Friedel–Crafts-Type Cyclodehydration of 1,3-Diphenyl-1-propanones. Kinetic Evidence for the Involvement of Dication

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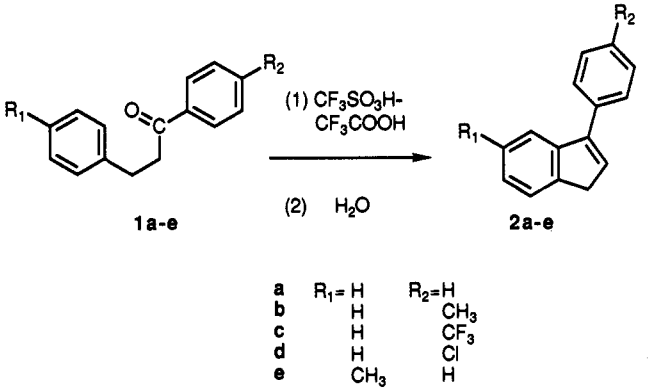
Abstract: The mechanism of intramolecular ketone–aromatic cyclodehydration of 1,3-diphenyl-1-propanones to give 1-phenyl-1*H*-indenes in trifluoromethanesulfonic acid (TFSA) was investigated. The rate of the reaction of the monoprotonated diphenylpropanone increased proportionally to the acidity (H_0) of the TFSA – trifluoroacetic acid matrix. This observation suggested that a species formed by a second protonation participates in the reaction. The O,O-diprotonated ketone is proposed as the true reactive intermediate. The substituent effect was also investigated.

Though the acid-catalyzed reaction of aldehydes and ketones with benzenes was reported by Baeyer as early as 1872,[1] this Friedel–Crafts-type reaction has not been studied to the same extent as the corresponding Friedel–Crafts reactions involving alkyl halides or acyl halides, probably because the yields of the reactions are generally low, and the use of concentrated sulfuric acid as the catalyst often makes the reactions messy.[2] The use of strong Lewis acids also makes it difficult to analyze the mechanism of the reactions. We recently analyzed an acid-catalyzed reaction of cinnamaldehyde and its analogs with benzene which gives β-phenylated products in good yields and showed that the reaction involves a doubly protonated species that reacts with benzene.[3] This analysis was made possible by the use of trifluoromethanesulfonic acid (TFSA), which is a nonoxidative superacid; TFSA is 10^3 times stronger than sulfuric acid.[4] In addition, TFSA has a low freezing point, which enabled us to study the reaction at low temperature.

During the study of the cinnamaldehydes, we found that TFSA works as a very efficient catalyst in the Friedel–Crafts-type intramolecular ketone–aromatic cyclodehydration: the ketones obtained by the reaction of cinnamaldehyde with benzene further cyclized to give indenes.[3] The reaction is homogeneous and the reaction conditions could be strictly defined and kinetic data could be collected. The Zucker–Hammett postulation[5,6] suggests that the rate of an acid-catalyzed reaction is proportional to the acidity (H_0) when the reaction of the protonated species with the substrate is the rate-determining step, and when the steady-state concentration of the protonated species is low. Thus, if the rate increases proportionally to the acidity in the higher acidity region than that where the substrate is completely protonated, a species formed by a second protonation must participate in the reaction. Fortunately, the TFSA-trifluoroacetic acid (TFA) system can cover a wide range of acidity,[7] which makes it possible to test the dependency of the rate on the acidity.

In this paper we deal with the acid-catalyzed intramolecular cyclization of 1,3-diphenyl-1-propanones to 3-phenyl-1*H*-indenes.

Scheme 1



The mechanism of the reaction is discussed on the basis of the finding that rate measurements support the involvement of diprotonated species in the reaction.

Results

Acidity-Yield Relationships in the Acid-Catalyzed Cyclodehydration of 1,3-Diphenyl-1-propanones. In a previous paper we showed that 3,3-diphenylpropanal, which is a primary product formed from cinnamaldehyde and benzene in TFSA, cyclized to give 1-phenyl-1*H*-indene under the same conditions.[3] Stimulated by this observation, we decided to examine the intramolecular reaction of 1,3-diphenyl-1-propanones (**1**) (Scheme 1), which may give us an insight into the intermolecular cyclodehydration of carbonyl compounds with benzene.

The reaction did not take place even when a TFA solution of 1,3-diphenyl-1-propanone (**1a**) was heated for 17 h at 80 °C. However, the reaction did proceed on the addition of TFSA to the TFA solution. The cyclized product, 3-phenyl-1*H*-indene (**2a**), was obtained in 7% yield in 5% (w/w) TFSA–95% TFA solution (H_0 = –9, 80 °C, 17 h). In TFSA (H_0 = –14[8]), the reaction proceeded more quickly and in quantitative yield (Table 1).

The rate of the reaction and the yield of **2a** depend greatly upon the acidity of the solution. However, the basicity (pK_{BH^+}) of **1a** should be comparable to the pK_{BH^+} of acetophenone (pK_{BH^+}

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(1) Baeyer, A. *Ber.* **1872**, *5*, 1094–1100.

(2) For review, see: Hofmann, J. E.; Schriesheim, A. *Friedel-Crafts and Related Reactions*; Olah, G. A., Ed.; Wiley: New York, 1964: Vol. II, Chapter XIX, pp 597–640.

(3) Ohwada, T.; Yamagata, N.; Shudo, K. *J. Am. Chem. Soc.* **1991**, *113*, 1364–1373.

