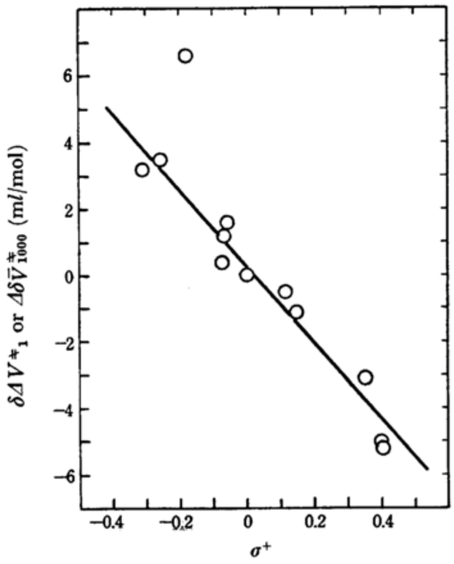


Fig. 3. Plot of $\delta\Delta V^{\neq}{}_1$ or $\delta\bar{V}^{\neq}_{1000}$ against σ^+.

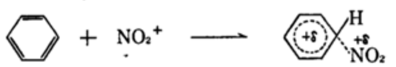
Those values are plotted in Fig. 3 against σ^+; the line passes through the point of origin. The correlation shown in Fig. 3 reveals this relation:

$$\delta\Delta V^{\neq}{}_1 = -11.6\sigma^+ + 0.24.^{*8}$$

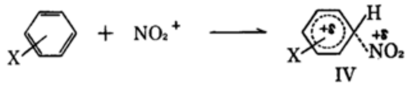
The dependence of the ρ value for nitration by nitric-sulfuric acid in acetic acid on the pressure is evident.

Discussion

Effect of Pressure on f_m and f_p. Since no kinetic isotope effect was observed in the nitration of benzene and a number of its derivatives of widely differing reactivities,[14] the observed $\delta\Delta V^{\neq}$ values represent the difference in $\Delta V^{\neq}$ between the following two processes (in Eqs. (10) and (11), NO_2^+ represents a weaker electrophilic precursor of the nitronium ion):[8]


(10)

III


(11)

IV

According to Evans and Polanyi,[2] $\delta\Delta V^{\neq}$ is separated into two terms, $\delta\Delta_1 V^{\neq}$ and $\delta\Delta_2 V^{\neq}$ (Eq. (12)):

$$\delta\Delta V^{\neq} = \Delta V^{\neq}_{\mathrm{X}} - \Delta V^{\neq}_{\mathrm{H}} = (\Delta_1 V^{\neq}_{\mathrm{X}} - \Delta_1 V^{\neq}_{\mathrm{H}}) + (\Delta_2 V^{\neq}_{\mathrm{X}} - \Delta_2 V^{\neq}_{\mathrm{H}}) = \delta\Delta_1 V^{\neq} + \delta\Delta_2 V^{\neq} \quad (12)$$

When the replacement of a hydrogen atom of benzene molecule with a different substituent, X, occurs at a point sufficiently remote from the reaction site, a condition for the applicability of the $\rho\sigma^+$ equation is fulfilled; the first term, $\delta\Delta_1 V^{\neq}$, is decided by the difference in the C···N bond length in the two transition states, III and IV. The position of the trasition state on the reaction coordinate might change with the reactivity of the substrate; however, it is unlikely that the C···N bond length changes so greatly that $\delta\Delta_1 V^{\neq}$ amounts to several milliliters.[*9] The detritiation of methylbenzenes seems a good example indicating that the position of the transition state does not change with the substituents. Ansell and Taylor[15] found that $\log f_o^{\mathrm{Me}}$: $\log f_p^{\mathrm{Me}}$ ratio for *m*-xylene is 0.885±0.035, exactly the same as in toluene, in spite of the fact that the former is 200 times as reactive as the latter. From this result they concluded that the transition states are not sufficiently different for any effect of the differing stabilizations of the *ortho* and *para* positions to show up. Consequently, if the attack by a nitrating agent occurs at a position *meta* or *para* to the substituent X, the $\delta\Delta_1 V^{\neq}$ should be nearly equal to zero; *i.e.*, $\delta\Delta_2 V^{\neq}$ should be responsible to the observed $\delta\Delta V^{\neq}$. When the substituent X is more electron-donating than the hydrogen atom, the charge on the nitrogen atom disperses more extensively into the benzene ring in IV than in III. Thus, the desolvation attributable to charge dispersion during the activation step should be more extensive in IV. On the other hand, when X is more electron-attracting than the hydrogen atom, the desolvation during the activation step should be less extensive in IV. The $\delta\Delta V^{\neq}$ values listed in Table 4 clearly reveal that this is the case. The anomalous pressure dependence of the reactivity of biphenyl will be discussed later.

