

Ketene-Forming Eliminations from Aryl Phenylacetates Promoted by R₂NH/R₂NH₂⁺ in Aqueous MeCN. Mechanistic Borderline between E2 and E1cb

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Elimination reactions of $2-X-4-NO_2C_6H_3CH_2C(O)OC_6H_3-2-Y-4-NO_2$ [X = H (1), NO₂ (2)] promoted by $R_2NH/R_2NH_2^+$ in 70 mol % MeCN(aq) have been studied kinetically. The base-promoted eliminations from 1 proceeded by the E2 mechanism when Y = Cl, CF_3 , and NO_2 . The mechanism changed to the competing E2 and E1cb mechanisms by the poorer leaving groups (Y = H, OMe) and to the E1cb extreme by the strongly electron-withdrawing β -aryl group (**2**, **X** = NO₂). The values of $\beta = 0.14$ and $|\beta_{lg}| = 0.10 - 0.21$ calculated for elimination from **1** (Y = NO₂) indicate a reactantlike transition state with small extents of proton transfer and C_{α} –OAr bond cleavage. The extent of proton transfer increased with a poorer leaving group, and the degree of leaving group bond cleavage increased with a weaker base. Also, the changes in the k_1 and k_{-1}/k_2 values with the reactant structure variation are consistent with the E1cb mechanism. From these results, a plausible pathway of the change of the mechanism from E2 to the E1cb extreme is proposed.

Introduction

One of the most interesting problems in elimination reaction is the mechanistic borderline.^{1–8} There are two possibilities by which the mechanism changes from one to another. The first is the "merging" of the transition states. The change in the mechanism from E2 to E1cb in eliminations from (2-arylethyl)ammonium ions³ and 9-(2-chloro-2-propyl)fluorene⁴ has been concluded to be of this type. It has been argued that it would be difficult for the energy maximum of the E2 mechanism and an energy well of the E1cb mechanism to coexist for a single compound at almost the same position on the energy diagram, and the "merging" becomes the favored alternative. On the other hand, if the energies of transition states for the competing reactions are similar, and if the positions of the transition states are significantly different, they should be able to coexist. Under this condition, the mechanism change could occur via a competing mechanism. Clear evidence in favor of concurrent E2 and

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E1 mechanisms has been reported for the MeONapromoted eliminations from 2-chloro-2-methyl-1-phenylpropane⁵ and *N*-(arylsulfonoxy)-*N*-alkylbenzylamine,⁶ as well as the solvolytic elimination of 9-(1-X-ethyl)fluorene.7

Recently, we have initiated a series of investigation on the ketene-forming elimination reactions to gain an insight into the E2 and E1cb borderline.⁹⁻¹¹ It is well established that the base-catalyzed hydrolysis of aryl p-nitrophenylacetates and other activated esters proceed by an E1cb mechanism to afford the ketene intermediate followed by the addition of water under various conditions.^{12–25} When the reaction condition was changed from OH⁻ in

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 $\rm H_2O$ to $\rm R_2NH$ in MeCN the reaction proceeded by the E2 mechanism via an E1cb-like transition state.^{9–11} Curved Hammett plots observed in this study were attributed to the highly carbanionic transition state.¹¹ Competing E2 and E1cb mechanisms were noted in eliminations from *p*-nitrophenyl *p*-nitrophenylacetates promoted by $\rm R_2$ -NH/R₂NH₂⁺ in 70 mol % MeCN(aq).⁹ By comparing with the literature data, it was concluded that the mechanism change could occur via the competing stage. However, it was not unambiguously established that the latter was indeed the intermediate stage between the two mechanisms.

To further expand our understanding on the E2 and E1cb borderline, we have investigated the reactions of aryl aryl acetates (1 and 2) with $R_2NH/R_2NH_2^+$ in 70 mol % MeCN(aq) (eq 1). The reaction mechanism and struc-



ture-reactivity relationship of the ketene-forming eliminations have been determined. Here we report that (i) elimination reactions from 1c-e proceed by the E2 mechanism, (ii) the mechanism changes to a competing E2 and E1cb mechanism by the change in the leaving group to a poorer one (1a and 1b) and (iii) to the E1cb extreme by a strongly electron-withdrawing β -aryl group (2a). This result provides the first unambiguous evidence that the elimination reaction mechanism changes gradually from E2 to E1cb via the concurrent mechanism by the systematic change of the reactant structure.

Results

Aryl *p*-nitrophenylacetates (**1**) were synthesized by the reaction between *p*-nitrophenylacetic acid, substituted phenols, 2-chloro-1-methylpyridinum iodide, and Et₃N in CH₂Cl₂ as reported previously.^{9–11,25} 4-Nitrophenyl 2,4-dinitrophenyl acetate (**2a**) was prepared by reacting 2,4-dinitrophenylacetyl chloride with 1 equiv of the sodium 4-nitrophenoxide in CH₂Cl₂ by the literature procedure.²⁶ The spectral and analytical data for the compounds were consistent with the proposed structures.

