

Substituent Effects of Positive Poles in Aromatic Substitution. Part VII.¹ Effect of Nitrogen and Arsenic Poles on the Orientation and Rate of Bromination by Hypobromous Acid

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The bromination of the phenyltrimethylammonium ion by hypobromous acid in aqueous sulphuric acid gives $66 \pm 1\%$ *meta*-substitution, $33 \pm 1\%$ *para*-substitution, and less than 2% *ortho*-substitution. Under the same conditions, bromination of the phenyltrimethylarsonium ion gives $90 \pm 2\%$ *meta*-substitution, $10 \pm 2\%$ *ortho*-substitution, and less than 3% *para*-substitution. The rates of bromination of these ions and of a number of other benzene derivatives with positively charged substituents have been measured. The results are compared with those obtained in nitration, and for the nitrogen poles are explained in terms of the electrostatic interaction between the pole and the charge on the aromatic ring or on the electrophile in the transition state. The substituent effects of other poles are shown to be consistent with the superposition of conjugative effects on this electrostatic interaction.

THE effects of the substituents -XMe_3^+ ($\text{X} = \text{N}, \text{P}, \text{As},$ or Sb), on the orientation and rate of nitration were compared in Part IV² of this series. As expected, the deactivating effect of the pole decreased with an increase in the atomic weight of the atom carrying the formal charge but the *meta*-directing effect of the phosphorus and arsenic poles appeared markedly greater than that of the nitrogen pole. This was explained in terms of the $-\text{M}$ effect of the phosphorus and arsenic poles, made possible by the vacant d -orbitals in the valence shell of these atoms. A more unexpected result was that with the antimony pole and possibly also with the arsenic pole,* the amount of *ortho*-substitution exceeded that of *para*-substitution.

The analysis of the nitration products was handicapped by our inability to synthesise the complete range of nitro-compounds involved and the interpretation of the amount of *ortho*-substitution is complicated by the possible steric hindrance between the methyl groups and the incoming nitro-group. Such steric hindrance is known to be much less for bromination by positive bromine³ and the corresponding bromo-compounds are more readily available. Kinetic studies on the bromination of the quaternary ions PhXMe_3^+ ($\text{X} = \text{N}, \text{P},$ or As) have therefore been carried out accompanied by studies of the products obtained. Unfortunately, the work on the products from the brominations of the phosphonium ion was complicated by side-reactions during analysis and could not be completed: the kinetic work and some ancillary studies are included below.

Products.—No previous investigation of the products of bromination of the phenyltrimethylammonium ion has been reported. Preliminary studies on synthetic mixtures containing the phenyltrimethylammonium ion, the three monobromophenyltrimethylammonium ions, and the 3,4-dibromophenyltrimethylammonium ion showed that the complete analysis of such mixtures is not easy. The u.v. spectra of these ions are too similar to be of value and the i.r. spectra are of little use because of overlapping bands. Separation into three fractions contain-

ing the unbrominated material, the monobromo-derivatives, and the dibromo-derivative could be obtained with both paper chromatography and electrophoresis but further analysis of the monobromo-fraction was not found possible by these techniques.⁴

In most solvents, the n.m.r. peak of the methyl protons in the *ortho*-isomer lies at *ca.* 0.1–0.2 p.p.m. to low field of the combined peaks for the methyl protons in the *meta*- and *para*-isomers. Fortunately, in the solvents aniline and 50/50 mixtures of aniline and nitrobenzene, the methyl peaks of all three monobromo-isomers are distinct (see Experimental section) but the usefulness of this as an analytical technique is limited by overlapping of these peaks with the absorption of the unbrominated material. Demethylation of the mixtures of quaternary salts followed by the use of g.l.c. to separate the corresponding tertiary amines was also investigated. Reaction with lithium aluminium hydride was found to provide the required quantitative demethylation without disturbance of the isomer ratios (providing that none of the 3,4-dibromo-derivative was present). The analysis of the synthetic mixtures by g.l.c. was successful and has been reported separately.⁵

The bromination of the phenyltrimethylammonium ion by hypobromous acid was carried out in various molarities of sulphuric acid with an excess of the aromatic substrate to prevent the formation of dibromo-compounds. The product, together with the excess of the aromatic reactant, was isolated as the perchlorate or tetraphenylborate and was analysed by using the n.m.r. spectrum of the methyl protons and by g.l.c. after demethylation. No *ortho*-substitution could be detected by either technique and the amount of such substitution must be less than 2%. Both analytical techniques indicated that the monosubstituted product derived from about 67% *meta*-substitution and about 33% *para*-substitution. The results from g.l.c. are considered to be the more accurate and are outlined below for the various acidities studied. There is no significant

* It was not possible to determine separately the amounts of substitution *ortho* and *para* to the arsenic pole.

¹ Part VI, S. R. Hartshorn, and J. H. Ridd, *J. Chem. Soc. (B)*, 1968, 1068.

² Alicia Gastaminza, T. A. Modro, J. H. Ridd, and J. H. P. Utley, *J. Chem. Soc. (B)*, 1968, 534.

³ P. B. D. de la Mare, J. T. Harvey, M. Hassan, and S. Varma, *J. Chem. Soc.*, 1958, 2756.

⁴ F. Roy, Ph.D. Thesis, London, 1968.

