tivity coefficients for quite similar ions and molecules cannot be accounted for in simple hydration terms, there is no reason why this approach should be successful when applied to activated complexes for the discrimination of mechanisms of acid catalysis.

Although recent studies on the failure of the activity coefficient postulate cannot help but undermine our confidence in many of the uses to which acidity functions have been put, the situation in the long run is far from hopeless. As more research is done on direct measurements of activity coefficients and equilibrium constants it should be possible in suitable cases to derive exact treatments or very good estimates for the acid-catalyzed behavior of various substrates under different mechanisms. It may also be possible to find acidic media in which the activity coefficient postulate does hold. We are investigating both of these possibilities.

Steric Effects of the Nitro Group on the Uncatalyzed Halogenation of Methylbenzenes[1]

BY ENRICO BACIOCCHI AND GABRIELLO ILLUMINATI

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Bromination and chlorination rates of the nitro derivatives of mesitylene, isodurene, and durene have been measured in nitromethane and acetic acid solutions, respectively. In all three compounds the deactivating effect of the nitro group is very strong, i.e., in the order of 6 to 7 powers of ten. However, with the aid of free energy relationships, the reactivity of nitrodurene (p-NO$_2$) with molecular halogen is found to be higher than that predicted from the electrical effect assumed for the nitro group in electrophilic substitutions. The acceleration involves only small factors and is ascribed to steric inhibition of resonance of the nitro group. With nitromesitylene and nitroisodurene (m-NO$_2$) a slight increase in deactivation is observed instead. Here, the expectedly minor effect of steric inhibition of resonance is possibly overshadowed by increased hindrance to the approach of the reagent at the reaction center. It is believed that a precise calculation of the fractional loss of resonance for the p-NO$_2$ group is prevented by the latter effect and/or some uncertainty in the available reference parameters involved in it.

Introduction

In a previous paper[2] it was pointed out that there has been a tendency in the literature to overestimate in some cases, such as the dinitration of mesitylene, the effects of steric inhibition of resonance (hereafter indicated as s.i.r.) on chemical reactivity. Use of free energy relationships has yielded a simple tool to appraise such effects in a quantitative manner.[3,4] One of the original objectives of our studies on the reactivity of methylbenzenes was the investigation of s.i.r. effects on the rate of electrophilic substitution of nitrodurene; this was made possible by the applicability of free energy relationships in this and similar systems. In this paper we report the relative rates of uncatalyzed bromination and chlorination of the nitro derivatives of durene, mesitylene, and isodurene. It will be seen that the results are suggestive of some of the main kinds of molecular deformations to be expected from these overcrowded systems and complement the information obtained from the study of other properties.[3,5-8]

Results

Earlier attempts[9] to measure the bromination rates of nitrodurene in acetic acid showed the high inertness of this compound in this solvent. However, in nitromethane solution, all the nitropolymethylbenzenes examined could be made to react with bromine at a measurable rate in the concentration range 0.035 to 0.055 M. Autocatalytic phenomena began to appear beyond 10% change in the case of nitromesitylene and nitroisodurene but before such a percentage was reached in the case of nitrodurene. Therefore, for the latter compound the first 5 to 6% change was considered as the portion of reaction useful to the present study and the t_{10} values were obtained by extrapolation as in the case of cyanodurene.[10] The results are reported in Table I. The probable error for the relative rate of nitrodurene is higher (15%) than for most investigated rates (4%)[11a] but sufficiently small with respect to the magnitude of the steric effect to be discussed below. Chloromesitylene was used as the compound of intermediate reactivity to assess the R and k/k_0 values as given in Table I. The results on nitrodurene were found to be in essential agreement with those obtained

TABLE I

KINETIC DATA FOR THE UNCATALYZED BROMINATION OF SOME NITROPOLYMETHYLBENZENES IN NITROMETHANE SOLUTION AT 30.0°

Aromatic compound	Substituent	Concn.,[a] M	t_{10},[b] min.	R[c]	10^{7} (k/k_0)[d]
3-Nitrodurene	p-NO$_2$	0.055	30,000	7.34×10^{-4}	14.67
2-Nitromesitylene	m-NO$_2$	.055	7,410	2.97×10^{-3}	
4-Nitroisodurene	m-NO$_2$	.035	9,000	6.67×10^{-3}	0.944[e]
		.055	3,300		
2-Chloromesitylene		.035	3.1	20.6[f]	
		.055	1.0[g]		

[a] Molarity in both reactants. [b] Time at 10% reaction. [c] Rate relative to durene (= 1000). Mean values obtained with the aid of determinations on chloromesitylene and nitroisodurene as the compounds of intermediate reactivity in either 0.035 or 0.055 M solution. [d] Reactivity relative to the parent hydrocarbon (ref. 11a). [e] Mean of the reactivity values of 2-nitromesitylene and 4-nitroisodurene. [f] For this value see ref. 11a. [g] See ref. 4.