Thus, the extent of solvation in the transition state of the nitration of benzene derivatives changes with the substituents. Accordingly, the ρ value increases with an increase in the pressure. The reported independency of the ρ value of the saponification of ethyl benzoates[6] must have its origin in its relatively small ρ value ($\rho \doteqdot 2$), which makes the difference in $\Delta V^{\neq}$ small.

Abnormal Deactivation of Biphenyl by Pressure. The *para* and *ortho* positions to phenyl group are anomalously deactivated with an increase in the pressure. From the plot of $\delta\Delta V^{\neq}{}_1$ against σ^+, $\delta\Delta V_1^{\neq}$ may be expected to be approximately 2.5 m*l*/mol for the *para* position of biphenyl.

[*8] The results for biphenyl were not included in the calculation.

[14] Numerous investigations of kinetic isotope effects in nitration have been conducted. See H. Zollinger, Ref. 1, p. 163.

[*9] If one arbitrarily assumes that the van der Waals cross-sectional area of the C···N bond is equal to $1.5^2 \times 3.14 = 7.07$ Å^2, there must be *ca.* 1 Å difference in the C···N bond length in order for $\delta\Delta_1 V^{\neq}$ to amount to 4.3 m*l*/mol.

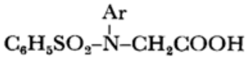
[15] H. V. Ansell and R. Taylor, *J. Chem. Soc.*, *B*, **1968**, 526.

The observed value, 6.6 ml/mol, is more than twice that expected. The deviation from the $\delta\Delta V^{\neq}_1$-σ^+ plot implies a pressure dependence of the substituent constant, $\sigma^+_{p-\mathrm{Ph}}$.

Stock and Brown[16] pointed out that the reactivity of the *para* position in biphenyl increases significantly with an increase in the electron demand of the substitution reaction; that is, $\sigma^+_{p-\mathrm{Ph}}$ decreases as the electrophile becomes less reactive. They attributed this anomaly to the variation in the angle between two rings and explained as follows: "……the full contribution of the substitutent is not achieved because of steric repulsions among the four hydrogens.……As the selectivity of the electrophilic reaction increases, the steric forces are, in part, overcome by the increased energy requirements of the transition state."

As the other substituents do not show any anomaly, the anomalous deactivation of biphenyl by pressure must be due to the change of the angle between two rings. However, the cause of the increased angle should not be the increase in the reactivity of the attacking incipient nitronium ion as a result of the pressure, because an ion should be solvated more strongly at high pressures than at atmospheric pressure. It seems to be rather reasonable to consider that, as the angle between two phenyl groups at the transition (and ground) state becomes greater, the volume of the system decreases.

McCune *et al.*[17] have reported that the racemization of sodium salt of L-6-nitro-2,2′-carboxybiphenyl is retarded by an increase in the pressure to an extent corresponding to $\Delta V^{\neq}=2$ ml/mol at 1 atm in a 0.1 N aqueous sodium hydroxide solution. McKelvey and Brower[18] independently studied the effect of the pressure on the rate of the racemization of three compounds with the general strcture V, where Ar denotes an aryl group with hindering *ortho* substituents. In ethanol the rate constant decreased with an increase in the pressure ($\Delta V_1^{\neq}\fallingdotseq 2$ ml/mol). Although the exact reason for these activation volumes could not be obtained, it may be quite all right to assume that as the angle between two phenyl groups in the transition (and ground) state decreases, the volume of the system increases. Consequently, under high pressure the angle will increase and the resonance contribution will decrease to some extent. We suggest that the observed $\delta\Delta V^{\neq}$ value reflects not only the volume change during the activation step, but also the decreased resonance contribution caused by an external pressure. In other words, the structure of the transition state changes with the pressure.



