

THE INFLUENCE OF PRESSURE ON THE KINETICS AND ORIENTATION
OF FRIEDEL-CRAFTS BENZOYLATIONS

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Summary

It has been found that the second-order rate constant for the benzylation of benzene, catalysed by aluminium chloride in benzoyl chloride solution at 29.6°, is doubled when the pressure is raised from 1 atm to 1500 atm.

The same change of pressure has no measurable effect on the orientation of benzoyl substitution in toluene.

INTRODUCTION

This paper is one of a series concerned with the effects of hydrostatic pressure on electrophilic aromatic substitutions.

The previous two papers^{1,2} have dealt with kinetic and orientational effects, respectively, in nitration reactions. In the present work we have made similar measurements on a representative type of Friedel-Crafts reaction. We selected the benzylation of an aromatic compound, catalysed by aluminium chloride in benzoyl chloride solution, because this reaction is amongst the few that are homogeneous and obey simple kinetic laws.^{3,4}

EXPERIMENTAL

(a) Materials

Brown and Jensen³ have found that it is essential to use extremely pure and dry chemicals to secure reliable kinetic data on Friedel-Crafts acylations. We therefore followed their procedures for purifying benzoyl chloride and aluminium chloride, and obtained products whose mixtures remained clear and colourless for many days.

The benzene and toluene were the best available commercial products, further purified by careful drying and fractionation.

The *ortho*-, *meta*-, and *para*-methylbenzophenones, used to standardize the isomer analyses, were synthesized from the corresponding toluic acids by converting these to the acid chlorides and condensing the chlorides with benzene by Friedel-Crafts reactions.

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¹ Coillet, D. W., and Hamann, S. D., *Trans. Faraday Soc.*, 1961, **57**, 2231.

² Coillet, D. W., and Hamann, S. D., *Nature*, 1963, **200**, 166.

³ Brown, H. C., and Jensen, F. R., *J. Am. Chem. Soc.*, 1958, **80**, 2291.

⁴ Jensen, F. R., and Goldman, G., in "Friedel-Crafts and Related Reactions." (Ed. G. A. Olah.) Vol. III, Part 2, p. 1003. (Interscience: New York 1964.)

*(b) Kinetic Procedure**Reactions at Atmospheric Pressure*

The reactions at atmospheric pressure were carried out in a glass flask fitted with a ground glass stopper and having a side arm just below the stopper. The side arm was connected to a supply of dry nitrogen at a pressure slightly above atmospheric, so that when the stopper was removed dry nitrogen flowed out of the mouth of the flask.

A standard solution of aluminium chloride in benzoyl chloride, prepared in the manner described by Brown and Jensen,³ was introduced into the flask and diluted to the required strength with benzoyl chloride. In these and in all other manipulations the liquids were transferred over as short distances as possible in pipettes that had previously been flushed with dry nitrogen. The solution was placed in a constant temperature bath at 29.6°, and the reaction started by adding benzene from a weight pipette. At suitable intervals, samples of the mixture were removed by a micropipette and analysed to determine the amount of benzophenone that had been formed.

Our method of analysis differed from that of Brown and Jensen,³ which involved a rather tedious process of isolating and weighing the benzophenone. We made use of the fact that when benzophenone is dissolved in concentrated sulphuric acid it is quantitatively protonated to the carbonium ion species $(C_6H_5)_2C^+OH$ which has an intense optical absorption centred at 346 m μ .^{5,6} The other components of the reaction mixture were found to be transparent at that wavelength in sulphuric acid. In detail, the method was to add an aliquot (0.1–0.5 ml) of the reaction mixture to 10 ml of cold anhydrous acetic acid and then add sufficient pure sulphuric acid to bring the total volume of the solution to 100 ml at 25°. The analysis was performed by measuring the optical density of the final mixture at 346 m μ . The acetic acid served both to quench the reaction and to act as a mutual solvent for the benzophenone and sulphuric acid. It was found that the presence of up to 15% of acetic acid in the final solution had no effect on the molar extinction coefficient of the carbonium ions. The method was calibrated by examining standard solutions of recrystallized benzophenone in 90 : 10 sulphuric acid/acetic acid. The solutions obeyed Beer's Law, and the extinction coefficient at 346 m μ was 2.90×10^4 cm² mmole⁻¹.

Reactions at High Pressures

The reactions under pressure were carried out in thin polyethylene capsules surrounded by hydraulic oil contained in a suitable steel pressure vessel (see, e.g., Buchanan and Hamann⁷) in a constant temperature bath at 29.6°. The capsules were sealed by Teflon plugs which, themselves, had small removable stoppers to allow samples to be taken from time to time.