The product of the reaction between **1a** and i-Pr₂NH/ i-Pr₂NH₂⁺ in 70 mol % MeCN(aq) was previously identified as *N*,*N*-diisopropylbenzamide and *p*-nitrophenoxide.⁹ Similarly, *N*,*N*-diisobutyl-2,4-dinitrobenzamide was obtained as the only product from the reaction of **2a** *i*-Bu₂-NH/*i*-Bu₂NH₂⁺ in 70 mol % MeCN(aq). For elimination reactions from **1a**–**e** and **2a**, the yields of the aryloxides as determined by comparison of the UV absorption of the infinity sample of the kinetic runs with those of the authentic samples were in the range 93–99%. The possibility of a competing aminolysis had been ruled out as previously reported.⁹

TABLE 1. Rate Constants for Ketene-Forming Eliminations from $4-NO_2C_6H_4CH_2CO_2C_6H_3$ -2-Y- $4-NO_2^a$ Promoted by $R_2NH/R_2NH_2^+$ in 70 mol % MeCN(aq) at 25.0 $^{\circ}C^{b,c}$

		$k_2^{\rm E}$, M ⁻¹ s ^{-1 f,g}				
R_2NH^d	pKa ^e	1a ^h	1b ^h	1c	1d	1e
Bz(<i>i</i> -Pr)NH <i>i</i> -Bu ₂ NH <i>i</i> -Pr ₂ NH 2,6-DMP ^{<i>i</i>}	16.8 18.2 18.6 18.9	0.170 ^{<i>i</i>} 0.530 1.77	0.130 0.390 1.15	15.5 34.8 30.9 52.1	27.1 60.4 45.0 70.9	43.6 70.1 61.0 85.8

^{*a*} [Substrate] = 4.0×10^{-5} M. ^{*b*} [R₂NH]/[R₂NH₂⁺] = $1.0. {}^{c} \mu = 0.10$ M (Bu₄N⁺Br⁻). ^{*d*} [R₂NH] = 9.6×10^{-4} to 6.0×10^{-2} M. ^{*e*} Reference 9. ^{*f*} Average of three or more rate constants. ^{*g*} Estimated uncertainty, $\pm 5\%$. ^{*h*} Calculated from the k_{obs} by using eq 2. ^{*i*} $k_2^{E} = 0.160$ and 0.230 M⁻¹ s⁻¹when [R₂NH]/[R₂NH₂⁺] = 0.5 and 2.0, respectively. ^{*j*} *cis*-2,6-Dimethylpiperidine.

The rates of elimination reactions were followed by monitoring the increase in the absorption at the λ_{max} for the aryloxides in the range of 400-434 nm. In all cases, the ionic strength was maintained to be 0.10 M with Bu₄N⁺Br⁻. Excellent pseudo-first-order kinetics plots, which covered at least three half-lives, were obtained. The rate constants are summarized in Tables S1-6 in Supporting Information. The plots of k_{obs} versus base concentration for the reaction of 1c were straight lines passing through the origin (Figures 1 and S1). This result indicates that (i) the reaction is overall second order, first order to the substrate and first order to the base concentration, (ii) OH⁻⁻ or solvent-promoted elimination does not contribute to the observed rates, (iii) the slopes of the straight lines are the overall second-order rate constants k_2^{E} . Hence, the rate constants for the basepromoted eliminations from 1d and 1e were determined at a single base concentration (Table S2). The k_2^{E} values were obtained by dividing the k_{obs} by the base concentration. Values of k_2^{E} for eliminations from 1c-e are summarized in Table 1. Except for the rate data determined with *i*-Pr₂NH, the rate increased with the basicity and the leaving group ability. The slower rate of eliminations from 1c-e with *i*-Pr₂NH than with *i*-Bu₂NH as the base can be attributed to the greater steric requirement of the former. On the other hand, the same plot for the reaction of **2a** showed a saturation curve typical for the E1cb mechanism. The rate data showed excellent correlation with eq 2 when fitted without the first term.



Figure 1 shows the plots of k_{obs} versus base concentration for the elimination reactions of **1c** and **2a** with Bz(*i*-Pr)-NH/Bz(*i*-Pr)NH₂⁺ in 70 mol % MeCN(aq). Similar plots were obtained for the reactions of **1c** and **2a** with other bases (Figures S1,2).

In contract to the reactions of **1c** and **2a**, the plots of k_{obs} versus base concentration for the reactions of **1a** and **1b** were curves at low base concentration but became straight lines at higher base concentration. A typical

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FIGURE 1. Plots of k_{obs} versus base concentration for eliminations from 4-NO₂C₆H₄CH₂CO₂C₆H₃-2-Cl-4-NO₂ (**1c**, \blacksquare) and 2,4-(NO₂)₂C₆H₃CH₂CO₂C₆H₄-4-NO₂ (**2a**, \bullet) promoted by Bz(*i*-Pr)NH/Bz(*i*-Pr)NH₂⁺ in 70 mol % MeCN(aq) at 25.0 °C, [Bz(*i*-Pr)NH]/[Bz(*i*-Pr)NH₂⁺] = 1.0, $\mu = 0.10$ M (Bu₄N⁺Br⁻).