$$\mathrm{C_6H_5SO_2{-}\overset{\overset{\textstyle Ar}{|}}{N}{-}CH_2COOH}$$

V

TABLE 5. EFFECT OF PRESSURE ON THE *ortho* : *para* RATIOS IN THE NITRATION OF MONOSUBSTITUTED BENZENES BY MIXED ACID IN ACETIC ACID AT 45°C

Substituent	P (kg/cm^2)		
	1	1000	2000
Methyl	1.35	1.38	1.39
t-Butyl	0.117	0.127	0.136
Phenyl	1.65	1.66	1.64
Fluoro	0.102	0.103	0.102
Chloro	0.303	0.312	0.312
Bromo	0.380	0.390	0.395

Effect of the Pressure on the *ortho* : *para* Ratio. The *ortho*:*para* ratios at various pressures are shown in Table 5. Except for the cases of biphenyl and fluorobenzene, the *ortho* nitration increases with the pressure, and as substituent becomes larger the tendency becomes even more remarkable. These results show a tendency the reverse of that reported by Coillet and Hamann.[11] They reported the nitration of toluene and chlorobenzene by anhydrous nitric acid in acetic acid at 0°C. Their results are quoted in Table 6.

TABLE 6. EFFECT OF PRESSURE ON THE ISOMER DISTRIBUTIONS IN THE NITRATION OF TOLUENE AND CHLOROBENZENE BY NITRIC ACID IN ACETIC ACID AT 0°C

P (atm)	Toluene				Chlorobenzene		
	o-%	*m*-%	*p*-%	*o*-/*p*-	*o*-%	*p*-%	*o*-/*p*-
1	56.0	2.0	42.0	1.33	24.7	75.3	0.328
1200	55.0	2.2	42.8	1.29			
2000	54.3	2.4	43.3	1.25	20.4	79.6	0.256

Obviously, the *ortho* : *para* ratios decrease with the pressure and the tendency is more remarkable in chlorobenzene. These two inconsistent results can most plausibly be explained in terms of the difference in solvation in the two systems. The activation volume of the *ortho* nitration can be separated into four terms, as in Eq. (13).

$$\Delta V^{\neq}(\mathit{ortho}) = \Delta_1 V^{\neq} + \Delta_2 V^{\neq} = (\Delta_1 V^{\neq}_{\mathrm{bond}} + \Delta_1 V^{\neq}_{\mathrm{steric}}) + (\Delta_2 V^{\neq}_{\mathrm{el}} + \Delta_2 V^{\neq}_{\mathrm{steric}}) \tag{13}$$

$\Delta_1 V^{\neq}_{\mathrm{bond}}$: volume change of the reacting molecules due to changes in the bond length during the activation process. In the present case, $\Delta_1 V^{\neq}_{\mathrm{bond}}<0$.

$\Delta_1 V^{\neq}_{\mathrm{steric}}$: volume change of the reacting molecules due to the overlap of interfering atoms in the transition state. $\Delta_1 V^{\neq}_{\mathrm{steric}}<0$.

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[16] Ref. 7, p. 108.

[17] C. C. McCune, F. Wm. Cagle, Jr., and S. S. Kistler, *J. Phys. Chem.*, **64** 1773 (1960).

[18] D. R. McKelvey and K. R. Brower, *ibid.*, **64**, 1958 (1960).

$\Delta_2 V^{\ddagger}_{el}$: volume change of the solvent due to the changing electrostatic interaction of the reacting molecules with the solvent during the activation process. In the present case, $\Delta_2 V^{\ddagger}_{el} > 0$.

$\Delta_2 V^{\ddagger}_{steric}$: volume change of the solvent due to the steric inhibition of solvation in the transition state. $\Delta_2 V^{\ddagger}_{steric} > 0$.