(4) (a) Stang, P. J.; White, M. R. *Aldrich. Acta* **1983**, *16*, 15–22. (b) Howells, R. D.; Mc Cown, J. D. *Chem. Rev.* **1977**, *77*, 69–92.

(5) Zucker, L.; Hammett, L. P. *J. Am. Chem. Soc.* **1939**, *61*, 2791–2798.

(6) Long, F. A.; Paul, M. A. *Chem. Rev.* **1957**, *57*, 935–1010.

(7) Saito, S.; Saito, S.; Ohwada, T.; Shudo, K. *Chem. Pharm. Bull.* **1991**, *39*(10), 2718–2720.

(8) In ref 7, we reported that the acidity (H_0) of TFSA was –13.7. However, by the extremely careful use of a dry bag, we were able to obtain TFSA with the acidity of –14.1 ± 0.1. See: Grondin, J.; Sagnes, R.; Commeyras, A. *Bull. Soc. Chim. Fr.* **1976**, 1779–1783. This value of the acidity is among the lowest reported so far for TFSA.

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Table 1. Cyclodehydration of 1,3-Diphenyl-1-propanones (1) at 80 °C

substrate	medium (w/w)	H_0	time	yield (%)	recovery (%)
1a ($R_1 = R_2 = H$)	TFA	−2.7	17 h	0	94
	5% TFSA–95% TFA	−9	17 h	7	73
	TFSA	−14	17 h	72	3
1b ($R_1 = H$, $R_2 = CH_3$)	5% TFSA–95% TFA	−9	144 h	16	67
	TFSA	−14	144 h	86	3
1c ($R_1 = H$, $R_2 = CF_3$)	5% TFSA–95% TFA	−9	20 min	2	84
	TFSA	−14	20 min	68	2
1d ($R_1 = H$, $R_2 = Cl$)	5% TFSA–95% TFA	−9	18 h	22	47
	TFSA	−14	18 h	84	5
1e ($R_1 = CH_3$, $R_2 = H$)	5% TFSA–95% TFA	−9	5.5 h	28	55
	TFSA	−14	5.5 h	84	2

= −6.4,[9] *vide infra*), and therefore **1a** is essentially fully monoprotonated even in the solution with the acidity of −9. The acceleration of the reaction in the solution with high acidity ($H_0 < -9$) cannot be explained in terms of the degree of *mono*protonation. The relationship between the chemical yield of **2a** and the acidity of the catalyst suggests the involvement of a further protonation of the conventional monocationic species.

Substituent Effects. Substituents on the benzyl or the benzoyl group (R_1 or R_2, respectively) of **1** affected the rate of the reaction. To avoid protonation on the substituent, methyl and trifluoromethyl were chosen as electron-donating and electron-withdrawing groups, respectively. The influence of substituents on the benzoyl group, which affects the reactivity of the electrophilic center, was examined. Compared with the unsubstituted parent compound (**1a**), the compound bearing a 4-methyl group (**1b**, $R_2 = CH_3$) cyclodehydrated at a slower rate (80 °C, 144 h) in TFSA. On the other hand, the compound bearing a 4-trifluoromethyl group (**1c**, $R_2 = CF_3$) reacted faster (80 °C, 20 min) in TFSA. The rate of the chlorine-bearing compound (**1d**, $R_2 = Cl$) is similar to that of the unsubstituted compound. The activation of the electrophilic carbon center by an electron-withdrawing group is favorable to the reaction.

The 4-methyl substituent on the benzyl group (**1e**, $R_1 = CH_3$) somewhat enhanced the cyclodehydration (80 °C, 5.5 h) in TFSA.[10] Consequently, both the electrophilicity of the carbon atom of the (activated) carbonyl group and the nucleophilicity of the phenyl group of the benzyl moiety play important roles in the reaction. This result shows that the bond formation of the carbonyl carbon atom with the phenyl group is involved in the rate-determining step of the reaction. Analogously with the reaction of the parent compound **1a**, the rates of the reaction of **1b–e** were faster in the solution with higher acidity.

Protonation States of 1 in TFSA–TFA Solutions. The pK_{BH}^+ of **1a** was estimated by titration using ^1H NMR and UV spectroscopy. To cover the range of $H_0 = -4$ to −10, the TFSA–2,2,2-trifluoroethanol (TFE) solvent system was used, together with the TFSA–TFA solvent system ($H_0 = -8$ to −14). The chemical shift movement of the α-methyl or methylene group was selected for estimation of the pK_{BH}^+ by the NMR method.[11] For the determination of pK_{BH}^+ by the UV method, the extinction coefficient (ε) of the λ_{max} of the protonated ketone in TFSA and also the λ_{max} of the nonprotonated ketone in TFA or TFE were used.[12,13] Thus, the pK_{BH}^+ of the acetophenone was estimated to be −4.9 in TFSA–TFE solution. This value is somewhat different from the reported pK_{BH}^+ value of −6.4[9] or −6.3[11,12] in H_2SO_4–H_2O solution, which was also reproduced in this experiment. The pK_{BH}^+ value of **1a** was estimated as −5.9 in the TFSA–TFE system, and the almost complete monoprotonation of **1a** in TFSA–TFA solution with acidity −9 is thus confirmed. The complete monoprotonation of **1c** in 20% (w/w) TFSA–80% TFA solution ($H_0 = -10$) was also confirmed by NMR titration at 30 °C.[14]

Kinetics. In order to further clarify the mechanism, we measured the rate constants of the reaction of **1** in solutions with defined acidities. The reaction was conducted in sealed tubes, and the concentration of **1** was followed by means of NMR spectroscopy. The results are shown in Figure 1 and in Table 2. All the reactions followed good first-order kinetics ($R > 0.99$). The order of the rate constants was **1c** > **1a** > **1b**. The calculated rate constants (80 °C) at $H_0 = -13$ were 3.63×10^{-5} s^{-1} for **1a**, 4.90×10^{-6} s^{-1} for **1b**, and 2.45×10^{-3} s^{-1} for **1c**, respectively. In every case, the logarithm of the rate constant increased proportionally to the acidity, and the slopes were 0.18 for **1a**, 0.22 for **1b**, and 0.29 for **1c**, respectively.