(1) Substitution in Polymethylbenzenes, part XVII. Part XVI in ref. 10.

(2) G. Illuminati, Nature, 179, 780 (1957).

(3) R. W. Taft, Jr., and H. D. Evans, J. Chem. Phys., 27, 1427 (1957).

(4) G. Illuminati, J. Am. Chem. Soc., 80, 4945 (1958).

(5) W. G. Brown and H. Reagan, ibid., 69, 1032 (1947); J. Trotter, Can. J. Chem., 37, 1487 (1959).

(6) P. Diehl and G. Svegliardo, Helv. Chim. Acta, 46, 461 (1963); E. Bullock, Can. J. Chem., 41, 711 (1963).

(7) B. M. Wepster, Rec. trav. chim., 76, 335 (1957).

(8) (a) A. C. Littlejohn and J. W. Smith, J. Chem. Soc., 2476 (1957); (b) H. Kofod, L. E. Sutton, P. E. Verkade, and B. M. Wepster, Rec. trav. chim., 78, 790 (1959).

(9) G. Illuminati, Gazz. chim. ital., 83, 905 (1953).

(10) G. Illuminati, J. Am. Chem. Soc., 80, 4941 (1958).

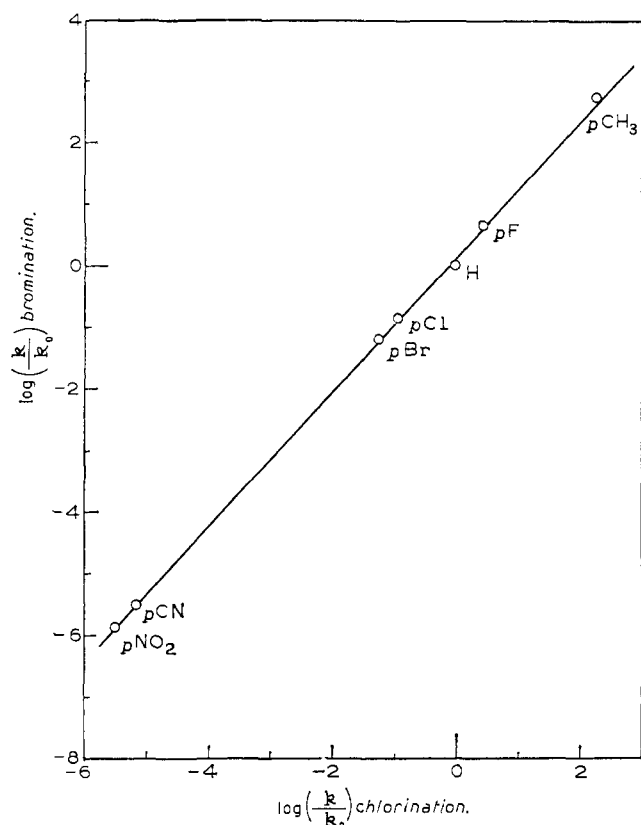(11) (a) G. Illuminati and G. Marino, ibid., 78, 4975 (1956); (b) unpublished studies.

Fig. 1.—Free energy correlation between bromination and chlorination in the durene series (see ref. 15; p-NO_2, present work).

KINETIC DATA FOR THE UNCATALYZED CHLORINATION OF SOME NITROPOLYMETHYLBENZENES IN ACETIC ACID SOLUTION AT 30.0°

Aromatic compound	Substituent	k_2, 1. mole^{-1} sec.$^{-1}$	$10^7 (k/k_0)^a$
3-Nitrodurene	p-NO_2	4.56×10^{-6}	29.62
2-Nitromesitylene	m-NO_2	1.435×10^{-4}	37.92^b
4-Nitroisodurene	m-NO_2	2.72×10^{-4}	

a Reactivity relative to the parent hydrocarbon (ref. 14). b Mean of the reactivity values of 2-nitromesitylene and 4-nitroisodurene.