In the *para* nitration the $\Delta_1 V^{\ddagger}_{steric}$ and $\Delta_2 V^{\ddagger}_{steric}$ terms are not present; accordingly, $\Delta_1 V^{\ddagger} = \Delta_1 V^{\ddagger}_{bond}$ and $\Delta_2 V^{\ddagger} = \Delta_2 V^{\ddagger}_{el}$. It seems to be plausible to assume $\Delta_1 V^{\ddagger}_{bond}$ (*para*) is equal to $\Delta_1 V^{\ddagger}_{bond}$ (*ortho*). Although it is not obvious whether or not $\Delta_2 V^{\ddagger}_{el}$ (*para*) is larger than $\Delta_2 V^{\ddagger}_{el}$ (*ortho*), the difference, $\Delta_2 V^{\ddagger}_{el}$ (*ortho*) $-$ $\Delta_2 V^{\ddagger}_{el}$ (*para*), will be small compared to the $\Delta_2 V^{\ddagger}_{steric}$ term. In view of the above approximations, the difference in the activation volumes in the *ortho* nitration and *para* nitration may be represented as in Eq. (14). In Eq. (14) $\Delta_1 V^{\ddagger}_{steric}$ is negative and $\Delta_2 V^{\ddagger}_{steric}$ is positive.

$$\Delta V^{\ddagger}(ortho) - \Delta V^{\ddagger}(para) \doteqdot \Delta_1 V^{\ddagger}_{steric} + \Delta_2 V^{\ddagger}_{steric} \qquad (14)$$

Accordingly, it depends on the relative magnitude of the above two terms whether the applied pressure increases the *ortho* : *para* ratio or decreases it. The solvation of an ionic species and a dipolar molecule should be more striking under Coillet and Hamann's conditions (acetic acid solution at 0°C) than in the present case (acetic acid solution at 45°C). Therefore, the volume increase due to the steric inhibition of solvation, $\Delta_2 V^{\ddagger}_{steric}$, should be larger at 0°C than at 45°C and $\Delta_2 V^{\ddagger}_{steric}$ should exceed the volume contraction arising from the overlap of interfering atoms, $\Delta_1 V^{\ddagger}_{steric}$, at 0°C. As a result, the *ortho* : *para* ratios decrease with an increase in the pressure. On the other hand, under the present conditions $\Delta_1 V^{\ddagger}_{steric}$ exceeds $\Delta_2 V^{\ddagger}_{steric}$ and the applied pressure causes the increase in the *ortho* : *para* ratio.

If the above explanation is correct, the *ortho*: *para* ratio in chlorobenzene should decrease more extensively with the pressure than in toluene at 0°C for reasons to be outlined below.

The initial state solvation should be more striking for chlorobenzene because of the larger polarization of the C–Cl bond than of the C–CH_3 bond.[*10] In the reaction of allyl chloride with phenoxide ion in water, the product ratio, (*o*-allylphenol)/(*p*-allylphenol), decreases with an increase in the pressure ($\delta\Delta V_1^{\ddagger} = 5.4$ m*l*/mol at 30°C).[12] The data in Table 6 are in accordance with the above prediction; the fact that the changes in the *ortho*: *para* ratios with the pressure in chlorobezene and in toluene are nearly equal at 45°C indicates that the difference in the initial state solvation is small and does not play a principal role in the effect of the pressure on the *ortho* : *para* ratios. Since the values of $\Delta_1 V^{\ddagger}_{steric}$ are not known, the extent of the volume increase due to the steric inhibition of solvation can not be discussed further on the basis of the data at hand.

Experimental

Materials. Unless otherwise stated, the materials used in the present experiment were prepared by standard methods; the purities were inspected by g.l.c. and had the following physical constants (all the melting and boiling points are uncorrected).