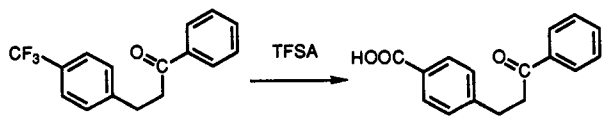
The reaction rates of **1a** in TFSA at three different temperatures were obtained in order to determine the activation parameters (Table 3): $\Delta H^{\ddagger}$ 84 kJ mol^{-1} (20 kcal mol^{-1}), $\Delta G^{\ddagger}$ 1.2×10^2 kJ mol^{-1} (29 kcal mol^{-1}) (80 °C), and $\Delta S^{\ddagger}$ -1.1×10^2 J K^{-1} mol^{-1} (−26 cal K^{-1} mol^{-1}). The large negative $\Delta S^{\ddagger}$ value observed in the reaction of **1a** is compatible with the idea that the intramolecular electrophilic cyclization step is involved in the rate-determining step.

Discussion

The reaction of a ketone with benzene under Friedel–Crafts conditions is best illustrated by the reaction of benzenes with trichloroacetaldehyde (chloral).[15] This reaction can be understood in terms of the involvement of a protonated chloral, $[CCl_3CHOH]^+$. This carbocationic species is stabilized by the hydroxyl

(9) Arnett, E. M. *Prog. Phys. Org. Chem.* **1963**, *1*, 223–403. The pK_{BH}^+ values collected from this ref. were corrected to the H_0 scale as evaluated: Jorgenson, M. J.; Hartter, D. R. *J. Am. Chem. Soc.* **1963**, *85*, 878–883.

(10) We synthesized and tried to cyclize compound **1f**. However, the only product which was isolated from **1f** was **6**, which may be obtained by the decomposition of the trifluoromethyl group.

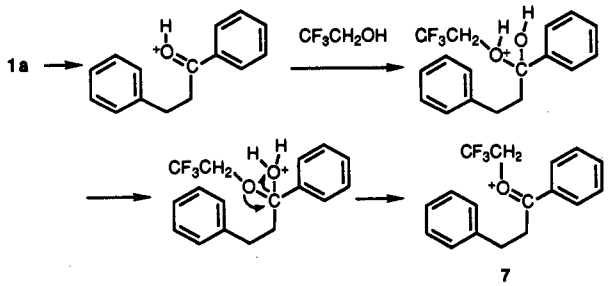


1f **6**

(11) Levy, G. C.; Cargioli, J. D.; Racela, W. *J. Am. Chem. Soc.* **1970**, *92*, 6238–6246.

(12) Greig, C. C.; Johnson, C. D. *J. Am. Chem. Soc.* **1968**, *90*, 6453–6457.

(13) In the highly acidic TFSA–TFE solution, the probable formation of the trifluoroethoxy monocation **7** prevented reliable measurements of UV absorption and the rate of the reaction in this solvent. Compound **7** would be formed by the following pathway.



7

(14) The pK_{BH}^+ value of 4-(trifluoromethyl)acetophenone was −7.8 in H_2SO_4–H_2O solution.

(15) Reference 2, pp 616–621.

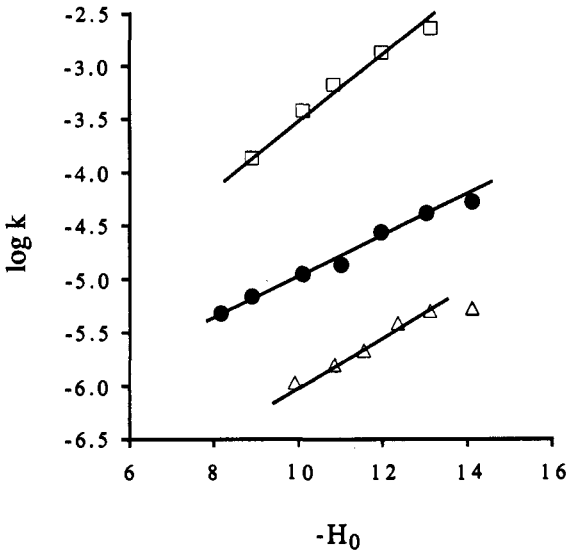


Figure 1. The acidity-rate relationship in the cyclodehydration of **1a** (●), **1b** (△), and **1c** (○) at 80 °C.

Table 2. The Rate Constants for the Cyclodehydration of 1a–c at 80 °C

1a		1b		1c	
H_0	10^5k (s^{-1})	H_0	10^5k (s^{-1})	H_0	10^5k (s^{-1})
−14.12	5.28	−14.12	0.530		*a*
−13.03	4.09	−13.12	0.502	−13.12	228
−11.95	2.72	−12.35	0.389	−11.97	134
		−11.54	0.215		
−11.00	1.37				
−10.96	1.38	−10.85	0.185	−10.84	66.8
−10.10	1.11	−9.92	0.108	−10.11	37.7
−8.90	0.69			−8.90	13.7
−8.17	0.48				

[a] In TFSA, this reaction was too fast for reliable measurement.