FIGURE 2. Plot of k_{obs} versus base concentration for eliminations from 4-NO₂C₆H₄CH₂CO₂C₆H₄-4-NO₂ (**1a**) promoted by Bz(*i*-Pr)NH/Bz(*i*-Pr)NH₂⁺ in 70 mol % MeCN(aq) at 25.0 °C, [Bz(*i*-Pr)NH]/[Bz(*i*-Pr)NH₂⁺] = 1.0, $\mu = 0.10$ M (Bu₄N⁺Br⁻). The closed circles are the experimental data, and the solid line shows the computer fitted curve by using eq 2 (see text). The curve is dissected into the E2 and E1cb reaction components (dashed lines).

plot of k_{obs} versus base concentration for the reaction of **1a** with Bz(*i*-Pr)NH/Bz(*i*-Pr)NH₂⁺ in 70 mol % MeCN-(aq) is shown in Figure 2. The possibility of the buffer association as the cause of the curvature was ruled out by the straight lines observed in the plot of k_{obs} versus base concentration for the reaction of **1c** (vide supra). Also, the possibility that the salt effect may have caused the steady increase in the k_{obs} at higher base concentration is negated because the ionic strength is maintained to be 0.10 M with Bu₄N⁺Br⁻. Hence the data were analyzed with a nonlinear regression analysis program by assuming that the reaction proceeds by concurrent E2 and E1cb mechanisms.²⁷ By utilizing the computer

TABLE 2. k_1 and k_{-1}/k_2 for Elimination from 2-X-4-NO₂C₆H₃CH₂CO₂C₆H₃-2-Y-4-NO₂^{*a*} Promoted by R₂NH/R₂NH₂⁺ in 70 mol % MeCN(aq) 25.0 °C^{*b,c*}

	k_1 , M ⁻¹ s ⁻¹ e			k_{-1}/k_2 , M ⁻¹ ^e		
$\mathbf{R}_2 \mathbf{N} \mathbf{H}^d$	1a	1b	2a	1a	1b	2a
Bz(<i>i</i> -Pr)NH <i>i</i> -Bu ₂ NH 2,6-DMP ^h	11.7 ^f 20.2 31.1	8.10 16.3 22.8	52.3 68.8 92.0	560 ^g 225 56.0	677 327 73.5	1187 289 133

^{*a*} [Substrate] = 4.0 × 10⁻⁵ M. ^{*b*} [R₂NH]/[R₂NH₂⁺] = 1.0 except otherwise noted. ^{*c*} μ = 0.10 M (Bu₄N⁺Br⁻). ^{*d*} [R₂NH] = 9.6 × 10⁻⁴ to 6.0 × 10⁻² M. ^{*e*} Calculated from the k_{obs} by using eq 2. ^{*f*} k_1 = 11.7 and 10.9 M⁻¹ s⁻¹ when [R₂NH]/[R₂NH₂⁺] = 0.5 and 2.0, respectively. ^{*g*} k_{-1}/k_2 = 551 and 536 M⁻¹ when [R₂NH]/[R₂NH₂⁺] = 0.5 and 2.0, respectively. ^{*h*} *cis*-2,6-Dimethylpiperidine.

program, the k_2^{E} , k_1 , and k_{-1}/k_2 values that best fit with eq 2 were calculated, and the plots were dissected into the E2 and E1cb components. Figure 2 shows that the correlation between the calculated and the experimental data is excellent, indicating the reliability of this kinetic analysis. To assess the effect of buffer ratio, the k_{obs} values for the ketene-forming eliminations from 1a have been measured at $Bz(i-Pr)NH/Bz(i-Pr)NH_2^+ = 0.5$ and 2.0, respectively (Table S5). When Bz(i-Pr)NH/Bz(i-Pr)- $NH_2^+ = 0.5$, the k_{obs} were determined up to [base] = 0.03 M because of the limited solubility. At a given base concentration, the k_{obs} increases gradually as the buffer ratio is changed from 0.5 to 1.0 to 2.0, as expected from eq 2 (Tables S4 and S5). In both cases, the rate data showed excellent correlations with eq 2 (Figures S3 and S4). Similar correlation was obtained for the reactions of **1a**-**b** with other buffer systems (Figures S5-9). These results provide additional evidence in support of the kinetic analysis given above. However, the rate data for the reactions of **1a**, **1b**, and **2a** promoted by i-Pr₂NH/i- $Pr_2NH_2^+$ were not included in the analysis because of the complications due to the steric effect (vide supra). Calculated values of k_2^{E} , k_1 , and k_{-1}/k_2 for the eliminations from 1a, 1b, and 2a are summarized in Tables 1 and 2. Except for the slightly larger k_2^{E} calculated at [B]/[BH⁺] = 2.0, the values of k_2^{E} , k_1 , and k_{-1}/k_2 for the Bz(*i*-Pr)-NH-promoted eliminations from 1a are nearly the same at all buffer ratios (Tables 1 and 2).