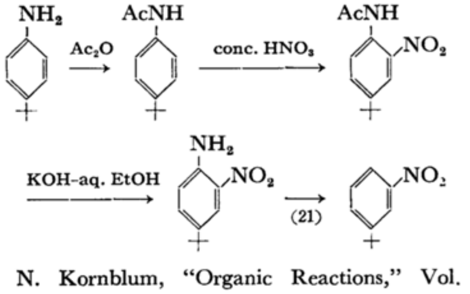
t-Butylbenzene, prepared by the method of Norris and Strugis[19]; bp 168.5°C, n_D^{27} 1.4889. Fluorobenzene, prepared by the method of Flood[20]; bp 85.5°C, n_D^{20} 1.4677. Nitrotoluenes, *o*- bp 110—111°C/28 mmHg, n_D^{27} 1.5424; *m*- bp 121°C/32 mmHg, n_D^{27} 1.5431; *p*- mp 51.9—52.1°C. *o*-Nitro-*t*-butylbenzene, prepared by the nitration of *t*-butylbenzene and collected by preparative g.l.c.; n_D^{27} 1.5141. *m*-Nitro-*t*-butylbenzene, prepared from *p*-*t*-butylaniline[*11]; n_D^{27} 1.5238. *p*-Nitro-*t*-butylbenzene, prepared by the nitration of *t*-butylbenzene and collected by preparative g.l.c.; mp 27°C, n_D^{27} 1.5305. Biphenyl; mp 70.0—70.5°C. *o*- and *p*-Nitrobiphenyls, purified by recrystallization, *o*-; mp 35.4—36.0°C from ethanol. *p*-; mp 114.3—115.0°C from methanol-chloroform. *m*-Nitrobiphenyl, prepared by the method of Elks *et al.*;[22] mp 59.9—60.0°C from ethanol. *o*-Nitrofluorobenzene, bp 95—96°C/15.5mmHg, $n_D^{22.6}$ 1.5292. *m*-Nitrofluorobenzene, kindly supplied by the Hashimoto Kasei Co., Ltd.; bp 82—83°C/19 mmHg, $n_D^{22.6}$ 1.5231. *p*-Nitrofluorobenzene, prepared by the method of Cheek *et al.*[23] from *p*-nitrobenzenediazonium tetrafluoroborate,[24] $n_D^{22.7}$ 1.5293. Nitrochlorobenzenes, *o*- mp 32.5—32.7°C; *m*- mp 44.7—44.9°C; *p*- mp 83.9—84.0°C. Nitrobromobenzenes, prepared by the method of Newman and Fones,[25] *o*- mp 41.6—

[*10] The dipole moments of chlorobenzene and toluene are 1.56 and 0.39 respectively.

[19] J. F. Norris and B. M. Strugis, *J. Am. Chem. Soc.*, **61**, 1415 (1939).

[20] D. T. Flood, "Organic Synthesis," Coll. Vol. II, p. 295 (1963).

[*11]



[21] N. Kornblum, "Organic Reactions," Vol. 2, p. 294 (1960).

[22] J. Elks, J. W. Haworth and D. H. Hey, *J. Chem. Soc.*, **1940**, 1285.

[23] P. H. Cheek, R. H. Wiley and A. Roe, *J. Am. Chem. Soc.*, **71**, 1863 (1949).

[24] K. Fukui, H. Kitano, R. Ijiri, Y. Inamoto and T. Matsufuji, *Nippon Kagaku Zasshi (J. Chem. Soc. Japan, Pure Chem. Sect.)*, **79**, 889 (1958).

[25] M. S. Newman and W. S. Fones, *J. Am. Chem. Soc.*, **69**, 1221 (1947).

42.0°C; *m*- mp 54.6—54.9°C; *p*- mp 127.0°C.

All the other materials and solvents were purified by ordinary methods. Guaranteed-reagent-grade nitric acid (d=1.42) and sulfuric acid (d=1.84) were used.

High-pressure Apparatus. The high-pressure apparatus has been described previously.[13]

Nitration and Analytical Procedure. Nitrations were carried out by adding an acetic acid solution of nitric-sulfuric acid to a solution of benzene, substituted benzene, and a suitable internal standard at room temperature. The initial concentrations of acids and water were as follows; for alkyl- and aryl-benzenes, H_2O=1.3M, HNO_3=0.6N, H_2SO_4=2.6N; for halobenzenes, H_2O =2.3M, HNO_3=1.0N, H_2SO_4=4.7N. The substrate concentrations were in the range of 0.15—1.15M.

About 2.5 m*l* of the reaction mixture was transferred to a reaction vessel (sealed tube or glass syringe) and maintained at 45°C at the desired pressure. The reaction was stopped by adding water after a few hours depending on the pressure. The mixture was neutralized with aqueous sodium hydroxide and extracted repeatedly with methylene chloride. The extracts were washed, concentrated carefully, and analyzed by g.l.c. The validity of this procedure was previously proved using synthetic mixtures of nitrobenzenes. Analyses were made for nitro aromatics, and this value was subtracted from the initial concentration of the aromatic to obtain the value of the final concentration.