Table 3. The Observed Rate Constants for the Cyclodehydration of 1a in TFSA (H_0 = −14.12) and Calculated Activation Parameters

temp (°C)	10^5k (s^{-1})	log k	$\Delta H^{\ddagger}$ (kJ mol^{-1})	$\Delta G^{\ddagger}$ (kJ mol^{-1})	$\Delta S^{\ddagger}$ (J K^{-1} mol^{-1})
70	2.46	−4.61			
80	5.28	−4.28	84	1.2×10^2	-1.1×10^2
90	13.1	−3.88			

group and destabilized by the electron-withdrawing trichloromethyl group, and the latter enhances the electrophilicity of the species, which makes the reaction proceed. Similar considerations apply to the facile reaction of trifluoroacetophenone with benzene.[16] The trifluoromethyl group is a very strong electron-withdrawing group, comparable to the protonated carbonyl group.[17]

Without any adjacent electron-withdrawing group to destabilize the cation, monoprotonated carbonyl compounds are very poor electrophiles toward nonactivated benzenes, even in intramolecular reactions. The discovery of the efficient intramolecular cyclization of 1,3-diphenyl-1-propanones in TFSA therefore prompted us to study the reaction in detail.

The cyclodehydration proceeds under highly acidic conditions, more acidic than H_0 = −9, at 80 °C. This condition cannot be obtained by using sulfuric acid because of sulfonation and other side reactions. The results of qualitative and quantitative studies of the cyclodehydration using TFSA as the strong acid support the idea that the diprotonated carbonyl is the active electrophilic species toward benzene, as summarized below.

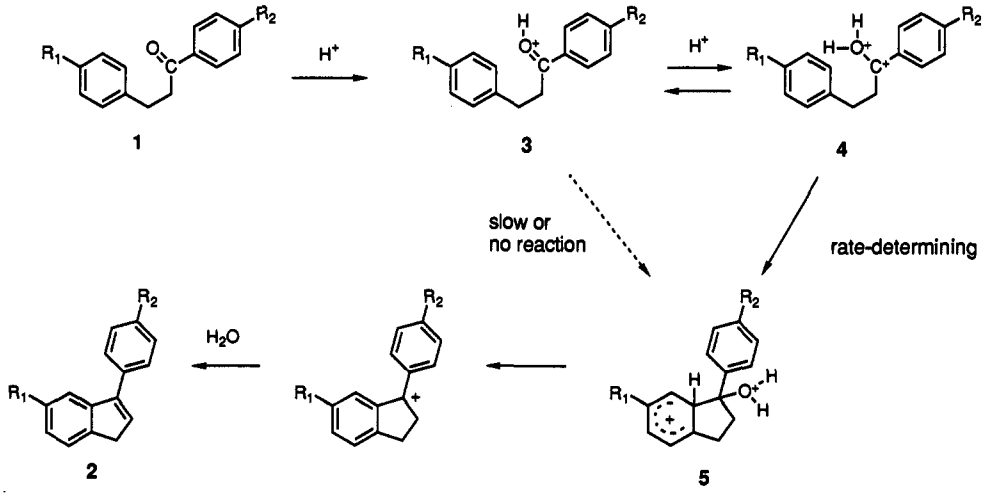
(16) Kray, W. D.; Rosser, R. W. *J. Org. Chem.* **1977**, *42*, 1186–1189.
(17) Ohwada, T.; Shudo, K. *J. Am. Chem. Soc.* **1988**, *110*, 1862–1870.

It is important to know the degree of protonation in the reaction medium. So we determined the pK_{BH}^+ of ketones in TFSA–TFE, a medium similar to the reaction medium. We expected that pK_{BH}^+ of ketones would not be affected by the composition of the solvent. However, there was a significant difference between the pK_{BH}^+ values of the acetophenone in TFSA–TFE solution and in H_2SO_4–H_2O solution. The pK_{BH}^+ of the acetophenone was −6.4 in H_2SO_4–H_2O solution and was −4.8 in TFSA–TFE solution, as obtained by the UV method. The NMR study showed that the pK_{BH}^+ of the acetophenone was −6.3 in H_2SO_4–H_2O solution and was −4.9 in TFSA–TFE solution. The two pK_{BH}^+ values determined by the two different methods were in good agreement, but they showed different values in different solvent systems. This result seems to be inconsistent with the proposal by Levy et al.[11] that the pK_{BH}^+ value is not affected by the composition of the acid solution. There might be a specific interaction between the fluorine rich moiety of TFE and the carbonyl group of the ketones which may affect the basicity of the ketones. However, the almost complete monoprotonation of acetophenone and the diphenylpropanone **1a** in 5% (w/w) TFSA–95% TFA solution (H_0 = −9) was confirmed by ^1H NMR and UV spectroscopy. Essentially complete monoprotonation of **1b**, **1d**, and **1e** in the 5% (w/w) TFSA–95% TFA solution is also reasonable, judging from the pK_{BH}^+ values of the corresponding acetophenones. Complete monoprotonation of **1c** in the 10% (w/w) TFSA–90% TFA (H_0 = −10) solution was also confirmed.