⁵ F. Roy, *J. Gas Chromatog.*, 1968, **6**, 245.

variation of the product composition with the acidity of the medium:

H ₂ SO ₄ (M)	3.0	5.5	6.0	7.0
% <i>para</i>	32.5	33.7	33.0	34.0

The application of the same methods to the analysis of mixtures of the corresponding aryltrimethyl phosphonium salts was unsuccessful, in part because of the increased complexity of the P-Me ¹H n.m.r. spectra (because of coupling of the protons with the phosphorus nucleus), but mainly because of our failure to find a quantitative method of demethylating the quaternary salts. The attempted demethylation of aryltrimethylphosphonium ions is accompanied by a side reaction involving fission of the aryl-phosphorus bond.⁶

The analysis of the products of bromination of the phenyltrimethylarsonium ion by hypobromous acid was carried out by the same combination of n.m.r. and g.l.c. measurements as outlined above for the corresponding ammonium ion. The reaction was carried out with an excess of the aromatic substrate in 5.8 and 7.0M-sulphuric acid and the products were precipitated as the tetraphenylborates. The n.m.r. spectrum of the As-Me protons indicated that the monobromo-fraction is mainly the *meta*-compound but with *ca.* 10% of *ortho*-substitution; there is no peak corresponding to *para*-substitution. Demethylation of these quaternary salts cannot be carried out with lithium aluminium hydride as the aryltrimethylarsines react further with this reagent. Studies on synthetic mixtures showed that pyrolysis of the quaternary chlorides provided a satisfactory method of demethylating the unsubstituted compound and its *meta*- and *para*-bromo-derivatives, but that, unfortunately, the greater part of the *ortho*-bromophenyltrimethylarsonium chloride underwent debromination during pyrolysis. G.l.c. of the bromination product after pyrolysis showed a strong peak for dimethylphenylarsine, a similar peak for the *meta*-bromo-derivative, a weak peak (1–2%) for the *ortho*-bromo-derivative, and no peak for the *para*-bromo-derivative. This confirms the absence of *para*-substitution and, in view of the decomposition of the *ortho*-isomer during pyrolysis, is consistent with the amount of *ortho*-substitution estimated from the n.m.r. spectrum. It is a little difficult to estimate the maximum amount of *para*-substitution that would remain undetected but the figure is probably *ca.* 3%.

Kinetics.—The kinetics of the reaction of deactivated aromatic compounds (including the phenyltrimethylammonium ion) with hypobromous acid in aqueous mineral acids have been studied by de la Mare and Hilton.⁷ At a given acidity, the kinetic form accords with the equation:

$$\text{Rate} = k_2[\text{ArH}][\text{HOBr}] \quad (1)$$

but the increase in the rate coefficient (k_2) with acidity

indicates that the electrophilic reagent is either the hypobromous acidium ion (H₂OBr⁺) or the bromine cation (Br⁺). The same authors have shown that the ratio of the rate coefficients of the phenyltrimethylammonium ion and benzene in this reaction is 1.6×10^{-5} . This figure refers to reaction in aqueous perchloric acid; an indirect estimate of this ratio for reaction in aqueous sulphuric acid was also calculated (0.4×10^{-5}).

We have extended this work by studying the bromination of a number of other positive ions in aqueous sulphuric acid and by directly relating the reaction rates to the rate of bromination of benzene in this solvent. The second-order rate coefficients obtained are collected in Table 1 and the results referring to mono-bromination are plotted logarithmically against H_0 in Figure 1. The

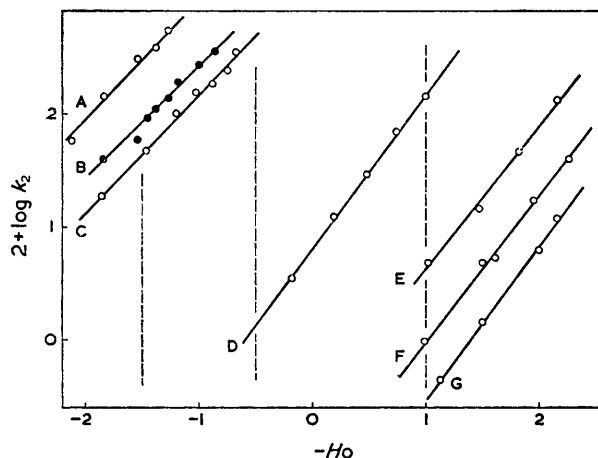


FIGURE 1 The variation of the second-order rate coefficient (k_2 , l. mole⁻¹ sec.⁻¹) with acidity for bromination by hypobromous acid: A, Ph[CH₂]₃N⁺Me₃; B, PhH; C, Ph[CH₂]₂N⁺Me₃; D, PhCH₂N⁺Me₃; E, PhAs⁺Me₃; F, PhP⁺Me₃; and G, PhN⁺Me₃.

use of the acidity function as abscissa is merely to facilitate the step-wise comparison of reactivities. The values of H_0 for concentrations of sulphuric acid greater than 0.1M are taken from the review by Paul and Long;⁸ the values for concentrations below this acidity are equated with $-\log_{10} C_{H^+}$. These values of C_{H^+} in dilute sulphuric acid are interpolated from the data given by Sherrill and Noyes.⁹

The slope of the plots in Figure 1 range from 1.0 for the bromination of benzene to 1.4 for the bromination of the phenyltrimethylammonium ion but much of this variation probably derives from the different ranges of acidity used for studying the reactions of these substrates. Relative reactivities are shown in Table 2 calculated by a step-wise comparison at the acidities indicated by dotted lines in Figure 1. Our values of the rate coefficient for the bromination of the phenyltrimethylammonium ion accord well with those of de la

⁶ G. F. Fenton, L. Hey, and C. K. Ingold, *J. Chem. Soc.*, 1933, 989.

⁷ P. B. D. de la Mare and I. C. Hilton, *J. Chem. Soc.*, 1962, 997.

⁸ M. A. Paul and F. A. Long, *Chem. Rev.*, 1957, **57**, 1.

⁹ M. S. Sherrill and A. A. Noyes, *J. Amer. Chem. Soc.*, 1926, **48**, 1861.

