Friedel-Crafts Aralkylation. II.[1] The $AlCl_3 \cdot CH_3NO_2$-catalyzed Phenethylation of Benzene and Toluene with 2-Arylethyl Chlorides in a Nitromethane Solution

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The rates of $AlCl_3 \cdot CH_3NO_2$-catalyzed phenethylations of benzene (50°C) or toluene (25°C) with 2-arylethyl (ring-substituted phenethyl) chlorides were measured in homogeneous nitromethane solutions. The reactions are first-order in the aromatic component, first-order in the phenethyl chloride, and second-order in aluminum chloride. Substituent effects in the phenethyl chlorides give linear relationships with Hammett's σ constants. A displacement mechanism involving a nucleophilic attack by the aromatic substrate on the phenethyl chloride-catalyst system is proposed for the reactions. Competitive phenethylations of benzene and toluene were also carried out at 50°C. Both the isomer distribution and the relative reactivity of toluene to benzene are affected by the ring-substituents, the effects of which are correlated closer with the substrate selectivity. These results suggest that the transition state in the rate-determining step for the phenethylations is in nature an (oriented) π complex rather than a σ complex.

The Friedel-Crafts alkylation reaction of aromatics with primary alkyl halides continues to present various interesting problems. In particular, there are arguments as to the structure of the activated complex in the rate-determining step for the reaction.[2]

In the previous paper,[1] we reported the kinetics of the $AlCl_3 \cdot CH_3NO_2$-catalyzed phenethylation of benzene and toluene with 2-phenylethyl chloride and suggested the displacement mechanism for the reaction.

In this paper, we will describe a study of the aralkylations (phenethylations) of benzene and toluene with 2-arylethyl chlorides using the $AlCl_3 \cdot CH_3NO_2$ complex as the catalyst in nitromethane solutions; we will thus attempt to elucidate the nature of the transition state in the rate-determining step and the effect of ring-substituents on the reaction rates and the isomer distributions. Electron-donating substituents tend to decrease the electron deficiency of the reaction center in an aralkylating agent, while electron-withdrawing substituents tend to increase it. Thus, it is possible to correlate the electrophilicity of the substituting agent with the selectivity by changing its electrophilicity systematically, while keeping the other factors constant.

Results and Discussion

The phenethylation reactions in homogeneous nitromethane solutions can easily be followed kinetically, and they are considered to be free from consecutive isomerization. Proof of the non-isomerizing conditions is given clearly by the experimental fact that the phenethylation of benzene with 2-(*m*-tolyl)- or 2-(*p*-tolyl)-ethyl chloride yielded no isomer mixture of 1-phenyl-2-tolylethanes.

The rates of noncompetitive phenethylations of benzene (50°C) or toluene (25°C) with substituted phenethyl chlorides ($XC_6H_4CH_2CH_2Cl$) were measured under the same conditions. The mole ratio of benzene: $XC_6H_4CH_2CH_2Cl$: aluminum chloride in the solution was 5.6: 1: 1, and that of toluene: $XC_6H_4CH_2CH_2Cl$: aluminum chloride was 4.7: 1: 1. Unfortunately, it was impossible to determine the reaction rates with 2-(*p*-nitrophenyl)ethyl chloride, since the reactions were too slow to be measured under the above conditions. It needed severe conditions (*e.g.*, using more than equimolar quantities of the catalyst to the chloride without nitromethane) to bring about *p*-nitrophenethylation, accompanied by side reactions.

During the course of the reactions, small amounts of by-products (di- or higher phenethylated and 1, 1-diarylethane-type rearranged products, and polymers resulting from the reactions between the aralkylating agents) were detected by gas chromatography and spectroscopic methods. In the early stages of the reactions, however, they are negligible and it is convenient to assume that only monoalkylation takes place under the present experimental conditions. Therefore, for all systems, pseudo-second-order plots were obtained, assuming that:

$$\frac{d[\text{product}]}{dt} = k_{obs}[\text{aromatic}][XC_6H_4CH_2CH_2Cl] \qquad (1)$$

The obtained results are summarized in Table 1. A second-order dependence on the catalyst concentration was found (when the concentration of the catalyst was reduced to one half, the values of k_{obs} with benzene for X=*p*-CH_3O, *p*-CH_3, and *p*-Cl were 2.65×10^{-3}, 1.43×10^{-3}, and 2.73×10^{-4} respectively), as in the previous investigation with 2-phenylethyl chloride (X=H).[1] Thus, the reactions are second-order with respect to the catalyst; that is, $k_{obs}=k_4[AlCl_3]^2$, where k_4 is the overall fourth-order rate constant.