This reaction is of first order, and the kinetic results can be used to test the Zucker–Hammett hypothesis. According to the hypothesis, when a low concentration of cationic species formed is the reactive species and is involved in the rate-determining step of the reaction, linear dependency of the rate on the acidity should be observed. As shown in Figure 1, the reaction rates for **1a–c** are proportional to the acidity of the medium.[18] It has been shown that the substrate **1** is already fully monoprotonated in solution with acidity −9. Therefore, the monoprotonated **1** is *not* the reactive intermediate responsible for the linear increase of the rate in this region of acidity (H_0 = −9 to −14). The reactive cationic species should be the diprotonated ketone, the dication, which is formed by a further protonation of the monoprotonated ketone.[19] The small slopes, which deviate from unit value, may reflect the special character of the monocation, which should be a positively charged non-Hammett base,[20] or this small slope may indicate that the second protonation is insufficient to form a discrete species. This situation could correspond to the "protosolvated" species proposed by Olah et al.,[21] the species being represented, at least formally, by the dication. The slopes of **1a–c** are somewhat different from each other, and this difference may reflect the slight difference of the transition-state structures in the rate-determining step. The acidity-rate profile of the reaction of **1b** is deflected in the highly acidic region (H_0 = −14), and this may suggest that the concentration of the dication is rather high in that region, and the rate is approaching the maximum value.[6,22]

(18) The pK_{BH}^+ and H_0 values were determined at 25 or 30 °C and the reactions were run at 80 °C. Therefore, the validity of the pK_{BH}^+ and H_0 values at 80 °C may be questioned. In a H_2SO_4–H_2O solvent system, it has been known that the H_0 is temperature dependent (see: Johnson, C. D.; Katritzky, A. R.; Shapiro, S. A. *J. Am. Chem. Soc.* **1969**, *91*, 6654–6662). However, the pK_{BH}^+ values of the indicators also depend on temperature. The changes of H_0 and pK_{BH}^+ are essentially cancelled out, and the protonation states of the bases are not significantly affected by the temperature. Considering this result, we assumed that the changes of H_0 and pK_{BH}^+ are cancelled out in TFSA–TFA solvent system, too.
(19) This result indicates that the proportion of the dication is low even in this highly acidic system. Therefore, the species cannot necessarily observed, even if it is a stable entity.
(20) Acetophenone itself is also a non-Hammett base. See ref 12.
(21) Olah, G. A.; Prakash, G. K. S.; Lammertsma, K. *Res. Chem. Intermed.* **1989**, *12*, 141–159.
(22) Schubert, W. M.; Latourette, H. K. *J. Am. Chem. Soc.* **1952**, *74*, 1829–1834.

Scheme 2



The finding that the order of the reaction rate is **1c > 1a > 1b**, shows that the electronic effect, which influences the electrophilicity of the substrate, controls the rate of the reaction. A 4-trifluoromethyl substituent (**1c**) on the benzoyl group reduces the basicity but enhances the electrophilicity of the carbonyl group, and in this reaction the electrophilicity of the diprotonated carbonyl group, rather than the concentration of the dication, plays an important role. Thus, the net effect results in a faster reaction. The slower reaction of **1b** can also be explained analogously. Substituents attached at the benzyl group also affect the rate of the reaction. The enhanced nucleophilicity of the 4-methylbenzyl group accelerates the rate of the reaction. These observations show that the rate-determining step involves the electrophilic attack of the diprotonated carbonyl group on the aromatic ring.

The structure of the diprotonated ketone has been deduced by calculation.[23] The O,O-diprotonated structure is favored.[24] Therefore, we propose the mechanism of this reaction to be as shown in Scheme 2. The monoprotonated ketone **3** is stable and has a negligible reactivity toward nonactivated benzene even in this intramolecular system. The O,O-diprotonated ketone (**4**), which is a strong electrophile, is the key intermediate in the reaction, and can be regarded as a superelectrophile, as proposed by Olah.[25] This electrophilic attack of the diprotonated carbonyl carbon on the aromatic ring (**4** → **5**) is the rate-determining step in the reaction.

So far we have shown that, at least in a few examples, dications participate in Friedel–Crafts-type reactions with benzene. The present results provide the first *kinetic* evidence for the participation of a dication in the reaction. Our present and previous experimental results[3,17,26] and proposals by Olah[21,25] strongly favor the hypothesis that dications are general reaction intermediates in electrophilic substitution reactions with benzene.

Conclusion

The carbocation formed by monoprotonation of a ketone is a stable cation, which has low or negligible reactivity toward benzene. The monoprotonated ketone reacts with benzene only after further protonation in media of higher acidity. Under such conditions, the O,O-diprotonated ketone is the *true* reactive electrophilic intermediate. This dication can be regarded as a superelectrophile. The kinetic results indicate that the reaction of O,O-diprotonated ketone with benzene is involved in the rate-determining step. Dications may be involved in many Friedel–Crafts-type reactions which require highly acidic conditions.

Experimental Section

General Methods. All the melting points were measured with a Yanagimoto hot-stage melting point apparatus (MP-500) and are uncorrected. Proton NMR spectra were measured on a JEOL GX 400-MHz NMR spectrometer with tetramethylsilane as an internal reference in $CDCl_3$ or with CH_2Cl_2 (5.30 ppm) as an internal reference in acid solutions at 30 °C. Ultraviolet spectra were measured on a Shimadzu UV 200S at 25 °C in acidic media. Flash column chromatography was performed on silica gel (Kieselgel 60, 230–400 mesh, Merck) with the specified solvent. All operations for kinetic studies, spectrophotometric studies, and NMR observation of acid solutions were carried out in an AtomosBag (Aldrich). Combustion analyses were carried out in the microanalytical laboratory of this faculty.