It was finally rewarding that the results from the two halogenations herein reported for the p-nitro group, despite the lower reliability of the bromination data, are in agreement with each other as shown by the excellent fit of such a group into the correlation reported in Fig. 1 and based on *para*-reactivity data available from previous work of this series.[15] An analogous good fit was found for a similar plot of the *meta*-reactivity data.

Discussion

The reactivity data (k/k_0) as reported in Tables I and II show that when a nitro group is attached to an overcrowded aromatic system, it essentially retains its strong deactivating influence in both bromination and chlorination, whether it serves as a m- or as a p-substituent. This result stands for the major role played by the inductive effect of the nitro group on the rate of electrophilic substitution by molecular halogen. With a superimposing conjugative effect in the p-position, the decrease in reactivity produced by the nitro group in nitrodurene, with respect to the parent hydrocarbon, should be higher than that produced by the m-nitro group in either nitroisodurene or nitromesitylene. However, if steric strain in nitropolymethylbenzenes is relieved by rotation of the nitro group about the C_{ar}-NO_2 bond, there will be a loss in conjugation with a tendency of the "resonance-inhibited" p-nitro group to give a kinetic effect approaching that of a "resonance-inhibited" m-nitro group. The expected relationship is $(k/k_0)_m \gtrsim (k/k_0)_p$. A direct inspection of the k/k_0 values does not allow one to assess the exact role of the steric inhibition of resonance in nitrodurene, although there is no apparent sign of any residual resonance effect. Thus in chlorination the observed reactivity order is $(k/k_0)_m \sim (k/k_0)_p$, in line with a complete steric inhibition of resonance, and in bromination it is $(k/k_0)_m < (k/k_0)_p$. Clearly the latter result cannot be accounted for by the operation of a s.i.r. effect alone.

A further progress in the understanding of the effects involved and an explanation of the above inconsistency are possible with the use of linear free energy relationships as established for the electrical effects of substituents in polymethylbenzenes.[10,13,15] A recent detailed statistical analysis of such relationships has revealed that small, however distinct, differences exist between selectivities of *meta* and *para* series in these systems.[15] If the k/k_0 values are reported in the proper plots together with the corresponding (previously established) ρ-σ^+ lines, the four diagrams of Fig. 2 and 3 are obtained. It can be seen that the reactivity pattern is essentially the same in both halogenations. The points for the reaction at the p-position fall above the

in I_2-catalyzed bromination experiments[11b] by extrapolating to zero I_2 concentration. However, there remains additional uncertainty in the precision of the above measurements, especially with regard to the p-NO_2 group due to the approximation used in the blank corrections (see Experimental) and to the kinetic complexity of the bromination reaction.[12]

Since from the experimental difficulties referred to above it would be reasonable to question the reliability of the results on the bromination rate of nitrodurene, we decided to extend the rate study to chlorination, a reaction usually characterized by higher rates and by regular second-order kinetics.[13]

In agreement with expectations, chlorination of the compounds examined in this paper was found to be strictly second order and could be followed to percentages of reaction as high as 60% in acetic acid solution. The experimental procedure was essentially the same as that described elsewhere.[13] The reaction was studied in the concentration ranges of 0.01 to 0.08 M and of 0.01 to 0.02 M in aromatic compound and in chlorine, respectively. The results are reported in Table II. The probable error in the mean values for the rate constants, k_2, was calculated to be less than 3%.

Nitrodurene and nitromesitylene were also tested for side-chain chlorination; the extents of this reaction were 6.7 and 13.4%, respectively. It was concluded that the relative rates were not appreciably affected by this side reaction and that the results could be confidently discussed in terms of nuclear substitution.

(12) R. M. Keefer and L. J. Andrews, *J. Am. Chem. Soc.*, **78**, 3637 (1956).
(13) E. Baciocchi and G. Illuminati, *Ric. Sci.*, **28**, 1159 (1958).

(14) E. Baciocchi, *Ric. Sci. Rend. Sez. A*, **3**, 1121 (1963).
(15) E. Baciocchi and G. Illuminati, *ibid.*, **3**, 1127 (1963).