Each reaction mixture was prepared as described in the last section, except that the solution of aluminium chloride in benzoyl chloride was cooled to 0° before benzene was added. After mixing, the solution was quickly transferred to the polyethylene reaction tube, the Teflon stopper was inserted, and the reaction mixture cooled to -10°. The capsule was then placed inside the pressure vessel and the desired pressure applied as quickly as possible by a 3000 atm pump. The precooling was planned to counteract the heat generated during compression¹ and had the additional benefit of quenching the reaction until pressure was applied.

At appropriate periods, samples were taken for analysis by releasing the pressure and removing the capsule. The capsule was washed free of oil and cooled to 0°; a sample was extracted and the capsule quickly cooled to -10° before being recompressed. The times needed to begin the reaction and to take samples were always very short in comparison with the total time for a kinetic run, and since the reaction was effectively stopped during these times they were not included in the figure for the reaction time t used to calculate the rate constant.

The method of analysis was the same as in the measurements at atmospheric pressure.

³ Treffers, P., and Hammett, L. P., *J. Am. Chem. Soc.*, 1937, **59**, 1708.

⁶ Scheibe, G., *Chem. Ber.*, 1926, **59**, 2617.

⁷ Buchanan, J., and Hamann, S. D., *Trans. Faraday Soc.*, 1953, **49**, 1425.

(c) *Determination of Isomer Distribution in the Benzoylation of Toluene*

The monobenzoylation of toluene was carried out by procedures identical with those used in the kinetic studies on benzene. The isomeric products were separated from the reaction solution by Procedure A of Brown and Jensen⁸ and their relative proportions were determined by gas chromatography using Carbowax 1500 at 140° as the stationary phase. Artificial mixtures of *ortho*-, *meta*-, and *para*-methylbenzophenones were prepared and analysed on the same chromatograph to identify the individual components and determine the response of the detector to each.

(d) *Melting Behaviour of Benzoyl Chloride under Pressure*

In high pressure kinetic experiments it is important to ensure that none of the components of the reaction mixture freezes or forms a separate phase under compression. To that end we carried out freezing point measurements on the solvent, benzoyl chloride, and its mixtures with 0.5 mole/l. aluminium chloride and 0.5 mole/l. benzene. The results for pure benzoyl chloride are:

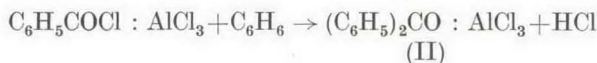
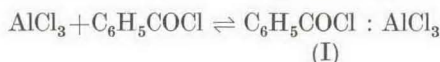
pressure (atm)	1	1160	1375	1680	1945
freezing temperature	-0.5°	+19.7°	+24.0°	+30.9°	+37.0°

Although the freezing pressure was slightly raised by the presence of dissolved aluminium chloride and benzene, we nevertheless deemed it safest to limit our upper working pressure to 1500 atm at 29.6°.

RESULTS

(a) *Kinetics*

The stoichiometry of the benzoylation of benzene, catalysed by aluminium chloride in benzoyl chloride solution, can be expressed by the equations³



Initially the aluminium chloride is present in the form of the addition complex (I) but as the reaction proceeds it preferentially forms an inactive complex (II) with benzophenone. Even in an excess of benzoyl chloride and benzene the reaction effectively stops when all the aluminium chloride has been consumed in this way.³

Brown and Jensen³ showed that, at atmospheric pressure, the reaction follows second-order kinetics:

$$\text{rate} = \frac{d[(\text{C}_6\text{H}_5)_2\text{CO} : \text{AlCl}_3]}{dt} = k[\text{C}_6\text{H}_5\text{COCl} : \text{AlCl}_3][\text{C}_6\text{H}_6]$$

and we have confirmed that the same kinetics hold at high pressures. The results for two typical runs are listed in Table I and the general results are summarized in Table 2. The rate constant at atmospheric pressure is within 10% of that found by Brown and Jensen.

Although the results show some scatter, it is clear that the reaction is accelerated by raising the pressure. Applying the quasi-thermodynamic relation:⁹

$$-RT \frac{\partial \ln k}{\partial P} = \Delta V^\ddagger$$

⁸ Brown, H. C., and Jensen, F. R., *J. Am. Chem. Soc.*, 1958, **80**, 2296.

⁹ Evans, M. G., and Polanyi, M., *Trans. Faraday Soc.*, 1935, **31**, 885.