The k_2^{E} values for eliminations from **1a**–**e** showed good correlation with the p K_a values of the promoting bases on the Brönsted plot (Figure 3). The β values are in the range of 0.14–0.47 and increase as the leaving group ability of the aryloxide decreases (Table 3). Values of both k_1 and k_{-1}/k_2 increased as the electron-withdrawing ability of the β -aryl group increased (Table 2). On the other hand, the k_1 increased and k_{-1}/k_2 decreased with a stronger base and a sterically less hindered leaving group.

The plots of the k_2^{E} values for $\mathbf{1a}-\mathbf{e}$ against the pK_{lg} values of the leaving group are depicted in Figure 4. The rate data showed good correlations on the straight lines, if the data for $\mathbf{1a}$, **b** were excluded. Therefore, the β_{lg} values were calculated from the straight lines without the date for $\mathbf{1a}$, **b**. The $|\beta_{lg}|$ values are in the range 0.21-0.10 and decrease as the pK_a value of the base increases (Table 4).

To provide additional evidence for the competing E1cb mechanism, the H–D exchange experiment was carried

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FIGURE 3. Brönsted plots for the ketene-forming eliminations from 4-NO₂C₆H₄CH₂CO₂C₆H₃-2-Y-4-NO₂ promoted by R₂-NH/R₂NH₂⁺ in 70 mol % MeCN(aq) at 25.0 °C, [R₂NH]/ $[R_2NH_2^+] = 1.0, \mu = 0.10 \text{ M} (Bu_4N^+Br^-). Y = H (1a, \blacksquare), OMe$ (1b, ●), Cl (1c, \blacktriangle), CF₃ (1d, \checkmark), NO₂ (1e, ♦).

TABLE 3. Brönsted β Values for Elimination from 4-NO₂C₆H₄CH₂CO₂C₆H₃-2-Y-4-NO₂ Promoted by R₂NH/ $R_2NH_2^+$ in 70 mol % MeCN(aq) at 25.0 °C^{a,b}

	1a	1b	1c	1d	1e
$\overline{ \substack{ \mathbf{p} \mathbf{K}_{\mathrm{lg}}^c \ eta } }_{eta}$	$\begin{array}{c} \textbf{20.7} \\ \textbf{0.47} \pm \textbf{0.01}^{d} \end{array}$	$\begin{array}{c} \textbf{20.6} \\ \textbf{0.44} \pm \textbf{0.08}^d \end{array}$	$\begin{array}{c} 18.1\\ 0.25\pm0.01\end{array}$	$\begin{array}{c} 17.0\\ 0.21\pm0.04\end{array}$	$\begin{array}{c} 16.0\\ 0.14\pm0.01\end{array}$

^{*a*} $[R_2NH]/[R_2NH_2^+] = 1.0$. ^{*b*} $\mu = 0.10$ M (Bu₄N⁺Br⁻). ^{*c*} Reference 30. $d_{k_2}^{E}$ values calculated from the k_{obs} by using eq 2 have been used.

out by mixing **1a** and **2a** with *i*-Bu₂NH/*i*-Bu₂NH₂⁺ in 70 mol % MeCN-30% D₂O at -10 °C. The reactant was recovered immediately after mixing. The NMR spectrum indicated that approximately 30% of benzylic C-H bond of **1a** was converted to the C–D bond. On the other hand, **2a** underwent complete H–D exchange.

Discussion

Mechanism of Eliminations from 1c-e and 2a. Results of kinetic investigations and product studies reveal that the reactions of 1c-e with $R_2NH-R_2NH_2^+$ in 70 mol % MeCN(aq) proceed by the E2 mechanism.^{1,2,28,29} The reactions produced only elimination products and exhibited second-order kinetics, negating all but bimolecular elimination pathways. The $(E1cb)_{R}$, (E1cb)_{ip}, and internal return mechanisms are ruled out by the observed general base catalysis with the Brönsted β values ranging from 0.14 to 0.25 because these mechanisms would exhibit either a specific base catalysis or Brönsted β values near unity.¹ In addition, the possibility that the relatively small values of $|\beta_{lg}| = 0.21 - 0.10$ might be due to the $(E1cb)_{\rm irr}$ mechanism $^{\rm 29}$ is negated by the interaction coefficients, i.e., $p_{xy} = \partial \beta / \partial \mathbf{p} K_{\text{lg}} = \partial \beta_{\text{lg}} / \partial \mathbf{p} K_{\text{BH}}$ > 0 (vide infra). On the other hand, the results are



FIGURE 4. Plots of log k_2^{E} versus pK_{lg} values of the leaving group for eliminations reactions of 4-NO₂C₆H₄CH₂CO₂C₆H₃-2-Y-4-NO₂ (1a-e) promoted by R₂NH/R₂NH₂⁺ in 70 mol % MeCN(aq) at 25.0 °C, $[R_2NH]/[R_2NH_2^+] = 1.0$, $\mu = 0.10$ M $(Bu_4N^+Br^-)$. $R_2NH = Bz(i-Pr)NH$ (\blacksquare), $i-Bu_2NH(\bullet)$, 2,6-DMP-(▲).