In order to clarify the mode in which a substituent group exerts its effect upon the reaction rate, the results in Table 1 are plotted against the substituent constants. Fairly good correlations with Hammett's σ constants were obtained (Fig. 1). The apparent reaction constants, ρ, calculated by the method of least squares,[3] are -1.71 (r=0.940) for the reaction with

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[1] Part I: M. Ichii, *Bull. Inst. Chem. Res., Kyoto Univ.*, **49**, 114 (1971).

[2] For recent reviews see: a) G. A. Olah, "Friedel-Crafts and Related Reactions", Vol. I, Wiley-Interscience, New York, N. Y. 1963, p. 853; b) R. Nakane, *Nippon Kagaku Zasshi*, **90**, 17 (1969); c) G. A. Olah, *Accounts Chem. Res.*, **4**, 240 (1971).

[3] H. H. Jaffé, *Chem. Revs.*, **53**, 191 (1953).

TABLE 1. THE RATES OF $AlCl_3 \cdot CH_3NO_2$-CATALYZED PHENETHYLATION OF BENZENE OR TOLUENE WITH $XC_6H_4CH_2CH_2Cl$ IN NITROMETHANE SOLUTION[a]

$XC_6H_4CH_2CH_2Cl$	Benzene at 50°C		Toluene at 25°C[b]	
	k_{obs} ($l\ mol^{-1}min^{-1}$)	Relative rate	k_{obs} ($l\ mol^{-1}\ min^{-1}$)	Relative rate
p-CH_3O	1.04×10^{-2}	3.53	3.12×10^{-3}	12.9
p-CH_3	5.53×10^{-3}	1.87	1.36×10^{-3}	5.62
m-CH_3	3.90×10^{-3}	1.32	4.72×10^{-4}	1.95
H[c]	2.95×10^{-3}	1.00	2.42×10^{-4}	1.00
p-Cl	1.23×10^{-3}	0.417	3.47×10^{-5}	0.143

a) Initial concentration, $[AlCl_3]=0.400 mol/l$. b) The description of the isomer distributions of the products is omitted, because they are almost identical to those obtained in the competitive reactions described later. c) See Ref. 1.

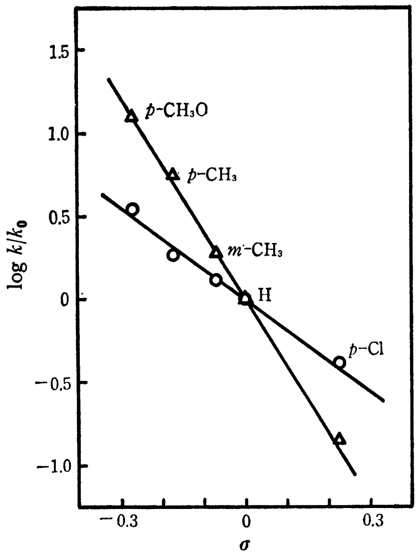
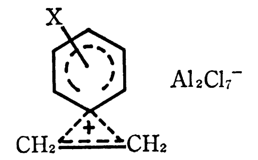


Fig. 1. Hammett plots for the $AlCl_3 \cdot CH_3NO_2$-catalyzed phenethylation of benzene (○) at 50°C or toluene (△) at 25°C with $XC_6H_4CH_2CH_2Cl$.

benzene and −3.72 (r=0.942) for toluene. The linear relationships with Hammett's σ, but not with Brown's σ^+ constants, suggest that the rate-determining step does not involve a phenonium ion-type intermediate (**1**) as an electrophile.[4] If any neighboring aryl