TABLE 1
RATE DATA FOR THE BENZOYLATION OF BENZENE AT 29.6°
Initial concentrations (mole fractions): $[C_6H_6] = 0.058$,
 $[C_6H_5COCl : AlCl_3] = 0.035$

Time (min)	1 Atm		Time (min)	1000 Atm	
	Percentage Reaction	10^4k (mole-fraction ⁻¹ sec ⁻¹)		Percentage Reaction	10^4k (mole-fraction ⁻¹ sec ⁻¹)
48	10.3	6.6	51	11.9	7.5
100	14.9	5.0	100	25.7	9.3
158	22.9	5.1	150	35.7	9.6
200	31.7	6.1	238	47.1	9.2
275	36.0	5.3	300	50.8	8.3
350	42.6	5.3	350	55.1	8.2
400	48.9	5.8	400	59.7	8.3
452	49.7	5.3	450	64.6	8.7
500	53.7	5.7	500	64.6	7.9
		Av.: 5.6			Av.: 8.6

TABLE 2
EFFECT OF PRESSURE ON THE RATE CONSTANT FOR BENZOYLATION
OF BENZENE AT 29.6°

Initial Concentrations (mole fractions)		Pressure (atm)	10^4k (mole-fraction ⁻¹ sec ⁻¹)
$[C_6H_6]$	$[C_6H_5COCl : AlCl_3]$		
0.086	0.037	1	6.2
0.058	0.035	1	5.6
0.047	0.102	1	5.3
0.055	0.050	1	5.8
0.104	0.050	1	5.8
			Av.: 5.7
0.086	0.037	1000	9.9
0.058	0.035	1000	8.3
0.047	0.102	1000	8.6
0.055	0.050	1000	8.3
			Av.: 8.8
0.058	0.035	1500	11.7
0.047	0.102	1500	12.2
0.055	0.050	1500	12.2
0.045	0.036	1500	13.1
			Av.: 12.3

we find that the pressure effect corresponds to a volume of activation $\Delta V^\ddagger = -11.4 \pm 1 \text{ cm}^3 \text{ mole}^{-1}$.

(b) *Isomer Distribution Ratios*

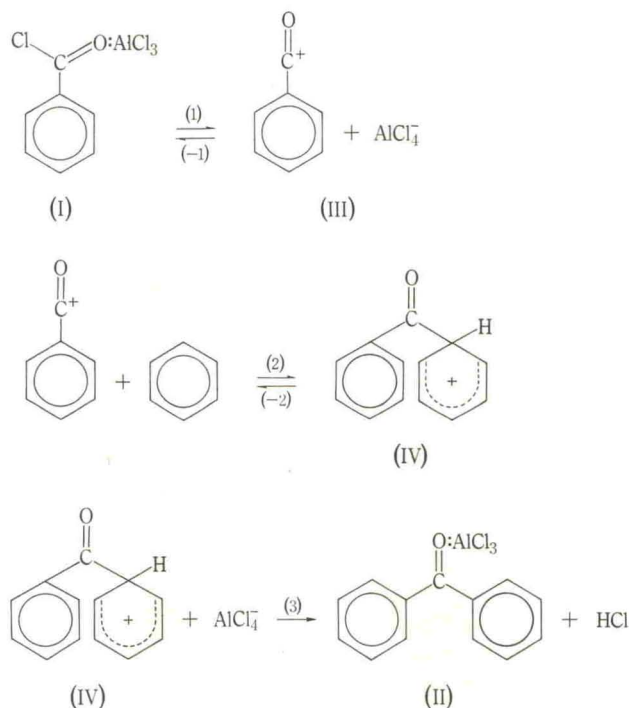
Table 3 (p. 1916) lists the results of 11 separate measurements of the relative yields of methyl benzophenones formed by benzoylating toluene under the conditions described in the Experimental section.

The isomer ratios were very close to those found by Brown and Jensen,⁸ and were not measurably altered by increasing the pressure.

DISCUSSION

(a) *Kinetics*

Although the exact mechanism of Friedel-Crafts benzoylations is not known with certainty,⁴ it is probable that the present reaction proceeds by the following steps:



This mechanism would give the observed second-order kinetics if (3) were the rate-determining step, or if the ions (III) existed mainly as ion pairs and (2) were the rate-determining step. The second alternative is the more likely, since it is known that the rate of benzoylation of hexadeuterobenzene⁴ is not very different from that of benzene; if (3) were the slow step the kinetics would show a marked isotope effect.