Materials. Trifluoromethanesulfonic acid (TFSA) was purchased from 3M Co. or Central Glass Co. and was purified as reported.[7] Extreme care was required to obtain anhydrous TFSA which showed the acidity of −14.1.[7,8] Trifluoroacetic acid (TFA) and the indicators were also purified as reported.[7] 2,2,2-Trifluoroethanol (TFE) was purified by distillation over a small amount of CaH_2 (bp 76 °C). The acidity (H_0) of TFSA, TFA, and the mixed acids was checked before use for the kinetic studies and for NMR and UV experiments. 1,3-Diphenyl-1-propanone (**1a**) was prepared by the hydrogenation of the chalcone over 10% Pd/C at atmospheric pressure. Other propanones (**1b–e**) were prepared by condensation of the corresponding benzyl alcohol and acetophenone in the presence of lithium or lithium hydride.[27]

1,3-Diphenyl-1-propanone (1a): mp 69–70 °C (recrystallized from MeOH) (lit.[28] 69–70 °C); ^{1}H NMR 3.07 (t, 2 H, 7.7 Hz), 3.31 (t, 2 H, 7.7 Hz), 7.21 (t, 1 H, 7.0 Hz), 7.3 (m, 4 H), 7.45 (t, 2 H, 7.5 Hz), 7.56 (dt, 1 H, 1.5, 7.3 Hz), 7.96 (d, 2 H, 7.0 Hz). Anal. Calcd for $C_{15}H_{14}O$: C, 85.68; H, 6.71. Found: C, 85.43; H, 6.70.

1-(4-Methylphenyl)-3-phenyl-1-propanone (1b): mp 68 °C (recrystallized from MeOH) (lit.[29] 70 °C); ^{1}H NMR 2.41 (s, 3 H), 3.06 (t, 2 H, 7.9 Hz), 3.28 (t, 2 H, 7.7 Hz), 7.21 (t, 1 H, 7.0 Hz), 7.2–7.35 (m, 6 H), 7.86 (d, 2 H, 8.4 Hz). Anal. Calcd for $C_{16}H_{16}O$: C, 85.68; H, 7.19. Found: C, 85.44; H, 7.22.

(23) For recent ab initio studies, see: Hartz, T.; Rasul, G.; Olah, G. A. *J. Am. Chem. Soc.* **1993**, *115*, 1277–1285. Krivdin, L. B.; Zinchenko, S. V.; Kalabin, G. A.; Facelli, J. C.; Tufro, M. F.; Contreras, R. H.; Denisov, A. Yu.; Gavrilyuk, O. A.; Mamatyuk, V. I. *J. Chem. Soc. Faraday Trans.* **1992**, *88*, 2459–2463. Koch, W.; Heinrich, N.; Schwarz, H. *J. Am. Chem. Soc.* **1986**, *108*, 5400–5403.

(24) See, also: Farcasiu, D.; Ghenciu, A. *J. Org. Chem.* **1991**, *56*, 6050–6052. For the protonation of related iminium salts, see, Pankratz, M.; Childs, R. F. *J. Org. Chem.* **1985**, *50*, 4553–4558.

(25) Olah, G. A. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 767–788.

(26) Yato, M.; Ohwada, T.; Shudo, K. *J. Am. Chem. Soc.* **1991**, *113*, 691–692.

(27) Pratt, E. F.; Evans, A. P. *J. Am. Chem. Soc.* **1956**, *78*, 4950–4952.

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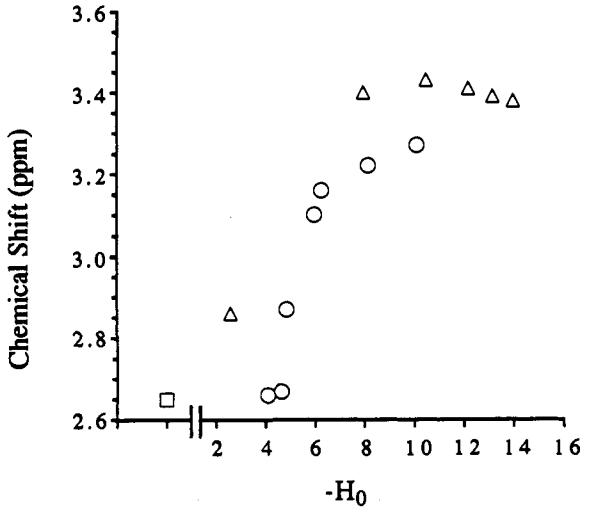

Figure 2. 2. The protonation of acetophenone detected by NMR spectroscopy in TFSA–TFE (△), TFSA-TFA (○), and in TFE (□) solutions.