TABLE 4. β_{lg} for Elimination from $4-NO_2C_6H_4CH_2CO_2C_6H_3-2-Y-4-NO_2$ (1a-e) Promoted by R₂NH/R₂NH₂⁺ in 70 mol % MeCN(aq) at 25.0 °C^{a,b}

		R_2NH			
	Bz(<i>i</i> -Pr)NH	<i>i</i> -Bu ₂ NH	2,6-DMP ^c		
$\beta_{ m lg}$	-0.21 ± 0.01	-0.15 ± 0.04	$-0.10{\pm}~0.01$		
a [R ₂ NH]/[R ₂ NH ₂ ⁺] = 1.0. $^{b}\mu$ = 0.10 M (Bu ₄ N ⁺ Br ⁻). c cis-2,6 Dimethylpiperidine.					

consistent with an E2 mechanism in which there is partial cleavage of the C_{β} -H and C_{α} -OAr bonds in the transition state.

In contrast to the reactions of 1c-e, the plots of the $k_{\rm obs}$ versus the base concentration for the elimination reaction of **2a** with $R_2NH/R_2NH_2^+$ showed saturation curves, reaching at a plateau at [base] > 0.01 M (Figure 1). The result can most reasonably be explained with an E1cb mechanism, i.e., $k_{obs} = k_1 k_2 [B] / (k_{-1} [BH^+] + k_2)$.¹ This predicts that the plot of k_{obs} should change from a straight line at a low base concentration, i.e., $k_{obs} = k_1[B]$ when $k_{-1}[BH^+] \ll k_2$, to a plateau at a higher base concentration, i.e., $k_{obs} = k_1 k_2 / k_{-1}$ when $k_{-1} [BH^+] \gg k_2$. The excellent agreement between the experimental data and the theoretically fitted curve provides strong evidence for this mechanism (Figures 1 and S2). Moreover, the calculated k_1 and k_{-1}/k_2 values are consistent with the trends observed for 1a and 1b (vide infra). Finally, the NMR spectrum of the recovered reactant for the reaction of **2a** with *i*-Bu₂NH/*i*-Bu₂NH₂⁺ in 70 mol % D₂O in MeCN indicated complete absence of the benzylic C-H bond at δ 4.43, providing additional support for this mechanism.

Mechanism of Eliminations from 1a,b. The plots of the k_{obs} values for eliminations from **1a** and **1b** against base concentration are curves at low buffer concentration

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and become straight lines at [base] > 0.01 M (Figures 2 and S3-9). This result cannot be explained with the change in the rate-limiting step because the rate should have reached a plateau at a higher base concentration in such a case (vide supra). In contrast, the rate data can readily be explained if one assumes that the reactions proceed by the concurrent E2 and E1cb mechanisms, i.e., $k_{\text{obs}} = k_2^{\text{E}} + k_1 k_2 [\text{B}] / (k_{-1} [\text{BH}^+] + k_2)$ (eq 2). As shown in Figures 2 and S3-9, all of the rate data for the reactions of **1a,b** with $R_2NH/R_2NH_2^+$ show excellent correlation with eq 2. Note that the shapes of the dissected lines are typical for the E2 and E1cb mechanisms. In addition, the k_{obs} values for the reactions of **1a** with Bz(*i*-Bu)NH/Bz- $(i-Bu)NH_2^+$ increases gradually with the change in the buffer ratio from 0.5 to 1.0 to 2.0, as expected from eq 2 (Tables S4 and S5).