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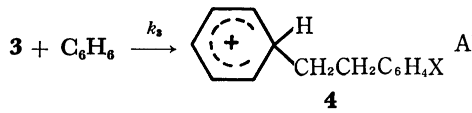
participation takes place, much larger substituent effects would be observed through a resonance interaction between the substituent and the reaction site, and then the reaction rates might be correlated with Brown's σ^+ constants. This is not true for the present phenethylation. Thus, the present results are more consistent with a displacement mechanism involving a rate-determining nucleophilic attack by the aromatic substrate on the phenethyl chloride-dimeric aluminum chloride system (Eq. (4)).[5] The transition state in

$$XC_6H_4CH_2CH_2Cl + AlCl_3\text{-}CH_3NO_2 \underset{k_{-1}}{\overset{k_1}{\rightleftarrows}} XC_6H_4CH_2CH_2Cl\text{-}AlCl_3 + CH_3NO_2 \quad (2)$$

2

$$\mathbf{2} + AlCl_3\text{-}CH_3NO_2 \underset{k_{-2}}{\overset{k_2}{\rightleftarrows}} XC_6H_4CH_2\overset{\delta+}{CH_2}\text{—}\overset{\delta-}{Cl}\cdots Al_2Cl_6 + CH_3NO_2 \quad (3)$$

3



(4)

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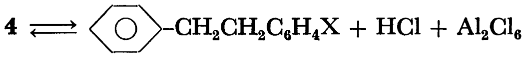
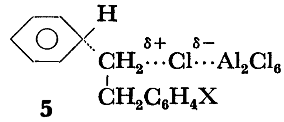


$$\mathbf{4} \rightleftarrows C_6H_5\text{-}CH_2CH_2C_6H_4X + HCl + Al_2Cl_6 \quad (5)$$

the rate-determining step may be represented as an oriented π-complex(**5**):[6,7]



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From the proposed mechanism, we can obtain the appropriate rate expression by using the steady-state approximation and by assuming that k_{-1}, $k_{-2} \gg k_1$, k_2, k_3:

$$\text{rate} = \frac{k_1k_2k_3}{k_{-1}k_{-2}}[XC_6H_4CH_2CH_2Cl][C_6H_6][AlCl_3\text{-}CH_3NO_2]^2 \quad (6)$$

This is in substantial agreement with Eq. (1).

The value of k_{obs} includes the k_1/k_{-1} and k_2/k_{-2} terms, the equilibrium constants for the formation of **3**. It seems reasonable to consider that the obtained ρ-value is determined largely by the preceding equilibria, especially by the k_1/k_{-1} term.[5] This explains the rather large negative ρ-values. Therefore, the substituent effects on the rate-determining step may be small. This means that the extent of the C–Cl bond cleavage has a great effect on the reactivity. In the case of the p-NO_2 group, little formation of **3** may take place. It appears that the group becomes much more electron-withdrawing than an ordinary one

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[4] M. A. McMahon and S. C. Bunce, *J. Org. Chem.*, **29**, 1515 (1964).

[5] H. C. Brown and M. Grayson, *J. Amer. Chem. Soc.*, **75**, 6285 (1953).

[6] G. A. Olah, S. J. Kuhn, and S. H. Flood, *ibid.*, **84**, 1688 (1962).

[7] R. Nakane, O. Kurihara, and A. Natsubori, *ibid.*, **91**, 4528 (1969).

Table 2. Competitive phenethylation of benzene and toluene with $XC_6H_4CH_2CH_2Cl$ in nitromethane solution at 50°C

$XC_6H_4CH_2CH_2Cl$	k_T/k_B	Isomer distribution (%)			Partial rate factors			p_f/m_f
		ortho	*meta*	*para*	o_f	m_f	p_f	
p-CH_3O	4.61	54.0	14.2	31.8	7.47	1.96	8.80	4.48
o-CH_3	4.33	51.7	17.6	30.7	6.72	2.29	7.97	3.48
p-CH_3	4.06	51.1	17.9	31.0	6.22	2.18	7.55	3.46
m-CH_3	3.80	51.5	18.5	30.0	5.87	2.11	6.84	3.24
H[a)]	3.31	48.7	19.8	31.5	4.84	1.97	6.26	3.18
p-Cl	2.81	47.6	21.1	31.3	4.01	1.78	5.28	2.97
m-Cl	2.48	47.8	21.6	30.6	3.55	1.61	4.55	2.83
p-NO_2[a)]	2.85							