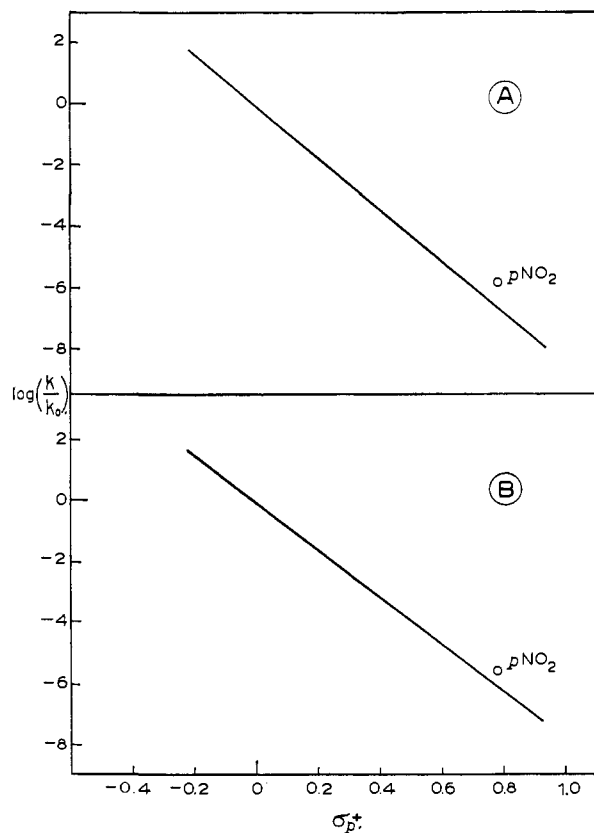Fig. 2.—ρ-σ analysis illustrating steric effects of the nitro group on the rates of bromination (A) and chlorination (B) of nitrodurene. The A line was based on 7 points and the B line on 6 points (see ref. 15).
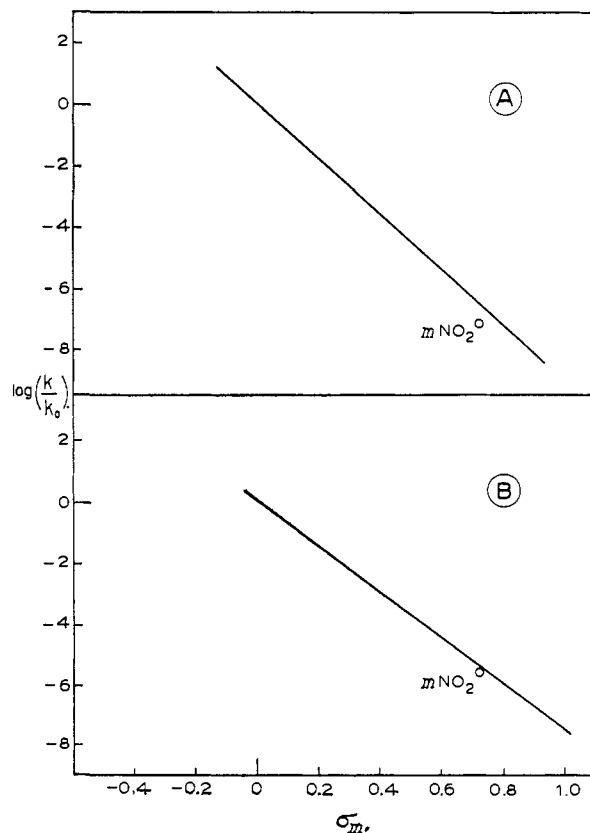

Fig. 3.—ρ-σ analysis illustrating steric effects of the nitro group on the rates of bromination (A) and chlorination (B) of nitro-substituted isodurene and mesitylene. The A line was based on 8 points and the B line on 7 points (see ref. 15).

corresponding lines (Fig. 2), while for the reaction at the m-position they fall slightly below the lines (Fig. 3). The extent of deviation is relatively small in all cases; that it is generally significant can be confidently deduced from the excellent fit of the free energy correlations involved ($r > 0.99$).

Only in the case of the *para* reactivities is the above result consistent with an s.i.r. effect which, for the nitro group, is expected to involve a rate increase in electrophilic substitution. The reaction of nitrodurene with Br_2 and Cl_2 is 5.6 and 2.8 times as fast, respectively, as would be predicted from the ρ-σ_p^+ lines[16a] (Fig. 2). These factors are very small indeed when compared to the residual deactivating effect of the nitro group as illustrated by the k/k_0 values of Tables I and II. Yet they correspond to a fairly high fractional loss of resonance contribution in the electrical effect of the nitro group (see further). This is in substantial agreement with what is found for other investigations[3,6-8] in nitrodurene and related compounds.