TABLE 1

Second-order rate coefficients (l. mole⁻¹) sec.⁻¹ for bromination in aqueous sulphuric acid at 25°

Ph ⁺ NMe ₃ ClO ₄ ⁻	H ₂ SO ₄ (M)	2.53	3.25	4.35	4.74		
	10 ² k ₂	0.43	1.42	6.12	11.8		
Ph ⁺ PMe ₃ ClO ₄ ⁻	H ₂ SO ₄ (M)	2.26	2.41	3.25	3.48	4.25	4.97
	10 ² k ₂	0.97	1.62	4.77	5.22	17.0	40.0
Ph ⁺ AsMe ₃ ClO ₄ ⁻	H ₂ SO ₄ (M)	2.33	3.19	3.93	4.74		
	10 ² k ₂	4.80	14.6	46.6	132		
<i>m</i> -BrC ₆ H ₄ AsMe ₃ ClO ₄ ⁻	H ₂ SO ₄ (M)	3.52	4.29	5.26			
	10 ² k ₂	2.05	6.40	24.0			
<i>p</i> -BrC ₆ H ₄ AsMe ₃ ClO ₄ ⁻	H ₂ SO ₄ (M)	3.33	4.05	5.17			
	10 ² k ₂	2.60	7.00	36.5			
PhCH ₂ N ⁺ Me ₃ ClO ₄ ⁻	H ₂ SO ₄ (M)	0.45	0.91	1.36	1.82	2.27	
	10 ² k ₂	3.45	12.2	29.4	70.0	143	
Ph[CH ₂] ₂ N ⁺ Me ₃ ClO ₄ ⁻	H ₂ SO ₄ (M)	0.0091	0.023	0.0454	0.0681		
	10 ² k ₂	18.8	46.7	101.2	155		
		0.0909	0.119	0.143			
		182	283	343			
Ph[CH ₂] ₃ N ⁺ Me ₃ ClO ₄ ⁻	H ₂ SO ₄ (M)	0.00476	0.00952	0.0190	0.0286	0.0381	
	10 ² k ₂	58.3	142	306	384	542	
PhH	H ₂ SO ₄ (M)	0.0095	0.019	0.0238	0.0286		
	10 ² k ₂	39.6	58.8	90.6	109		
		0.0381	0.0476	0.0714	0.0952		
		136	191	270	350		

Mare and Hilton⁷ and our value of the relative reactivity of this ion and benzene is in reasonable agreement with their estimate.

TABLE 2

Reaction rates, relative to benzene, for bromination and nitration in aqueous sulphuric acid at 25°

Substrate	Relative rate	
	Bromination	Nitration *
Ph[CH ₂] ₃ N ⁺ Me ₃	3.5	3.2
PhH	1.0	1.0
Ph[CH ₂] ₂ N ⁺ Me ₃	0.51	0.22
PhCH ₂ N ⁺ Me ₃	1.4 × 10 ⁻³	7.9 × 10 ⁻⁵
Ph ⁺ AsMe ₃	4.1 × 10 ⁻⁵	1.3 × 10 ⁻⁶
Ph ⁺ PMe ₃	8.7 × 10 ⁻⁶	1.6 × 10 ⁻⁷
PhN ⁺ Me ₃	2.6 × 10 ⁻⁶	3.4 × 10 ⁻⁸

* Some of these values have been recalculated (*cf.* ref. 2) so that all are now based on our most recent estimate of the reactivity of the phenyltrimethylammonium ion relative to benzene (T. A. Modro and J. H. Ridd, *J. Chem. Soc. (B)*, 1968, 528).

The relative reactivities of the same compounds towards nitration in aqueous sulphuric acid are included in Table 2. Considering only *meta*- and *para*-substitution it follows from Brown's extension¹⁰ of the Hammett equation that a logarithmic plot of the relative reactivities for bromination against those for nitration should be linear with a slope equal to the ratio of the *p*-values for these reactions. However, *ortho*-substitution does not follow these linear free-energy relationships and, to the extent to which *ortho*-substitution is important, some deviations may be expected. The logarithmic plot of the relative reactivities in these two reactions is shown in

Figure 2. The plot is essentially linear but the more reactive substrates show deviations in that the rate of bromination is greater than would be expected from the rate of nitration. This is consistent with the smaller steric hindrance to *ortho*-bromination (by positive

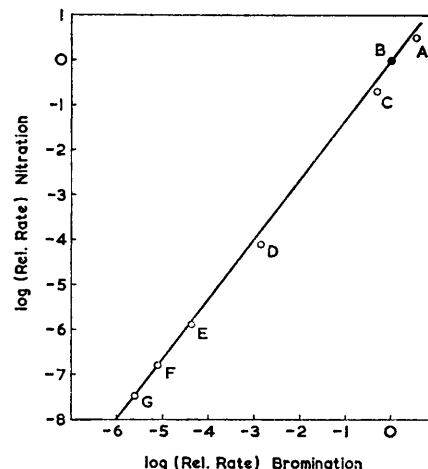


FIGURE 2 The relationship between relative rates (with respect to benzene) for nitration and bromination. Lettering as for Figure 1

bromine) compared with *ortho*-nitration.³ The slope of the plot (1.3) indicates that, in free-energy terms, substituent effects on the rate of nitration are 30% greater than those on the rate of bromination.

The Electrostatic Model for Substituent Effects.—This paper concludes our study of how the substituent effect of a charged group depends on the nature of the atom

¹⁰ L. M. Stock and H. C. Brown, *Adv. Phys. Org. Chem.*, 1963, 1, 35; see esp. p. 78 et seq.

bearing the formal charge and we wish now to rationalize the results obtained in terms of a simple model of the transition state. The results of the present work and some of those reported previously by ourselves and other groups have therefore been collected in Tables 3 and 4.