a) See Ref. 1. b) Mole ratio of reactants, aromatics: *p*-$NO_2C_6H_4CH_2CH_2Cl$:$AlCl_3$=37:1:2, without nitromethane. The k_T/k_B value seems to be influenced by the transalkylation of the products. The isomeric 1-(*p*-nitrophenyl)-2-tolylethanes were not separable by gas chromatography.

through complex formation with aluminum chloride.[8]

Competitive phenethylations of benzene and toluene at 50°C were also carried out by treating equimolar amounts of aromatic components in nitromethane solutions. The mole ratio of aromatics: $XC_6H_4CH_2CH_2Cl$ catalyst was always 10 : 1 : 1 unless otherwise noted. In the course of the reaction, the isomer distribution and the rate of toluene relative to benzene were found to remain almost unchanged. The average values of the relative rates and isomer distributions, together with the partial rate factors for substitution, are summarized in Table 2. The competitive reaction with 2-(*p*-nitrophenyl)ethyl chloride was unsuccessful so long as it was conducted in a nitromethane solution.

The data of Table 2 reveal the most significant effects of substituents on the relative rates and the isomer distributions. That is, both substrate and positional selectivities are affected by changing the electrophilicity of the reagent. However, the effects are more remarkable in the former selectivity. The electron-donating substituents tend to increase the relative rate, k_T/k_B; at the same time they tend to decrease the amount of the *meta*-isomer, as reflected by the increasing ratio of the partial rate factors for the *para*- and *meta*-positions of toluene, p_f/m_f, shown at the last column in Table II. On the other hand, the electron-withdrawing substituents decrease both the k_T/k_B and p_f/m_f ratios. In other words, a more stable and, hence, weaker electrophile has higher substrate and positional selectivities. The formation of the nonionized intermediate (**3**) with a electron-withdrawing substituent is difficult. However, once it is formed, it is highly energetic and reacts with benzene or toluene, discriminating slightly between them and at the same time slightly between the *ortho*- or *para*- and the *meta*-positions in toluene. Hence, it is possible to correlate the electrophilicity of the substituting agent with its selectivity. In fact, as is shown in Fig. 2, a plot of the $\log p_f$ *versus* the substituent constant indicates a simple relationship between these quantities. The p_f-value is utilized as the measure of the substrate selectivity in order to eliminate any possible complications from steric factors. On the other hand, no simple relationship[9] exists between the electrophilicity and the positional selectivity as reflected in the p_f/m_f ratio, although the latter actually depends on the former. These observations and the low k_T/k_B ratios suggest that the transition state in the displacement step should be regarded as an (oriented) π complex rather than as a σ complex.[2]

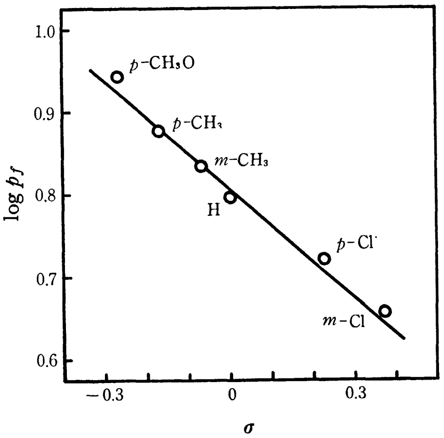

Fig. 2. Relationship between log p_f and Hammett's σ.