The calculated rate constants for the E2 and E1cb pathways provide additional support for this mechanism. (i) The $k_2^{\rm E}$, k_1 , and k_{-1}/k_2 values for the reactions of **1a** with Bz(*i*-Bu)NH/Bz(*i*-Bu)NH₂⁺ are very similar regardless of the buffer ratio, indicating that the same mechanism is operating under these conditions (Tables 1 and 2). (ii) The k_2^{E} values for **1a** and **1b** nicely fit in the trend observed for 1c-e, i.e., the k_2^E of 1a-e increase gradually with a stronger base and a better leaving group (Table 1). The only exception to this trend is the larger k_2^{E} of 1a compared to that of 1b, which may be attributed to the leaving group steric effect. Because the p-nitrophenoxide in 1a is the only leaving group without an ortho substituent, it should be sterically less hindered than other substrates in the series, to increase the rate.¹¹ (iii) The observed increase in the k_1 with a stronger base and a more acidic benzylic C-H bond (2a), as well as a small decrease in the k_1 with the leaving group steric effect (1b), is consistent with what would be expected for the deprotonation step (Table 2). (iv) The increase of the k_{-1} / k_2 values in the order $\mathbf{1a} < \mathbf{1b} < \mathbf{2a}$ is also consistent (Table 2). If the k_1 of **1b** is smaller than that of **1a**, the k_{-1} of **1b** should be larger than that of **1a**. On the other hand, the values of k_2 for **1a** and **1b** are expected to be similar because a fraction of the difference in the leaving group pK_{lg} values ($\Delta pK_{lg} = 0.1$) will be reflected in the k₂. Also, the *ortho* nitro group is expected to stabilize the carbanion intermediate to increase k_{-1} and decrease k_2 of **2a**, and this effect should be much larger for k_{-1} than k_2 because the second step involves a higher energy barrier. A combination of these factors would be to increase the k_{-1}/k_2 values in the order **1a** < **1b** < **2a**, as observed. (v) The increase in the k_{-1}/k_2 ratio with a weaker base can also be explained similarly (Table 2). The k_{-1} should increase with the acidity of $R_2NH_2^+$, although little change is expected for k_2 by the base strength variation. This predicts an increase in the k_{-1} / k_2 ratio with a weaker base.

The NMR spectrum of the recovered reactant from the reaction of **1a** with *i*-Bu₂NH/*i*-Bu₂NH₂⁺ in 70 mol % MeCN-30% D₂O at -10 °C indicated that approximately 30% of the benzylic C–H bond underwent H–D exchange. All of these results provide strong evidence that eliminations from **1a,b** promoted by R₂NH/R₂NH₂⁺ in 70 mol % MeCN(aq) proceed by the concurrent E2 and E1cb mechanism. ^{1,29}

It should be noted that the k_2^E values for **1a,b** show large negative deviations in Figure 4. This result indi-

cates that the transition state structures for 1a,b do not fit in the trends observed for 1c,e. Although the values of $|\beta_{lg}|$ for **1a,b** are not available, the negative deviation could be explained if the extents of C_{α} –OAr bond cleavage are assumed to be smaller than those of 1c-e. The transition state would then be destabilized as a result of the difficulty associated with the charge transfer from the β - to the α -carbon, to decrease the degree of double bond character and the rate. Also, a close examination of Table 3 reveals that the Brönsted β values increase abruptly from 0.14-0.25 to 0.44-0.47 as the substrate structures are changed from **1c**–**e** to **1a**,**b**, indicating a sharp increase in the extent of proton transfer. These results seem to indicate that the transition state structures for the E2 pathway of the buffer-promoted eliminations from **1a**,**b** are more E1cb-like with greater extent of proton transfer and limited degree of the leaving group bond cleavage, compared with 1c-e.

Effect of Bu₄N⁺Br⁻ on the Elimination from 1a. The relative rates of the E2 and E1cb pathways of the elimination reactions of **1a** change dramatically by the addition of Bu₄N⁺Br⁻. Figure 2 shows that the rate of E1cb reaction is always faster than the E2 reaction in the presence of Bu₄N⁺Br⁻ for all concentration ranges employed in this study. In contrast, when the reaction was carried out without Bu₄N⁺Br⁻, the E1cb reaction was faster when [base] < 0.02 M, after which the E2 reaction became the major reaction pathway.9 The faster rate of the E1cb reaction in the presence of $Bu_4N^+Br^-$ can be attributed to the salt effect. As the ionic strength is increased by the addition of $Bu_4N^+Br^-$, the dipolar ionic atmosphere would stabilize the anionic E1cb transition state more than the E2 transition state, which would in turn result in a preferential enhancement of the E1cb rate.

The structures of E2 transition states are also changed by the Bu₄N⁺Br⁻. Comparison with earlier results reveals that the Brönsted β and $|\beta_{1g}|$ values decrease from 0.66 to 0.47 and 0.26 to 0.10–0.21, respectively (Tables 3 and 4).⁹ This indicate small decrease in the extents of C_{β}–H and C_{α}–OAr bonds in the presence of Bu₄N⁺Br⁻.

Mapping of the E2 Transition State. The structures of the E2 transition states may be assessed by the Brönsted β and $|\beta_{lg}|$ values. The Brönsted β values indicate the extent of proton transfer in the transition state. For elimination from **1e**, the value of $\beta = 0.14$ was determined. This indicates a small degree of proton transfer in the transition state. The $|\beta_{lg}|$ values are usually taken as the extent of the leaving group bond cleavage. Hence the observed values of $|\beta_{lg}| = 0.21 - 0.10$ are consistent with limited extent of the C_{α} -OAr bond rupture. The combined results reveal that the keteneforming eliminations from 1e proceed by the E2 mechanism via a reactant-like transition state with limited extents of proton transfer and C_{α} -OAr bond cleavage. Therefore, it seems reasonable to locate the transition state near the right corner of the More-O'Ferall-Jencks diagram (Figure 5).