The relative reactivities were calculated by Eq. (15)[26]:

$$k_X/k_H = [\log [XC_6H_5]_0 - \log [XC_6H_5]_t]/[\log [C_6H_6]_0 - \log [C_6H_6]_t] \qquad (15)$$

The *meta*: *ortho* ratios in the nitration of halobenzenes were determined independently in order to obtain the exact concentration of *m*-nitrohalobenzenes.

The kinetic runs were performed at least three times under each set of conditions; the averaged values are shown in Tables 1 and 2. A typical example is shown in Table 7.

TABLE 7. COMPETITIVE NITRATION OF BENZENE AND *t*-BUTYLBENZENE AT 2000 kg/cm²

k_{Bu}/k_H	*o*- %	*m*- %	*p*- %	f_o^{Bu}	f_m^{Bu}	f_p^{Bu}
12.4	10.9	7.8	81.2	4.1	2.9	60.4
12.6	10.9	7.9	81.2	4.1	3.0	61.4
12.0	11.3	8.4	80.3	4.1	3.0	57.8
12.0	11.1	8.3	80.6	4.0	3.0	58.0
12.5	11.0	7.9	81.1	4.1	3.0	60.8

In the reaction of biphenyl, the remaining biphenyl was determined directly. It was assumed that nitrobiphenyls consist of *o*- and *p*-nitrobiphenyl, for the separation of *m*-nitrobiphenyl from the *para* isomer on g.l.c. was not enough to determine its quantity; however, the quantity is very small and the obtained partial rate factors for the *ortho* and *para* positions should be real ones.

TABLE 8. GAS CHROMATOGRAPHY ANALYTICAL DATA

Nitrobenzene	Retention time (min)	Nitrobenzene	Retention time (min)
Toluene		**Chlorobenzene**	
Tricresyl phosphate 10%, 3 m, 158°C,		PEG 20M 10%, 3 m, 195°C, He 22.5 m*l*/min	
He 33 m*l*/min		Nitrobenzene	6.9
Nitrobenzene	5.4	*m*-Nitrotoluene[a]	9.2
o-Nitrotoluene	7.2	*m*-Nitrochlorobenzene	11.3
m-Nitrotoluene	8.7	*p*-Nitrochlorobenzene	12.7
p-Nitrotoluene	10.5	*o*-Nitrochlorobenzene	15.6
o-Nitrochlorobenzene[a]	14.7	**Bromobenzene**	
***t*-Butylbenzene**		PEG 20M 10%, 3 m, 210°C, He 21 m*l*/min	
Apiezon grease L 20%, 4.5 m, 198°C,		Nitrobenzene	4.3
He 15 m*l*/min		*p*-Nitrochlorobenzene[a]	7.6
Nitrobenzene	3.0	*m*-Nitrobromobenzene	10.9
p-Nitrotoluene[a]	4.6	*p*-Nitrobromobenzene	12.1
o-Nitro-*t*-butylbenzene	6.0	*o*-Nitrobromobenzene	14.6
m-Nitro-*t*-butylbenzene	7.9	**Biphenyl**	
p-Nitro-*t*-butylbenzene	10.1	Silicon oil KF 96 (Shinetsu Chemicals Co., Ltd.),	
Fluorobenzene		10%, 3 m, 163°C, He 25 m*l*/min.	
PEG 20M 10%, 3 m, 186°C, He 24 m*l*/min		Nitrobenzene	1.5
m-Nitrofluorobenzene	4.6	*p*-Nitrochlorobenzene[a]	2.5
p-Nitrofluorobenzene	5.5	Biphenyl	4.7
Nitrobenzene	6.4	219°C, He 22.5 m*l*/min.	
o-Nitrofluorobenzene	7.5	*o*-Nitrobiphenyl	3.2
m-Nitrotoluene[a]	8.5	*m*-Nitrobiphenyl	4.9
		p-Nitrobiphenyl	5.1

a) Internal standard substances

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[26] M. J. S. Dewar, T. Mole and E. W. T. Warford, *J. Chem. Soc.*, **1956**, 3576.

Gas-chromatographic Analysis. All analyses of the nitration mixtures were carried out on a Yanagimoto gas chromatograph Model GCG 5DH. A thermal-conductivity detector was used except for the determination of the *meta*: *ortho* ratio in the case of halobenzenes. For this purpose a flame-ionization detector was used. The analytical conditions and retention times are presented in Table 8.

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