Recently, Olah suggested that the position of the transition state in electrophilic aromatic substitutions is not a fixed one, but can be changed from a late one resembling the intermediate (σ complex) to an early one resembling the starting material (π complex).[2c] According to this proposal, our present work provides good examples of early transition states. In substitutions where the rate-determining transition state is of a π-complex nature, the transition states of the subsequent σ-complex formation (leading to positional selectivity) appear relatively early on the reaction coordinate. In this case, the role of the methyl group in toluene in stabilizing the σ complex becomes less

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[8] In above discussions, little reference was made concerning the possibility of the aryl migration from β- to α-carbon atom. It was found that the ethylation with $^{14}CH_3CH_2Cl$ in excess benzene (R. M. Roberts, G. A. Ropp, and O. K. Neville, *J. Amer. Chem. Soc.*, **77**, 1764 (1955)) or with $^{14}CH_3CH_2F$ in nitromethane solution (A. Natsubori and R. Nakane, *J. Org. Chem.*, **35**, 3372 (1970)) gave practically no rearranged product. Rearrangement studies for the present phenethylations are in progress.

[9] L. M. Stock and H. C. Brown, *Advan. Phys. Org. Chem.*, **1**, 35 (1963).

important with an increase in the electrophilicity of the reagent, and the higher proportion of *meta*-substitution is observed with a stronger electrophile. Consequently, the substrate selectivity is influenced directly by the electrophilicity of the substituting agent, which has relatively less effect on the positional selectivity.

Experimental

Materials.[10] The benzene, toluene, and 2-phenylethyl chloride (**6**) were commercial products of the highest available purity. They were further purified by distillation. The nitromethane was purified as has been described by Olah *et al.*[11] The preparation of 1,2-diphenylethane (**7**), 1-phenyl-2-tolylethanes (**8**), and 1,2-ditolylethanes (**9**) has been previously reported.[12] The 2-arylethanols were prepared as has been described in the literature.[13,14] They were converted to the corresponding chlorides by treatment with thionyl chloride. 2-(*p*-Anisyl)ethyl chloride (**15**); bp 98°C/4.5 mmHg (lit,[15] bp 90—92°C/2 mHg). 2-(*o*-Tolyl)ethyl chloride (**11**); bp 83—84°C/6 mmHg. 2-(*m*-Tolyl)ethyl chloride (**12**); bp 78—79°C/5 mmHg. 2-(*p*-Tolyl)ethyl chloride (**13**); bp 72—74°C/3 mmHg. 2-(*m*-Chlorophenyl)ethyl chloride (**14**); bp 91—92°C/3 mmHg. 2-(*p*-Chlorophenyl)ethyl chloride (**15**); bp 89—90°C/2 mmHg (lit,[16] bp 82—83°C/3 mmHg) 2-(*p*-Nitrophenyl)ethyl chloride (**16**) was obtained by the nitration of 2-phenylethyl chloride; mp 48.2—48.5°C (lit,[17] mp 48—49°C). Monosubstituted bibenzyls were prepared by treating the appropriate 2-arylethyl chloride with benzene in the presence of aluminum chloride. 4-Methoxybibenzyl (**17**); mp 54—56°C (lit,[18] mp 55—58°C). 3-Chlorobibenzyl (**18**); bp 130—131°C/2 mmHg (lit,[19] bp 148°C/3 mmHg). 4-Chlorobibenzyl (**19**); mp 47—48°C (lit,[19] mp 49°C). 4-Nitrobibenzyl (**20**); mp 68°C (lit,[20] mp 70—71°C). Non-contaminated isomer mixtures of 1-(*p*-anisyl)- (**21**), 1-(*m*-chlorophenyl)- (**22**), 1-(*p*-chlorophenyl)- (**23**), and 1-(*p*-nitrophenyl)-2-tolylethanes (**24**) were prepared by treating the appropriate 2-arylethyl chloride with toluene in the presence of aluminum chloride. Each isomer of **21**, **22**, and **23** was identified by a comparison of the infrared spectra (*o*-, 750—765 cm^{-1}, *m*-, 775—780 cm^{-1}; *p*-, 805—815 cm^{-1}) and gas chromatograms in a manner similar to that described previously.[21] Commercial aluminum chloride was sublimed before use.