This conclusion is supported by the interaction coefficients. Table 3 shows that the β values of the k_2^{E} process for **1a**–**e** decrease, as the leaving groups are made less basic. This effect corresponds to a positive p_{xy} interaction coefficient, $p_{xy} = \partial \beta / \partial p K_{\text{lg}}$, which describes the interaction between the base catalyst and the leaving group.^{13,14} The



FIGURE 5. Reaction coordinate diagram for the keteneforming elimination. The effect of the change to a poorer leaving group and a weaker base are shown by the shift of the transition state from A to B and A to C, respectively.

observed increase in the $|\beta_{lg}|$ values as the catalyst is made less basic (Table 4) is another manifestation of this effect, i.e., $p_{xy} = \partial \beta_{lg} / \partial p K_{BH} > 0$. On the More–O'Ferall– Jencks diagram in Figure 5, a change to a poorer leaving group will raise the energy of the bottom edge of diagram shifting the transition state toward the product and the E1cb intermediate. The transition state on the horizontal reaction coordinate will then move toward the left, with more proton transfer and a larger β , as depicted by a shift from A to B on the energy diagram (Figure 5).¹⁻³ Similarly, a weaker base will raise the energy of the left side of the diagram and shift the transition state from A to C to increase in the extent of C_{α} –OAr bond cleavage (Figure 5).^{1–3} The positive p_{xy} coefficients are not consistent with an E1cb mechanisms for which $p_{xy} = 0$ is expected but provide additional support for the concerted E2 mechanism.¹⁻³

Change of the Mechanism. The kinetic results described above clearly indicate that the elimination mechanism changes from E2 to a competing E2 and E1cb to E1cb as the reactant structure is changed from 1c-eto 1a,b to 2a. The most reasonable explanation for this result is as follows. As discussed above, the position of the E2 transition state for the reactions from 1e could be located at A in Figure 5. As the leaving group is made poorer (1c,d), the reactant-like E2 transition state gradually changes to the E1cb-like, as indicated by a shift from A to B (vide supra). When the leaving group ability is further decreased to Y = H and OMe (1a,b), the E2 transition state is destabilized and the E1cb mechanism emerges simultaneously. It is interesting to note that the E2 transition states for eliminations from 1a,b are more E1cb-like than 1c-e (vide supra). Finally, when the carbanion intermediate is stabilized by the strongly electron-withdrawing β -aryl group (**2a**), so that the E2 reaction can no longer compete, the E1cb mechanism becomes the predominant reaction pathway.

As stated in the Introduction, the change of the mechanism from E2 to E1cb could occur by the merging of the transition state, if it is difficult for the energy maximum of the E2 mechanism and an energy well of the E1cb mechanism to coexist for a single compound at almost the same position on the energy diagram.¹⁻⁴ However, if the positions of the transition states are significantly different, they should be able to coexist, as observed in the E2 and E1 borderline.^{5–7} The change in elimination mechanism observed in the present study is concluded to be of this type. Because the E2 transition state is located near the center of the horizontal reaction coordinate, which is far from the position of the E1cb transition state, there seems to be no reason for why the two transition states cannot coexist. Furthermore, the mechanism changes systematically from the concurrent E2 and E1cb mechanisms to E2 as the E2 transition state is stabilized by the better leaving group and to the E1cb extreme when the strongly electron-withdrawing β -aryl group stabilizes the latter transition state. To our knowledge, this is the first example that shows a gradual change in the elimination reaction mechanism from E2 to E1cb via a competing E2 and E1cb mechanism wrought by the systematic variation of the reactant structure.

Experimental Section

Materials. 4-Nitrophenyl *p*-nitrophenylacetate (**1a**) and 2,4dinitrophenyl *p*-nitrophenylacetate (**1e**) were available from previous study.⁹ Aryl *p*-nitrophenylacetates (**1b**–**d**) were prepared from 4-nitrophenylacetic acid and substituted phenols in the presence of Et₃N and 2-chloro-*N*-methylpyridinum iodide as previously reported.⁹ *p*-Nitrophenyl 2,4-dinitrophenylacetate (**2a**) was prepared by treating 2,4-ditrophenylacetyl chloride with 1 equiv of the sodium 4-nitrophenoxide in methylene chloride as previously reported.²⁶ The yield (%), melting points (°C), IR (KBr, C=O, cm⁻¹), NMR (300 MHz, CDCl₃), and combustion analysis data for the new compounds are as follows.

2-Methoxy-4-nitrophenyl *p*-Nitrophenylacetate (1b). Yield 34%; mp 101 °C; IR 1759 (C=O); ¹H NMR δ 3.88 (s, 3H), 4.04 (s, 2H), 7.17 (d, 1H, J = 8.7 Hz), 7.58 (d, 2H, J = 8.7 Hz), 7.83 (d, 1H, J = 2.6 Hz), 7.89 (dd, 1H, J = 8.7, 2.6 Hz), 8.25 (d, 2H, J = 8.7 Hz). Anal. Calcd for C₁₅H₁₂N₂O₇: C, 54.22; H, 3.64; N, 8.43. Found: C, 54.27; H, 3.65; N, 8.36.