From the ρ-σ_p^+ lines, a mean σ_p value of +0.70 for the "resonance-inhibited" nitro group is obtained; according to Taft's evaluation procedure,[3] such a value

(16) (a) The following ρ-values (see ref. 15) were used in the present paper: bromination, $\rho_p = -8.46$, $\rho_m = -9.17$; chlorination, $\rho_p = -7.68$, $\rho_m = -7.56$. (b) Fractional loss of resonance $= (\sigma_p^+ - \dot{\sigma})/(\sigma_p^+ - \sigma_1)$, with $\sigma_p^+ =$ substituent constant for the "resonance-uninhibited" p group in electrophilic substitution, $\sigma_1 =$ inductive substituent constant, and $\dot{\sigma} = \log (k/k_0)/\rho$. The following values for the NO_2 group were used in the present calculation: $\sigma_p^+ = +0.78$, $\sigma_1 = +0.63$. It should be noted that the σ_1 value is such as to yield a relatively high *para*-to-*meta* fall-off factor of the resonance contribution, $(\sigma_m - \sigma_1)/(\sigma_p^+ - \sigma_1) = 0.5$. Usually the fall-off factor is about 0.33 or less [R. W. Taft, Jr., and I. C. Lewis, *J. Am. Chem. Soc.*, **81**, 5343 (1959)]. This may indicate that the used value for the σ_1 constant is somewhat too low. The most probable value should fall in the vicinity of 0.67 (fall-off factor 0.33).

yields a 50% inhibition of the whole resonance contribution assumed for this group in electrophilic aromatic substitution.[16b] The actual s.i.r. effect probably is higher than shown by these results. Use of a somewhat too low value for the σ_1 parameter involved in the calculation[16b] and/or the operation of opposing steric effects (see further) are two possible factors tending to an underestimation of the effect.

Whatever the contribution of opposing steric factors may be, it is of interest to speculate into the equilibration of the steric compressions acting in the nitropolymethylbenzene systems. As already mentioned, nitromesitylene and nitroisodurene react slightly *slower* than predicted from the ρ-σ_m lines (Fig. 3). This decelerating effect involves kinetic factors of 0.3 (bromination) and 0.9 (chlorination), respectively. If opposing steric factors are at work here, they may well overshadow the s.i.r. effects which are expected to be much weaker in the m- than in the p-position.[2] It seems unlikely that the observed deceleration effect is caused by steric inhibition of hyperconjugation of the methyl groups since theoretical studies have revealed that hyperconjugation is not reduced on rotation of these groups.[17]

In agreement with an earlier proposal,[10] we tentatively attribute the observed decelerating effects to increased hindrance at the reaction center to the approach of the reagent. The rate of aromatic substitution is fairly sensitive to a change in the steric environment of the position of attack, as has appeared in recent work from the extremely lower reactivity of 1,3,5-

(17) H. H. Jaffé and J. L. Roberts, *ibid.*, **79**, 391 (1957).

tri-t-butylbenzene[18] as compared with that of mesitylene. In nitromesitylene slight changes in the same direction may occur by some bond bending of the methyl groups flanking the reaction center which become closer to each other under the steric compression of the nitro group. In-plane rather than out-of-plane bond bending should be more effective in this connection. Independent evidence for molecular deformations of this kind in nitromesitylene has been obtained from infrared spectra and dipole moment measurements.[8a,19] Possibly in nitrodurene any transmission of the steric compression of the nitro group to the reaction center is less relevant than in mesitylene and isodurene derivatives because of the higher rigidity produced by the buttressing action of the two vicinal methyl groups[19] *on each side*. On the other hand, the s.i.r. effect is expected to be greater and the over-all rate effect accelerating, as was indeed found. The operation of a small decelerating hindrance cannot, however, be excluded and may thus be responsible for the apparently limited extent of the s.i.r. effect discussed above.

That some transmission of the steric compression of the nitro group to the reaction center may occur is also indicated by comparison of the "resonance-inhibited" $\sigma_p(NO_2)$ value (0.70) as found in the present paper with the value (0.68) reported by Westheimer and Metcalf[20] from the hydrolysis of alkyl 4-nitro-3,5-dimethylbenzoate. Like nitromesitylene, the latter molecule is more flexible than nitrodurene as to bond-bending·deformations and, consequently, the nitro group should be rotated by an angle smaller than that of nitrodurene. In Westheimer and Metcalf's compound, however, bond deflections do not affect the reaction center and, like nitrodurene, s.i.r. effects are expected to be equally sensitive to the angle of rotation of the nitro group as this is in both cases *para* to the functional group. We ought to expect a "resonance-inhibited" σ_p value for the nitrodurene lower than that for Westheimer and Metcalf's compound, which is in fact in contrast with the observations.