Kinetic Measurements. Molar solutions in nitromethane of aluminum chloride and 2-arylethyl chloride were prepared. 20.0 m*l* of the catalyst solution and 10.0 m*l* of aromatic hydrocarbon (benzene or toluene) were placed in a 100 m*l*, three-necked flask equipped with a reflux condenser, a thermometer, and a stopcock. The flask was then placed in a constant-temperature bath (50 ± 0.1°C for benzene or 25 ± 0.1°C for toluene) and magnetically stirred. 20.0 m*l* of the 2-arylethyl chloride solution, maintained at the reaction temperature, was syringed through the stopcock into the flask. A small portion (2.0 m*l*) of the reaction mixture was drawn out from time to time with a calibrated syringe. Each sample was quenched with ice-water, washed with a small amount of water, dried over anhydrous sodium sulfate, and analyzed by gas chromatography. Each run consisted of at least 5 points, and the pseudo-second-order rate constant was determined graphically. The values obtained were corrected by blank experiments.

Competitive Phenethylations. A mixture (20.0 m*l*) of equimolar amounts of benzene and toluene was phenethylated in a nitromethane solution at 50°C in the same manner as has been described above. The samples were taken out periodically and analyzed by gas chromatography.

Analytical Procedure. The analyses were carried out with a Hitachi Perkin-Elmer model F6D gas chromatograph employing Golay-type capillary columns and a hydrogen flame ionization detector. For the determination of **6**, **7**, and **8**, a BDS-90 Golay column (length, 90 m; *i.d.*, 0.50 mm; coated with the butanediol succinate polyester) was used with a column temperature of 155°C and a nitrogen carrier-gas pressure of 1.0 kg/cm^2; for **8**, **9**, **11**, **12**, and **13**, 160°C and 1.2 kg/cm^2; for **10**, **17**, and **21**, 165°C and 1.5 kg/cm^2; for **14**, **15**, **18**, **19**, **22**, and **23**, 160°C and 1.5 kg/cm^2. Under these conditions, the isomer separation was complete. For the determination of **16**, **20**, and **24**, a Q-45 Golay column (length 45 m; *i.d.*, 0.50 mm, coated with Apiezon L) was with a column temperature of 170°C and a carrier-gas pressure of 1.5 kg/cm^2. In this case, however, the isomers of **24** were not separable. After the determination of the relative response data, the mol % were calculated from the areas of individual peaks by the internal standard method. The accuracy of measurements was found to be within the limit of a $\pm3.0\%$ relative error, based on analyses of mixtures of known composition.

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[10] All of the boiling and melting points are uncorrected. The structure of the authentic samples prepared was confirmed by infrared and NMR spectra. The infrared spectra were measured with a Hitachi EPI-S2 Spectrophotometer and the NMR spectra with a Varian T-60 Spectrometer.

[11] G. A. Olah, S. J. Kuhn, S. H. Flood, and B. A. Hardie, *J. Amer. Chem. Soc.*, **86**, 1039 (1964).

[12] S. Kunichika, S. Oka, T. Sugiyama, and M. Ichii, *Nippon Kagaku Zasshi*, **92**, 801 (1971).

[13] C. H. DePuy and D. H. Froemsdorf, *J. Amer. Chem. Soc.*, **79**, 3710 (1957).

[14] W. H. Saunders, Jr. and R. A. Williams, *ibid.*, **79**, 3712 (1957).

[15] G. A. Olah, M. B. Comisarow, E. Namanworth, and B. Ramsey, *ibid.*, **89**, 5259 (1967).

[16] C. H. DePuy and C. A. Bishop, *ibid.*, **82**, 2532 (1960).

[17] A. Iliceto, A. Fava, and A. Simeone, *Gazz. Chim. Ital.*, **90**, 600 (1960); *Chem. Abstr.*, **55**, 14335i (1961).

[18] R. L. Hinman and K. L. Hamm, *J. Amer. Chem. Soc.*, **81**, 3294 (1959).

[19] F. Bergmann, J. Weizmann, and D. Shapiro, *J. Org. Chem.* **9**, 408 (1944).

[20] L. M. Litvinenko and N. F. Levchenko, *Zh. Obshch. Khim.*, **29**, 3079 (1959); *Chem. Abstr.*, **54**, 13060e (1960).

[21] S. Kunichika, S. Oka, T. Sugiyama, C. Inoue, and M. Ichii, *Nippon Kagaku Zasshi*, **92**, 539 (1971).