Evidence of the prereaction equilibrium (1) is to be found in the extremely fast exchange of chloride ions between benzoyl chloride and aluminium chloride¹⁰ and the fact that mixtures of Friedel-Crafts catalysts with benzoyl chloride are electrolytic conductors.¹¹ However, the concentration of the ionized form must be small, since Susz *et al.*¹² were unable to detect it by infrared methods that have shown the presence, in analogous mixtures, of $\text{CH}_3\text{CO}+\text{AlCl}_4^-$ ¹³ and $\text{C}_6\text{H}_5\text{CO}+\text{SbF}_6^-$.¹⁴

TABLE 3
DISTRIBUTION OF ISOMERIC METHYL
BENZOPHENONES FORMED BY BENZOYL-
ATING TOLUENE

Pressure (atm)	Isomer Distributions (%)		
	<i>ortho</i>	<i>meta</i>	<i>para</i>
1	9.5	1.5	89.0
1	10.1	1.9	88.0
1	9.6	1.2	89.2
1	9.2	1.5	89.3
500	8.6	1.6	89.8
500	12.2	1.4	86.2
1000	9.8	2.2	88.7
1000	8.9	2.0	89.1
1500	9.6	1.7	88.7
1500	8.5	1.9	89.6
1500	9.2	2.7	89.1

If the postulated mechanism is correct, the effect of pressure on the measured rate constant k must depend on changes in both the equilibrium constant $K_1 (= k_1/k_{-1})$ and the rate constant k_2 . In fact ΔV^\ddagger must be a composite quantity:

$$\Delta V^\ddagger = -RT \frac{\partial \ln k}{\partial P} = -RT \frac{\partial \ln (K_1 k_2)}{\partial P} \\ = \Delta \bar{V}_1 + \Delta V_2^\ddagger$$

where $\Delta \bar{V}_1$ denotes the change of partial molar volumes for the ionization reaction (1) and ΔV_2^\ddagger is the activation volume for reaction (2). The kinetic data alone offer no means of separating the two contributions and there is at present no direct way of measuring K_1 and hence $\Delta \bar{V}_1$. But from theoretical arguments and from the known

¹⁰ Oulevey, G., and Susz, B. P., *Helv. Chim. Acta*, 1964, **47**, 1828.

¹¹ Singh, J., Prashar, R., Lakhanpal, M. L., and Paul, R. C., *J. Scient. Ind. Res. B*, 1962, **21**, 430.

¹² Susz, B. P., and Cassimatis, D., *Helv. Chim. Acta*, 1961, **44**, 395; Cooke, I., Susz, B. P., and Herschmann, C., *Helv. Chim. Acta*, 1954, **37**, 1280.

¹³ Cook, D., *Canad. J. Chem.*, 1959, **37**, 48.

¹⁴ Cook, D., *Canad. J. Chem.*, 1962, **40**, 445.

behaviour of analogous reactions^{15,16} we should expect both $\Delta \bar{V}_1$ and ΔV_2^\ddagger to be negative; the first because reaction (1) involves an increase in electrostriction, the second because reaction (2) is a bimolecular association which forms a new covalent bond. It follows that ΔV^\ddagger should also be negative and that the total reaction rate should increase with increasing pressure. The experiments have shown that it does.

(b) *Isomer Distribution*

The unusually low ratio of *ortho* to *para* isomers formed in the benzylation of toluene at atmospheric pressure (Table 3) suggests that substitution in the *ortho* position is sterically hindered,⁴ perhaps by the bulkiness of the attacking ion-pair (III). In other experiments^{2,17} it has been found that, under pressure, aromatic substitutions yield appreciably higher proportions of sterically strained isomers than they do at atmospheric pressure. For that reason we expected the *ortho*:*para* ratio to increase with increasing pressure. Surprisingly, there was no measurable change. This could mean that the influence of pressure on the steric effect is offset by other factors of the kind we have discussed in relation to the nitration of toluene² or, more probably, that the low *ortho*:*para* ratio is not really caused by steric hindrance.

¹⁵ Hamann, S. D., "Physico-Chemical Effects of Pressure." pp. 160-96. (Butterworths: London 1957.)

¹⁶ Hamann, S. D., in "High Pressure Physics and Chemistry." (Ed. R. S. Bradley.) Vol. II, pp. 163-207. (Academic Press: London 1963.)

¹⁷ Gonikberg, M. G., Prokhorova, N. I., and Litvin, E. F., *Dokl. Akad. Nauk. SSSR*, 1963, **148**, 105.