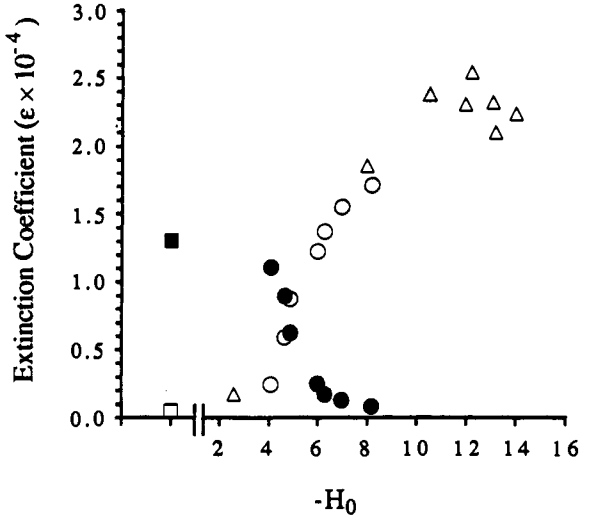

Figure 3. 3. Protonation of acetophenone detected by UV absorption measurements in TFSA–TFE (○, 296 nm, ●, 245 nm), TFSA–TFA (△, 296 nm), and in TFE (□, 296 nm, ■, 245 nm) solutions.

3-Phenyl-1-[4-(trifluoromethyl)phenyl]1-propanone (1c): mp 47 °C (recrystallized from MeOH); ^{1}H NMR 3.08 (t, 2 H, 7.7 Hz), 3.32 (t, 2 H, 7.5 Hz), 7.3 (m, 5 H), 7.72 (d, 2 H, 8.0 Hz), 8.05 (d, 2 H, 8.0 Hz). Anal. Calcd for $C_{16}H_{13}F_3O$: C, 69.06; H, 4.71. Found: C, 69.15; H, 4.74.

1-(4-Chlorophenyl)-3-phenyl-1-propanone (1d): mp 74–75 °C (recrystallized from EtOH) (lit.[29] 78 °C); ^{1}H NMR 3.06 (t, 2 H, 7.7 Hz), 3.28 (t, 2 H, 7.7 Hz), 7.2 (m, 3 H), 7.30 (t, 2 H, 6.4 Hz), 7.42 (dt, 2 H, 8.8, 2.2 Hz), 7.89 (dt, 2 H, 8.8, 2.2 Hz). Anal. Calcd for $C_{15}H_{13}ClO$: C, 73.62; H, 5.35. Found: C, 73.65; H, 5.38.

3-(4-Methylphenyl)-1-phenyl-1-propanone (1e): mp 33 °C (recrystallized from MeOH) (lit.[29] low melting solid); ^{1}H NMR 2.32 (s, 3 H), 3.03 (t, 2 H, 7.9 Hz), 3.28 (t, 2 H, 7.7 Hz), 7.11 (d, 2 H, 8.1 Hz), 7.15 (d, 2 H, 8.2 Hz), 7.45 (t, 1 H, 7.7 Hz), 7.56 (t, 2 H, 7.5 Hz), 7.96 (d, 2 H, 7.1 Hz). Anal. Calcd for $C_{16}H_{16}O$: C, 85.68; H, 7.19. Found: C, 85.71; H, 7.22.

Acetophenone was purchased and purified by distillation over a small amount of P_2O_5 under reduced pressure (bp. 113 °C/46 mmHg). 4-Trifluoromethylacetophenone was also purchased and purified by recrystallization from *n*-hexane (colorless needles, mp 29 °C).

Acid-Catalyzed Reactions of 1,3-Diphenyl-1-propanones. To a solution of acids (8.85 mL, 100 equiv) was added the ketone

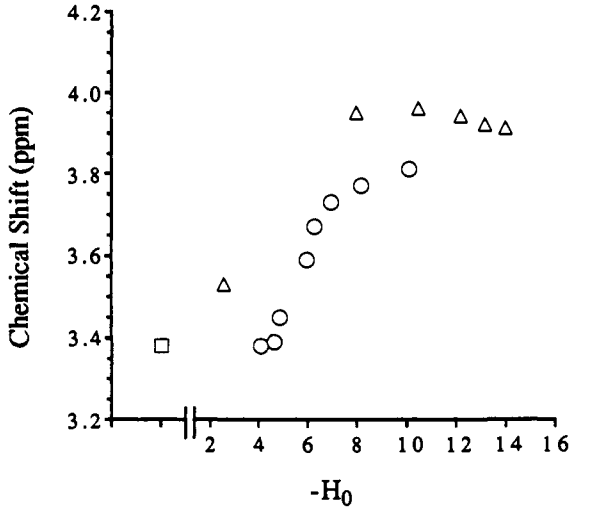

Figure 4. 4. The protonation of **1a** detected by NMR spectroscopy in TFSA–TFE (○), TFSA–TFA (△), and in TFE (□) solutions.

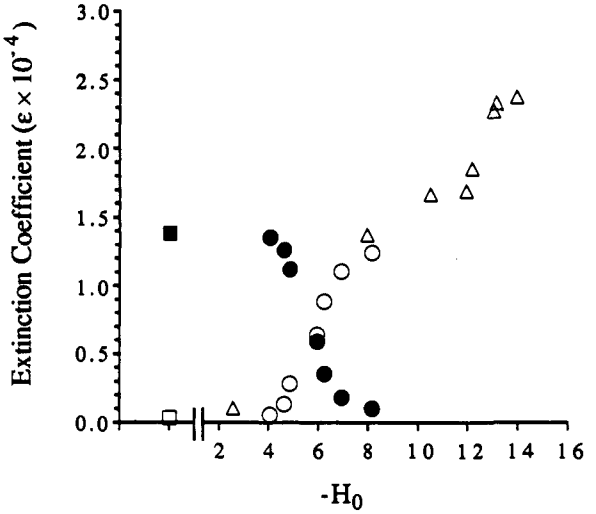

Figure 5. 5. Protonation of **1a** detected by UV absorption measurement in TFSA–TFE (○, 304 nm, ●, 245 nm), TFSA–TFA (△, 304 nm), and in TFE (□, 304 nm, ■, 245 nm) solutions.