2-Chloro-4-nitrophenyl *p***-Nitrophenylacetate (1c).** Yield 29%; mp 128 °C; IR 1764 (C=O); NMR δ 4.09 (s, 2H), 7.33 (d, 1H, J = 8.7 Hz), 7.60 (d, 2H, J = 8.7 Hz), 8.20 (dd, 1H, J = 8.4, 2.7 Hz), 8.28 (d, 2H, J = 8.4 Hz), 8.36 (d, 1H, J = 2.7 Hz). Anal. Calcd for $C_{14}H_9N_2O_6Cl:$ C, 49.94; H, 2.69; N, 8.32. Found: C, 49.90; H, 2.68; N, 8.23.

2-Trifluoromethyl-4-nitrophenyl *p*-Nitrophenylacetate (1d). Yield 25%; mp 131 °C; IR 1765 (C=O); NMR δ 4.08 (s, 2H), 7.49 (d, 1H, J = 8.7 Hz), 7.55 (d, 2H, J = 8.7 Hz), 8.26 (d, 2H, J = 8.7 Hz), 8.45 (dd, 1H, J = 8.7, 2.6 Hz), 8.58 (d, 1H, J = 2.6 Hz). Anal. Calcd for C₁₅H₉N₂O₆F₃: C, 48.66; H, 2.45; N, 7.57. Found: C, 48.67; H, 2.57; N, 7.60.

p-Nitrophenyl 2,4-Dinitrophenylacetate (2a). Yield 32%; mp 136 °C; IR 1759 (C=O); NMR δ 4.43 (s, 2H), 7.30 (d, 2H, J = 8.9 Hz), 7.70 (d, 1H, J = 8.9 Hz), 8.30 (d, 2H, J = 9.3 Hz), 8.54 (dd, 1H, J = 9.3, 2.4 Hz), 9.07 (d,1H, J = 2.4 Hz). Anal. Calcd for C₁₄H₉N₃O₈: C, 48.40; H, 3.67; N, 12.10. Found: C, 48.35; H, 3.55; N, 12.05.

Acetonitrile was purified as described before.⁹ The solutions of $R_2NH/R_2NH_2^+$ in 70 mol % MeCN(aq) were prepared by dissolving equivalent amount of R_2NH and $R_2NH_2^+$ in 70 mol

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% MeCN(aq). In all cases, the ionic strength was maintained to 0.1 M with $Bu_4N^+Br^-.$

Kinetic Studies. Reactions of **1a**–**e** and **2a** with R₂NH/ R₂NH₂⁺ in 70 mol % MeCN(aq) were followed by monitoring the increase in the absorbance of the aryl oxides at 400–434 nm with a UV–vis spectrophotometer as described before.^{9–11} In all cases, the ionic strength was maintained to be 0.10 M with Bu₄N⁺Br⁻.

Calculation of k_2^{E} , k_1 , and k_{-1}/k_2 Values. Utilizing the k_{obs} values and the base concentration, the k_2^{E} , k_1 , and k_{-1}/k_2 values that best fit with eq 2 have been calculated with the Origin program, which is a nonlinear square fitting routine based on the gradient search and function linearization method.²⁷

Product Studies. The product of elimination from **2a** promoted by *i*-Bu₂NH/*i*-Bu₂NH₂⁺ in 70 mol % MeCN(aq) were identified as described previously.^{9–11} From this reactions, *N*,*N*-diisobutyl-2,4-dinitrobenzamide was obtained in 70% yield. Also, the yields of the aryloxides from the reactions of **1a**–**e** and **2a** determined by comparing the UV absorptions of the infinity samples with those for the authentic aryloxides were in the range of 93–99%.

H–D Exchange Experiment. To determine whether **1a** and **2a** may undergo H–D exchange reaction, the substrates (0.19 mmol) were added to *i*·Bu₂NH/*i*·Bu₂NH₂⁺ (0.1 M, 3.4 mL)

in 70 mol % MeCN–30% D₂O at –10 °C. The reaction was quenched, and the reactant was isolated as described before.^{9–11} The proton NMR spectrum of the recovered reactant from **1a** was identical to that of the substrate except that the integration at δ 4.05 decreased by approximately 30%. From the reaction of **2a**, the NMR spectrum of the recovered reactant indicated compete absence of the benzylic proton resonance at δ 4.43.

Control Experiments. The stabilities of 1a-e and 2a were determined as reported earlier.⁹⁻¹¹ They were stable for at least 3 weeks in MeCN solution at room temperature.

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Supporting Information Available: Rate constants for eliminations from **1a**–**e** and **2a** promoted by $R_2NH/R_2NH_2^+$ in 70 mol % MeCN(aq) and plots of k_{obs} versus base concentration. This material is available free of charge via the Internet at http://pubs.acs.org.

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