TABLE 3

The orientation of bromination and nitration

Substrate	Bromination (%)			Nitration (%)			Ref.
	<i>o</i>	<i>m</i>	<i>p</i>	<i>o</i>	<i>m</i>	<i>p</i>	
PhN ⁺ Me ₃	*	66	33	*	89	11	<i>a, b</i>
PhNHMe ₂ ...	3	64	33	*	78	22	<i>b, c</i>
PhNH ₃				1.5	62	36.5	<i>d</i>
PhOPh ₂						100	<i>e</i>
PhAsMe ₃	10	90	†	<4	96	<4	<i>a, f</i>
PhSbMe ₃				8	87	5	<i>f</i>
PhSeMe ₂	5	91	4	4	90	6	<i>g, h</i>

* <2%. † <3%.

^a This work. ^b M. Brickman, J. H. P. Utley, and J. H. Ridd, *J. Chem. Soc.*, 1965, 6851. ^c B. R. Suthers, P. H. Riggins, and D. E. Pearson, *J. Org. Chem.*, 1961, 27, 447. ^d S. R. Hartshorn and J. H. Ridd, *J. Chem. Soc. (B)*, 1968, 1063. ^e A. N. Nesmeyanov, T. P. Tolstaya, L. S. Isaeva, and A. V. Grib, *Doklady Akad. Nauk S.S.S.R.*, 1960, 133, 602. ^f A. Gastaminza, T. A. Modro, J. H. Ridd and J. H. P. Utley, *J. Chem. Soc. (B)*, 1968, 534. ^g H. M. Gilow and G. L. Walker, *J. Org. Chem.*, 1967, 32, 2580. ^h H. M. Gilow, R. B. Camp, and E. C. Clifton, *J. Org. Chem.*, 1968, 33, 230.

TABLE 4

Partial rate factors * for nitration (A) and bromination (B) in aqueous sulphuric acid at 25°
(For references see Table 3)

Substrate	Re- action	10 ³ <i>f</i>			$\frac{\log f_p}{\log f_m}$	
		10 ³ <i>f_o</i>	10 ³ <i>f_m</i>	10 ³ <i>f_p</i>	$\frac{\log f_p}{\log f_m}$	$\frac{\log f_o}{\log f_m}$
PhNH ₃	A	8.3	336	413	0.98	1.29
PhN ⁺ Me ₃	A	<0.2	9.1	2.2	1.09	>1.24
	B	<16	515	515	1.00	>1.23
PhAsMe ₃	A	<16	378	<31.4	>1.20	>1.26
	B	1230	11,100	<740	>1.30	1.25
PhSbMe ₃	A	1630	17,700	2040	1.25	1.28

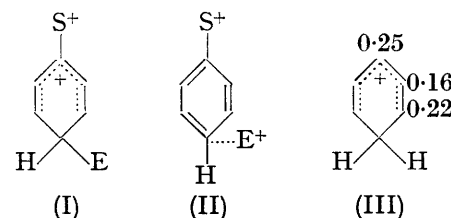
* See footnote to Table 2. The recalculated partial rate factors are about twice those reported previously.

For many years, positive poles have been regarded as *meta*-directing groups and the literature contains several explanations of such a directing effect. However, the above account of the bromination of the phenyltrimethylammonium ion together with other recent studies of the nitration of aniline¹¹ and of protodetriethylgermylation¹² show that the deactivating effect of a nitrogen pole can be almost identical at *meta*- and *para*-positions. The model must therefore explain this characteristic and also the mild *meta*-directing effect observed in the nitration of the phenyltrimethylammonium ion.

* The following line of argument has been outlined previously¹³ by one of us but without reference to *ortho*-substitution.

¹¹ S. R. Hartshorn and J. H. Ridd, *J. Chem. Soc. (B)*, 1968, 1063.

Probably the simplest approach is a development of Bjerrum's analysis of the effect of charges on acid-base equilibria. It is generally considered that the transition state for aromatic bromination and nitration is intermediate between structures of the kind illustrated, for *para*-substitution, by (I) and (II) below.* For each of these structures, it is possible to consider the substituent effect on the free energy of activation ($\delta\Delta G^\ddagger$) to derive from the electrostatic interaction between the charge on the substituent (S) and that on the ring or the electrophile (E) as calculated from Coulombs Law. The major uncertainty in calculations of this kind is the magnitude of the effective dielectric-constant but this can be avoided, to a first approximation, by considering the ratios of the substituent effects at the *ortho*-, *meta*-, and *para*-positions. The values of these ratios are given below the structures; these are calculated by assuming that the charge distribution in structure (I) is that for the protonation of a benzene ring (III) as estimated from n.m.r. studies on protonated pentamethylbenzene¹⁴ and that the electrophile in structure (II) is 2 Å above the point of attack. The S-C bond in both structures is taken as being 1.45 Å.



$\delta\Delta G_p^\ddagger/\delta\Delta G_m^\ddagger$	1.06	0.90
$\delta\Delta G_o^\ddagger/\delta\Delta G_m^\ddagger$	0.96	1.34

The crudity of these models implies that little significance should be attached to the exact values of the ratios above but they serve nevertheless as a useful first approximation to the results expected from electrostatic arguments and suggest the following conclusions. First, when the transition state resembles structure (I), there should be little discrimination between attack at the *ortho*-, *meta*-, and *para*-positions. Secondly, when the transition state resembles structure (II), *para*-substitutions should be favoured and *ortho*-substitutions more markedly retarded. Thirdly, since the electrostatic interactions for attack at all positions is greater for structure (I) than for structure (II), the reactions giving the smaller substituent effects with a given positive pole should be taken as those with transition states nearer to structure (II).

Substituent effects of poles on the protonation of amino-groups provide a guide to the magnitude of substituent effects in transition states of type (II), for the distance between the pole and the amino-nitrogen is similar but rather less than that between the pole and the electrophile in structure (II). In this connection,

¹² C. Eaborn and K. C. Pande, *J. Chem. Soc.*, 1961, 5082.