(**1**, 1 mmol). After the ketone had dissolved, the solution was heated to 80 °C for an appropriate period, and then the whole was poured into a large excess of iced water (500 mL) and extracted with *n*-hexane (200 mL). The organic layer was washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The residue was purified by flash column chromatography (*n*-hexane and/or AcOEt–*n*-hexane 1:10).

3-Phenyl-1*H*-indene (2a): colorless oil (molecular distillation 30 °C/2 mmHg) (lit.[30] oil); ^{1}H NMR 3.50 (d, 2 H, 2.2 Hz), 6.58 (t, 1 H, 2.2 Hz), 7.25 (t, 1 H, 7.5 Hz), 7.32 (t, 1 H, 7.5 Hz), 7.36 (tt, 1 H, 7.3, 1.7 Hz), 7.45 (t, 2 H, 7.3 Hz), 7.6 (m, 3 H). Anal. Calcd for $C_{15}H_{12}$: C, 93.71; H, 6.29. Found: C, 93.45; H, 6.44.

3-(4-Methylphenyl)-1*H*-indene (2b) mp 33.5–34.5 °C, colorless powder (sublimation 60 °C/4 mmHg) (lit.[31] oil); ^{1}H NMR 2.41 (s, 3 H), 3.50 (d, 2 H, 2.2 Hz), 6.55 (t, 1 H, 2.2 Hz), 7.2 (m, 3 H), 7.32 (t, 1 H, 7.2 Hz), 7.50 (d, 2H, 8.1 Hz), 7.53 (d, 1 H, 7.3 Hz), 7.59 (d, 1 H, 7.7 Hz). Anal. Calcd for $C_{16}H_{14}$: C, 93.16; H, 6.84. Found: C, 93.21; H, 6.86.

3-(4-Chlorophenyl)-1*H*-indene (2c) mp 62 °C, colorless powder (sublimation 45 °C/1 mmHg) (lit.[32] 60–62 °C); ^{1}H NMR 3.51 (d, 2 H, 2.2Hz), 6.58 (t, 1 H, 2.2 Hz), 7.27 (t, 1 H, 7.3 Hz), 7.33

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(d, 1 H, 7.5 Hz), 7.42 (dt, 2 H, 8.4, 2.2 Hz), 7.5–7.6 (m, 4 H). Anal. Calcd for $C_{16}H_{11}Cl$: C, 79.47; H, 4.89. Found: C, 79.47; H, 4.89. Found: C, 79.20; H, 4.91.

3-(4-(Trifluoromethyl)phenyl)-1*H*-indene (2d): mp 60 °C, colorless powder (sublimation 45 °C/1 mmHg); ^{1}H NMR 3.55 (d, 2 H, 1.8 Hz), 6.66 (t, 1 H, 2.2 Hz), 7.29 (t, 1 H, 7.7 Hz), 7.35 (t, 1 H, 7.5 Hz), 7.5–7.6 (m, 2 H), 7.71 (s, 4 H). Anal. Calcd for $C_{16}H_{11}F_3$: C, 73.62; H, 4.55. Found: C,73.45; H, 4.26.

5-Methyl-3-phenyl-1*H*-indene (2e): mp 44 °C, colorless powder (sublimation 55 °C/1 mmHg); ^{1}H NMR 2.41 (s, 3 H), 3.47 (d, 2 H, 2.2 Hz), 6.56 (t, 1 H, 2.2 Hz), 7.08 (d, 1 H, 7.7 Hz), 7.4 (m, 2 H), 7.42 (d, 1 H, 7.7 Hz), 7.46 (t, 2 H, 7.4 Hz), 7.60 (d, 2 H, 7.0 Hz). Anal. Calcd for $C_{16}H_{14}$: C, 93.16; H, 6.84. Found: C, 93.28; H, 6.81.

Kinetics. To a mixture of acids (10 mL, 1000 equiv) was added the ketone (ca. 0.11 mmol). After the ketone had dissolved, 1 mL aliquots of the solution were transferred into test tubes, which were sealed and heated to 80 ± 0.05 °C. At regular intervals, a tube was cooled in iced water, and kept cool (−20 °C). After the sampling was completed, the solution was transferred into an NMR tube, and the spectrum was digitally recorded. The spectrum was expanded or reduced adequately to integrate the signal (benzyl position) of **1** and the signal of the acid. The integrated value of the acid peak could be used as a sufficiently good internal standard for the integrated values of **1**.

Spectrophotometric Titrations. The solutions for spectrophotometric measurements for the determination of pK_{BH}^+ were prepared as reported by Gillespie et al.[33] Ketone concentration was kept at 0.1 M for NMR observations. Typical titration data obtained are illustrated in Figures 2–5.[34]

(33) Gillespie, R. J.; Peel, T. E.; Robinson, E. A. *J. Am. Chem. Soc.* **1971**, *93*, 5083–5087.

(34) In TFSA–TFA solution, the extinction coefficient seemed to increase in highly acidic reagion (see Figures 3 and 5). As described before, the extinction coefficient (ϵ) of the λ_{max} of the protonated ketone in TFSA was used for UV measurement. The λ_{max} of the protonated ketone will be affected by the composition of the solvent, and the change of the extinction coefficient may partly be attributed to this effect.