In conclusion, it can be stated that in addition to previous physical evidence an s.i.r. effect for nitrodurene is also observed in electrophilic substitution. However, it involves destruction of only a small fraction of the total deactivation of the molecule to which the major contribution is of inductive origin. Some minor contributions to deactivation are likely to arise from increased hindrance to the reagent approach in the overcrowded systems under examination. In any case, the s.i.r. effect is not sufficiently large to be recognized in the qualitative findings of preparative chemistry. We

then confirm our previous conclusions[2,21] that the "facile" dinitration of mesitylene and durene are to be ascribed to effects other than steric inhibition of resonance.

Experimental

Materials.—3-Nitrodurene, 4-nitroisodurene, chloromesitylene, and the solvents were prepared and purified according to the methods described in previous papers of this series[11,21,22]; an Eastman Kodak sample (reagent grade) of 2-nitromesitylene was purified by recrystallization.

Kinetic Measurements. (a) Bromination.—The rate measurements and the calculation of the R and k/k_0 parameters were carried out as previously described.[10] Corrections for the reaction of bromine with the solvent were made in the case of all the nitro compounds. A typical experiment is reported in Table III.

TABLE III

KINETIC DATA FOR THE BROMINATION OF 3-NITRODURENE IN NITROMETHANE SOLUTION AT 30.0°[a]

Time, min. $\times$ 10⁻²	Na$_2$S$_2$O$_3$, ml.	Blank corrn.[b]	Corrected titer	Reaction, %
0	8.52	0	8.52	0
1.10	8.41	0.02	8.43	1.06
2.625	8.32	.04	8.36	1.88
5.52	8.24	.08	8.32	2.35
8.39	8.11	.12	8.23	3.40
11.70	7.96	.16	8.12	4.69
15.85	7.76	.22	7.98	6.34
(30.00)[c]			(7.67)[c]	10

[a] Kinetic solution 0.055 M in both bromine and aromatic compound; iodometric titration with 0.025 N sodium thiosulfate on 2-ml. samples quenched in 6 ml. of 4% KI solution in 70% ethanol. [b] Evaluated graphically in a separate blank experiment. [c] The values in parentheses are based upon graphic evaluation.

(b) Chlorination.—The kinetic procedure was identical with that used in the chlorination of cyanomesitylene.[13] A typical experiment is reported in Table IV.

TABLE IV

KINETIC DATA FOR THE CHLORINATION OF 3-NITRODURENE IN ACETIC ACID SOLUTION AT 30.0°[a]

Time, min. $\times$ 10⁻²	Na$_2$S$_2$O$_3$,[b] ml.	Reaction, %	$\log (a - x)/(b - x)$
0	3.16	0	0.72168
5.392	2.70	14.50	.77797
9.770	2.40	24.05	.82119
15.490	2.03	35.76	.88347
22.615	1.68	46.83	.95585
28.710	1.44	54.43	1.0160
35.735	1.20	62.02	1.0879

[a] $[Cl_2] = 2.112 \times 10^{-2} M$; [3-nitrodurene] $= 1.113 \times 10^{-1} M$. [b] Iodometric titration with 0.02672 N sodium thiosulfate on 2-ml. samples quenched in 5 ml. of 4% KI solution in 70% ethanol.

Product Analysis for Side-Chain Chlorination.—Depending on the reactivity of the aromatic compound, the procedures adopted to determine the amount of side-chain chlorination varied somewhat from each other as previously described.[15,23]

(18) Unpublished work on the uncatalyzed bromination of 1,3,5-tri-t-butylbenzene; for the ZnCl$_2$-catalyzed bromination see L. J. Andrews and R. M. Keefer, *J. Am. Chem. Soc.*, **78**, 4549 (1956).

(19) A. Van Veen, P. E. Verkade, and B. M. Wepster, *Rec. trav. chim.*, **76**, 801 (1957).

(20) F. H. Westheimer and R. P. Metcalf, *J. Am. Chem. Soc.*, **63**, 1339 (1941).

(21) G. Illuminati and M. P. Illuminati, *ibid.*, **75**, 2159 (1953).

(22) G. Illuminati, *ibid.*, **74**, 4951 (1952); G. Illuminati and G. Marino, *ibid.*, **75**, 4593 (1953).

(23) E. Baciocchi and G. Illuminati, *Gazz. chim. ital.*, **92**, 89 (1962).