¹³ J. H. Ridd, *Chem. Soc. Special Publ.*, No. 21, 1967, p. 149.

¹⁴ C. Maclean and E. L. Mackor, *Mol. Phys.*, 1961, 4, 241.

it is interesting that the values¹⁵ of ΔpK_a for the effect of a $-\text{NH}_3^+$ pole on the acidity of another $-\text{NH}_3^+$ pole in diaminobenzenes are *ortho*, 3.7; *meta*, 2.06; *para*, 1.63. Hence, for a transition state resembling structure (II)

the partial rate factor for *meta*-substitution to a $-\text{NH}_3^+$ group should be about 10^{-2} .

Application to Nitrogen Poles.—Consider first substitution *meta*- and *para*- to the $-\text{NH}_3^+$ pole. Since $\delta\Delta G^\ddagger = -RT \ln f$, the ratio $\log f_p / \log f_m$ is equal to the corresponding ratio of substituent effects on the free energy of activation ($\delta\Delta G^\ddagger_p / \delta\Delta G^\ddagger_m$). Comparison of the experimental values (Table 4) with the calculated ratios below structures (I) and (II) shows that, for nitration, the directing effect of the pole accords best with the structure having the charge on the aromatic ring. The magnitude of the substituent effect is consistent with this, for the value of f_m (ca. 10^{-7}) is much lower than that expected for a transition-state resembling structure (II). The ratio $\log f_p / \log f_m$ for bromination suggests that the charge transfer to the ring is less complete and this is again consistent with the smaller deactivating effect of the pole ($f_m = 5 \times 10^{-6}$).

These substituent effects and, in particular, the large amount of the *para*-bromo-compound formed can therefore be understood in terms of this electrostatic model. The results also accord well with the earlier work of Pearson and his co-workers¹⁶ on the bromination of dimethylanilinium chloride in the presence of aluminium chloride (Table 3).^{*} This reaction was not originally considered to involve electrophilic attack on the *N*-protonated amine but the similarity of the product composition to our results on the bromination of the phenyltrimethylammonium ion makes it probable that the dimethylanilinium ion is the reactant. The idea that the lower the deactivating effect of the pole, the more the transition state has the characteristics expected of structure (II) receives support from the work of Eaborn and Pande¹² on protodegermylation. In this reaction, the substituent effect of the nitrogen pole is less than reported for bromination above, and for reaction in aqueous sulphuric acid the deactivating effect of a *para*- NMe_3^+ group is then less than that of a *meta*- NMe_3^+ group. Unfortunately, when the solvent is mainly acetic acid this order is reversed; such medium effects are not yet understood.

It is more difficult to test whether the amount of *ortho*-substitution is consistent with this electrostatic model, in part because of steric effects and in part because the calculated $\delta\Delta G^\ddagger$ ratios suggest that *ortho* : *meta* ratios should be very sensitive to the extent of charge transfer to the aromatic ring in the transition state.

^{*} The figures for this reaction in Table 3 have been recalculated to refer to the monobromo-fraction. The amount of other products is slight.

¹⁵ D. D. Perrin, 'Dissociation Constants of Bases in Aqueous Solution,' Butterworths, London, 1965.

The absence of detectable *ortho*-substitution in the nitration of the phenyltrimethylammonium ion could be attributed to steric hindrance or to electrostatic interaction or both, but the little *ortho*-substitution observed in the nitration of the anilinium ion (Table 3) points to some electrostatic deactivation of the *ortho*-position. The figures quoted are for reaction in 98% sulphuric acid; at lower acidities, more *ortho*-substitution is observed¹¹ so that in 82% sulphuric acid $\log f_o / \log f_m = 1.14$. The absence of detectable *ortho*-substitution in the bromination of the phenyltrimethylammonium ion also points to some electrostatic deactivation of the *ortho*-positions since the partial rate factors for bromination by positive bromine *ortho*- and *para*- to the *t*-butyl group³ differ only by a factor of 3. The more the transition state resembles structure (II) the more electrostatic deactivation of *ortho*-substitution would be expected. It may be significant therefore that the substituent effect of the $-\text{NHMe}_2^+$ group in protodesilylation¹⁷ is very different at *ortho*- and *para*-positions giving $\log f_o / \log f_p = 1.42$. This is a reaction not apparently subject to steric hindrance and in which the substituent effects of poles are less than those in nitration and bromination.

The results with the nitrogen poles can therefore be understood in terms of the electrostatic model if part of the charge is transferred to the aromatic ring in the transition state but enough remains on the electrophile to lead to some electrostatic interaction opposing *ortho*-substitution. This accords with the conclusions of Eaborn, Walton, and Young concerning the effect of the $-\text{NMe}_2\text{H}^+$ pole on *ortho*-protodesilylation.¹⁷ In general, it appears that the variation in the effect of a given pole with the nature of the reaction can also be understood in terms of the variation in the charge distribution between the electrophile and the ring in the transition state. However, the evidence on this with regard to *ortho*-substitution is still very limited.

Application to Other Poles.—The substituent effects of the nitrogen poles can be considered, in the first approximation, as the consequence of electrostatic interaction because there are no orbitals of the appropriate symmetry in the valence shell of quaternary nitrogen to overlap effectively with the π -orbitals of the aromatic ring. This is not true for the other poles included in Table 3 and we now consider to what extent these substituent effects can be understood as the superposition of conjugative and electrostatic interaction.

The oxygen pole ($-\text{OPh}_2^+$) is, in principle, capable of π -electron donation to the aromatic ring and, although the extent of this in the transition state should be slight, because of the positive charge on the substituent, the result should strongly favour *ortho*- and *para*-substitution. Since the electrostatic interaction should not

¹⁶ B. R. Suthers, P. H. Riggins, and D. E. Pearson, *J. Org. Chem.*, 1962, **27**, 447.

¹⁷ C. Eaborn, D. R. M. Walton, and D. J. Young, *J. Chem. Soc. (B)*, 1969, 15.

discriminate markedly between *meta* and *para*-substitution but should lead to some relative deactivation of the *ortho*-position, the *para*-directing effect of the oxygen pole¹⁸ can be understood.

The arsenic and antimony poles are more polarisable than the nitrogen poles and have vacant *d*-orbitals in the valence shell capable of accepting π -electrons from the ring. The difference in polarisability should reduce the magnitude of the electrostatic interaction for attack at all positions and electron acceptance by the *d*-orbitals should bring these substituents into Ingold's $-I$, $-M$ class. Such substituents have been known for many years to deactivate the *para*-position relative to both the *meta*- and the *ortho*-positions.^{19,20} In general, the results in Tables 3 and 4 accord with these expectations, for the deactivating effect of these poles is less than that of the nitrogen poles and the extent of *para*-substitution is decreased. However, the percentage of substitution *ortho*- to the antimony and arsenic poles (Table 3) appears at first sight to be unexpectedly high.

The occurrence of appreciable substitution *ortho* to a group $-\ddot{X}Me_3$ was not foreseen in the first analysis of these substituent effects²¹ but it can be rationalised as follows. First, the steric hindrance to substitution *ortho* to $-\ddot{X}Me_3$ should be reduced when X is changed from nitrogen to arsenic because the distance between the incoming electrophile and the methyl hydrogen atoms is thereby increased. Secondly, the values of $\log f_o/\log f_m$ for the arsenic and antimony poles are similar to that for the $-\ddot{N}H_3$ pole, where steric hindrance should also be low. Thus the high percentages of substitution *ortho* to the arsenic and antimony poles can be attributed in part to reduced steric hindrance and in part to the weaker deactivating-effect of these poles which in itself brings all three partial rate factors closer together.

The conjugative interaction between the sulphur pole (Table 3) and the ring could, in principle, involve both electron donation from the filled *3p*-orbital (favouring *para*-substitution) and electron acceptance into the vacant *d*-orbital (favouring *ortho*-, *meta*-substitution). The result of such effects, when superposed on the electrostatic interaction is not easy to predict: it is, however, satisfactory that the recent work of Gilow and his co-workers²² had provided *ortho* : *para* ratios between those of the oxygen and arsenic poles.

Conclusions.—The main conclusions from this work are (a) that the substituent effects of nitrogen poles in nitration and bromination can be understood in terms of the electrostatic approach outlined above and (b) that the substituent effects of other poles can be understood as a superposition of the normal conjugative effects on

this electrostatic effect. There is also some evidence that the variation in the directive effect of the $-\ddot{N}Me_3$ group in different reactions and the related variation in its deactivating effect can be understood in terms of the degree of charge transfer to the aromatic ring in the transition state.

Other recent work has shown that the variation in the deactivating effect of a nitrogen pole with its distance from the ring can be attributed to the electrostatic interaction between the pole and the charge on the ring in the transition state.²³ Hence, in spite of the crudity of these models for calculating electrostatic interaction, it seems worthwhile to look more generally at the electrostatic approach to aromatic substituent effects using the expected charge distribution in the transition state. We hope later to analyse the effects of dipolar substituents in this way.

EXPERIMENTAL

Materials.—*NN*-Dimethylaniline and the three isomeric *NN*-dimethylbromoanilines were purchased or prepared by conventional methods and were methylated to give the quaternary compounds by treatment with methyl iodide or dimethyl sulphate. The corresponding perchlorates were prepared from the iodides by reaction with silver perchlorate and were purified by repeated recrystallisation. Analytical data for these and the other quaternary salts is collected in Table 5. The perchlorates of the 2-phenethyltrimethylammonium ion and the 3-phenyl-*n*-propyltrimethylammonium ion were prepared in a similar way.

TABLE 5
Analysis results

Compound	Found (%)			Calculated (%)		
	C	H	N	C	H	N
<i>o</i> -BrC ₆ H ₄ · $\ddot{N}Me_3ClO_4^-$	34.9	4.4	26.0	34.4	4.2	25.4
<i>m</i> -BrC ₆ H ₄ · $\ddot{N}Me_3ClO_4^-$	35.0	4.0	25.8	34.4	4.2	25.4
<i>p</i> -BrC ₆ H ₄ · $\ddot{N}Me_3ClO_4^-$	34.6	4.9	25.3	34.4	4.2	25.4
PhCH ₂ · $\ddot{N}Me_3ClO_4^-$	45.7	5.8	6.1	45.9	6.0	5.9
Ph[CH ₂] ₂ · $\ddot{N}Me_3ClO_4^-$	50.1	6.9	5.3	49.9	7.0	5.2
PhPMe ₃ I ⁺	38.5	4.9		38.5	5.0	
<i>m</i> -BrC ₆ H ₄ · $\ddot{P}Me_3I^-$	31.7	4.0		30.1	3.7	
<i>p</i> -BrC ₆ H ₄ · $\ddot{P}Me_3I^-$	29.9	3.8		30.1	3.6	
PhAsMe ₃ ClO ₄ ⁺	36.5	4.9		36.4	4.7	
<i>o</i> -BrC ₆ H ₄ · $\ddot{As}Me_3ClO_4^-$	27.2	3.7		26.4	3.2	
<i>m</i> -BrC ₆ H ₄ · $\ddot{As}Me_3ClO_4^-$	26.8	3.3		26.4	3.2	
<i>p</i> -BrC ₆ H ₄ · $\ddot{As}Me_3ClO_4^-$	27.0	3.5		26.4	3.2	

Dimethylphenylphosphine was supplied by Mr. D. Goodwin. *meta*-Bromophenyldimethylphosphine was prepared from *meta*-bromophenyldiazonium fluoroborate by treatment with phosphorus trichloride essentially as described

¹⁸ A. N. Nesmeyanov, T. P. Tolstaya, L. S. Isaeva, and A. V. Grib, *Doklady Akad. Nauk. S.S.S.R.*, 1960, **133**, 602.

¹⁹ C. K. Ingold, *Reports Progr. Chem.*, 1926, **23**, 140.

²⁰ P. B. de la Mare and J. H. Ridd, 'Aromatic Substitution,' Butterworths, London, 1959, p. 82.

²¹ J. H. Ridd and J. H. P. Utey, *Proc. Chem. Soc.*, 1964, 24.

²² H. M. Gilow and G. L. Walker, *J. Org. Chem.*, 1967, **32**, 2580; H. M. Gilow, R. B. Camp, and E. C. Clifton, *J. Org. Chem.*, 1968, **33**, 230.

²³ T. A. Modro and J. H. Ridd, *J. Chem. Soc. (B)*, 1968, 528.

by Quin and Humphrey,²⁴ followed by treatment of the crude *meta*-bromophenyldichlorophosphine with methylmagnesium iodide. The overall yield of *meta*-bromophenyldimethylphosphine (b.p. 82°/0.4 mm.) was poor (*ca.* 10%). The corresponding *para*-bromo-compound (b.p. 85°/0.4 mm.) was prepared in a similar way but attempts to obtain the *ortho*-bromo-compound were unsuccessful. Methylation to the quaternary compounds was carried out by adding, under nitrogen, a slight excess of methyl iodide to a solution of the phosphine in ether at 0°. The iodides were converted to the perchlorates as described above.

Phenyltrimethylarsonium perchlorate was prepared as described previously.² *ortho*-Bromophenyldimethylarsine was prepared from *ortho*-arsanilic acid by a Sandmeyer reaction with cuprous bromide followed by conversion of the *ortho*-bromophenylarsonic acid formed to *ortho*-bromophenyldichloroarsine by treatment with concentrated hydrochloric acid and sulphur dioxide. The product was treated with methylmagnesium iodide to give *ortho*-bromophenyldimethylarsine, b.p. 85–86°/0.8 mm. The corresponding *para*-bromo-compound (b.p. 91°/1 mm.) was prepared in a similar way. *meta*-Bromophenyldimethylarsine (b.p. 88°/1 mm.) had not been prepared previously; it was obtained by the Bart reaction on *meta*-bromophenylarsonic acid followed by conversion into the dichloroarsine and treatment with methylmagnesium iodide as outlined above. Great care should be taken in handling the bromophenyldichloroarsines as they appear to be powerful vesicants. The three bromophenyldimethylarsines were methylated to the corresponding quaternary compounds as outlined above for the phosphines.

Aqueous solutions of hypobromous acid were prepared by distillation from aqueous solution of bromine and silver phosphate as described by Shilov and Kaniev.²⁵ The distillate was kept for up to 3 days in darkened bottles over mercuric oxide and, before use, was repeatedly extracted with carbon tetrachloride to remove traces of bromine. The sulphuric acid and sodium thiosulphate were of AnalaR purity.

Product Analyses.—The following experiments are typical of the considerable number of analytical studies carried out in the course of this work.

A solution of trimethylanilinium perchlorate (7.22 g.) in sulphuric acid (3M; 50 ml.) was added to a solution of hypobromous acid (0.0348M; 661 ml.) in sulphuric acid (3M). These concentrations correspond to 30% excess of aromatic substrate. The reaction mixture was protected from light by aluminium foil and was left overnight at 25°. The solution was then diluted ($\times 4$) with distilled water and a slight excess of barium chloride was added. After removal of the barium sulphate by centrifugation and filtration, the low concentration of barium ions remaining was assessed by the method of Vogel²⁶ with rhodizonic acid as indicator, and the equivalent amount of sulphuric acid was added. After filtration, the filtrate was evaporated to dryness and samples were analysed in various ways.

One sample was examined by electrophoresis and gave two bands of approximately equal intensity located correctly for the starting material and the mono-brominated product: no band corresponding to dibrominated material was

observed. Another sample was analysed by combustion, giving C, 39.8; H, 4.9; Br, 13.2%. This corresponds closely to the figures for 48% of the aromatic reactant with 52% of the monobromo-compound (C, 39.9; H, 5.0; Br, 13.2%). The n.m.r. spectrum of a third sample was studied in acetone as solvent. The spectrum of the *N*-methyl protons consisted of two peaks at τ 6.04 and 6.08, the relative areas being 0.55 : 1. The first of these peaks is that of the *meta*-bromo-compound, the second that of the sum of the unbrominated substrate and the *para*-bromo-compound. In conjunction with the combustion analysis, this result implies that the monobromo-fraction contains about 68% of the *meta*-compound. No peak at τ 5.9, corresponding to the *ortho*-bromo-compound was observed.

In other experiments, the reaction mixture was neutralised and the quaternary ions were precipitated as the tetraphenylborates, under the conditions recommended by Flashka and Barnard.²⁷ The n.m.r. spectrum of the *N*-methyl protons was then examined in a 50 : 50 mixture of nitrobenzene and aniline as solvent with the same results as described above. The tetraphenylborates were converted to the chlorides with concentrated hydrochloric acid as described by Zeidler²⁸ and the quaternary chlorides were reduced by lithium aluminium hydride to the corresponding tertiary amines. Studies with synthetic mixtures of the three monobromophenyltrimethylammonium tetraphenylborates showed that these reactions did not change the product composition. Conditions for the reaction with lithium aluminium hydride are outlined below.

The finely ground quaternary chlorides were added to a five-fold excess of lithium aluminium hydride in dry tetrahydrofuran and the mixture was heated under reflux for 12 hr. The excess lithium aluminium hydride was removed by centrifugation and water was cautiously added. The mixture was then heated under reflux with ether for a further 3 hr. The ether layer was separated, the ether was removed, and the remaining material was dissolved in pentane. The amines were then separated from neutral material by the formation and decomposition of the hydrochlorides, and were analysed by g.l.c. as described elsewhere.⁵ The overall yield of tertiary amines from the quaternary compounds was 80% with *ca.* 5% debromination of the monobromo-compounds.

The bromination of phenyltrimethylarsonium perchlorate was also studied with an excess (30%) of the aromatic substrate. The product was precipitated as the tetraphenylborate as outlined above and the n.m.r. spectrum of the As-Me protons was studied in 50 : 50 aniline-nitrobenzene as solvent. In this solvent, the As-Me peaks are well separated as illustrated in Figure 3. Two peaks were present in the spectrum in the ratio 1 : 0.07. The larger peak was in the position expected for the superposed absorption of the unbrominated substrate and the *meta*-bromo-product; the smaller peak was in the position expected for the *ortho*-bromo-product. A bromine analysis on the product after conversion into the chloride indicated 65% bromination giving the amount of *ortho*-substitution as 10% of the monobromo-fraction. No dibromination was expected since a bromine substituent reduced the rate of

²⁴ L. D. Quin and J. S. Humphrey, *J. Amer. Chem. Soc.*, **1961**, **83**, 4124.

²⁵ E. A. Shilov and N. Kaniaev, *Compt. rend. Acad. Sci. U.R.S.S.*, **1939**, **24**, 890; *cf.* D. H. Derbyshire and W. A. Waters, *J. Chem. Soc.*, **1950**, 564.

²⁶ A. I. Vogel, 'Quantitative Inorganic Analysis,' Longmans, London, 1961, 3rd edn., p. 275.

²⁷ H. Flashka and A. J. Barnard, *Adv. Analyt. Chem. and Instrumentation*, **1960**, **1**, 1.

²⁸ L. Zeidler, *Z. physiol. Chem.*, **1952**, **291**, 177.

further bromination (Table 1). No peak corresponding to the *para*-bromo-isomer was detected.

Unfortunately, the procedure used for demethylating the quaternary ammonium salts is not applicable to the arsenic analogues since the bromophenyldimethylarsines react further with lithium aluminium hydride. However, it was found possible to demethylate the arsonium chlorides by

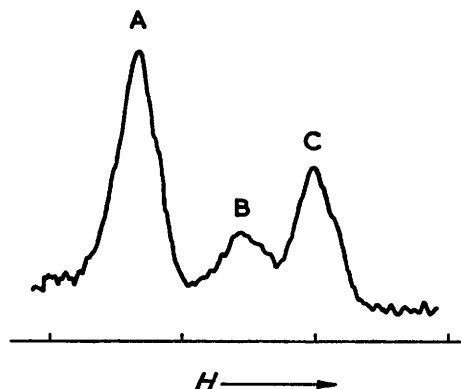


FIGURE 3 Illustrating the separation of the As-Me peaks in the n.m.r. spectrum (60 Mc.) of a synthetic mixture of mono-bromophenyltrimethylarsonium tetraphenylborates dissolved in a 50:50 mixture of aniline and nitrobenzene. A, *ortho*; B, *para*; C, *meta* + unsubstituted. The scale divisions are 5 Hz apart

heating them to 200° under nitrogen at 0.4 mm. Some decomposition occurs but studies with synthetic mixtures showed that the *meta*:*para* ratio was not changed by demethylation. The decomposition of the *ortho*-isomer was more marked: thus, pyrolysis of a mixture of mono-brominated quaternary salts containing 9.1% of *ortho*-substituted material gave a mixture of bromophenyldimethylarsines which, on analysis by g.l.c., proved to contain $2.8 \pm 1.0\%$ of the *ortho*-compound. Similar treatment of the product obtained by brominating the phenyltrimethylarsonium ion gave peaks corresponding to the unbrominated material, the *meta*-bromo-compound and the *ortho*-bromo-compound. The absence of the peak for the *para*-bromo-compound is consistent with the n.m.r. analysis of this product. The area of the peak for the *ortho*-bromo-compound (1–2%) is of little value in estimating the extent of *ortho*-substitution

but, allowing for the decomposition during pyrolysis, is consistent with the estimate of *ortho*-substitution made from the n.m.r. spectrum.

Kinetics.—Reaction was started by adding an aqueous solution of bromine-free hypobromous acid (10 ml.; ca. 0.05M) at 25° to excess of the quaternary perchlorate in aqueous sulphuric acid (90 ml.) at 25°. The reaction vessel was protected from light and aliquots (ca. 5 ml.) were withdrawn at suitable intervals, usually by an automatic pipette. These aliquots were run into excess of an ice-cold solution of potassium iodide in boiled water and the liberated iodine was titrated. Most of the kinetic runs were short (ca. 30 min.) and decomposition of the hypobromous acid during the run was not appreciable. Blank runs were always carried out and some correction was made for such decomposition where necessary. Good second-order kinetics were observed as shown by the typical run in Table 6 and, in

TABLE 6

Bromination of benzyltrimethylammonium perchlorate in aqueous sulphuric acid (0.91M) at 25°

[ArH] = 0.01M

[HOBr] = 0.00546M

Time (min.)	$10^3[\text{HOBr}]$	k_2 (mole ⁻¹ sec. ⁻¹) *
0.5	5.32	
1.0	5.12	0.126
2.0	4.80	0.117
4.0	4.18	0.123
6.0	3.71	0.122
8.0	3.28	0.123
10.0	2.93	0.123
13.0	2.51	0.123
16.0	2.21	0.118

* Integrated from the time of the first reading to avoid errors arising from the finite time of mixing

general, infinity readings corresponded to about 95% reaction.

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