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## Theoretical Studies on the Gas-Phase Pyrolysis of Carbonate Esters, Hydroxy-Esters and -Ketones<sup>1</sup>

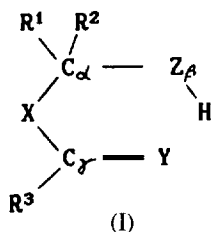
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Gas-phase pyrolyses of carbonate esters,  $\alpha$ - and  $\beta$ -hydroxy esters and  $\beta$ -hydroxy ketones have been studied theoretically by the AM1 MO method. Carbonate esters were found to decompose by two types of processes; in the reaction pathway involving an intermediate, the decomposition of the intermediate was rate-limiting, but direct pyrolyses were also possible *via* a six-membered cyclic transition state in which the methoxy oxygen attacks a hydrogen atom on the  $\beta$ -carbon. The hydroxy esters and ketones were found to decompose in a concerted process involving a six-membered cyclic transition state. Successive methylation on the  $\alpha$ - and  $\gamma$ -carbon led to an increase in the reactivity in agreement with experiments.

### Introduction

In our previous works,<sup>2</sup> we have shown theoretically by the semiempirical MO methods of MNDO and AM1 that the gas-phase pyrolysis of esters, **I** (X, Y=O or S; R<sup>1</sup>, R<sup>2</sup>, R<sup>3</sup>=H or CH<sub>3</sub>; Z=CH<sub>2</sub>) proceeds through a six-membered cyclic transition state (TS) conforming to a concerted process of the retro-ene reaction,<sup>3</sup> which can be conveniently interpreted using the frontier orbital (FMO) theory<sup>4</sup> of three-species interactions.<sup>5</sup> We have explicitly shown that the most impor-



tant step controlling the reactivity is the facility to form a bond between Y and H in **I**, *i.e.*, the ease of nucleophilic attack of Y upon H; this required a greater  $\pi$ -donating ability of the  $\pi$ -HOMO of the donor ( $C_\gamma=Y$ ) and the accepting ability of the  $\sigma^*$ -LUMO of the acceptor ( $C_\alpha-H$ ) for a greater reactivity, the cleavage of the  $C_\alpha-X$  bond being of little importance. These theoretical findings supported in general the mechanism proposed based on extensive experimental studies.<sup>6</sup> However our theoretical analysis provided us with a more detailed and concrete understanding for the cyclic concerted reaction mechanism based on orbital properties of the TS as well as the ground state (GS) of the ester decomposition.

In this work we have extended our theoretical investigations of the gas-phase decomposition mechanism using the AM1 method<sup>7</sup> to carbonate esters (**I** with X, Y=O or S; Z=CH<sub>2</sub>; R<sup>1</sup>, R<sup>2</sup>=H or CH<sub>3</sub>; R<sup>3</sup>=OCH<sub>3</sub>),  $\alpha$ -hydroxy esters (**I** with X, Y=O or S; Z=O; R<sup>1</sup>, R<sup>2</sup>, R<sup>3</sup>=H or CH<sub>3</sub>),  $\beta$ -hydroxy esters (**I** with X=CH<sub>2</sub>; Y=Z=O; R<sup>1</sup>, R<sup>2</sup>=H or CH<sub>3</sub>; R<sup>3</sup>=OCH<sub>3</sub>) and  $\beta$ -hydroxy ketones (**I** with X=CH<sub>2</sub>; Y=Z=O; R<sup>1</sup>, R<sup>2</sup>=H or CH<sub>3</sub>; R<sup>3</sup>=CH<sub>3</sub>).

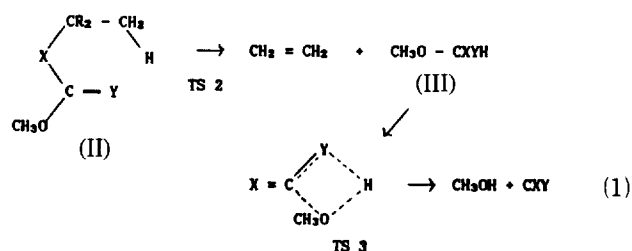
### Calculation

The computations were carried out with AM1.<sup>7</sup> All geometries were fully optimized. Transition states were located by the reaction coordinate method,<sup>8</sup> refined by the gradient norm minimization,<sup>9</sup> and characterized by confirming only one negative eigenvalue in the Hessian matrix.<sup>10</sup>

### Results and Discussion

**Pyrolysis of Carbonate Esters.** Carbonate esters correspond to formate esters with a methoxy group substituted at the  $\gamma$ -carbon.

Two decomposition pathways, (1) and (2), are possible in



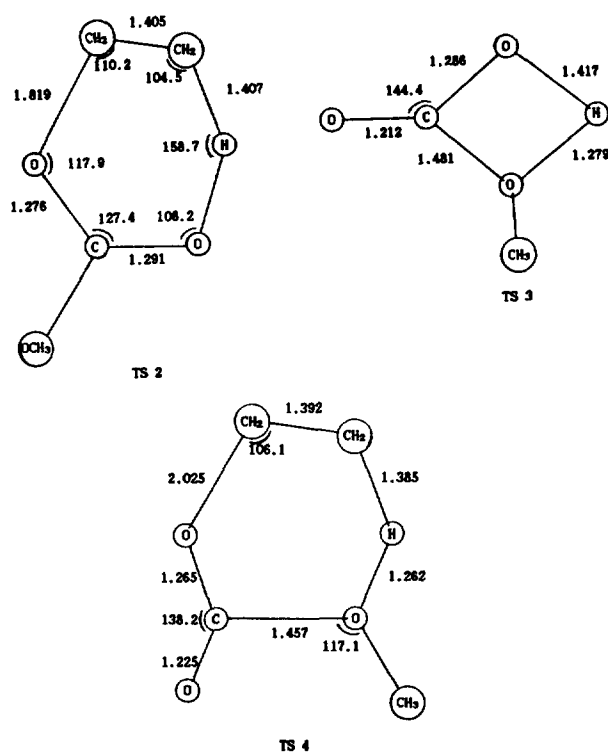
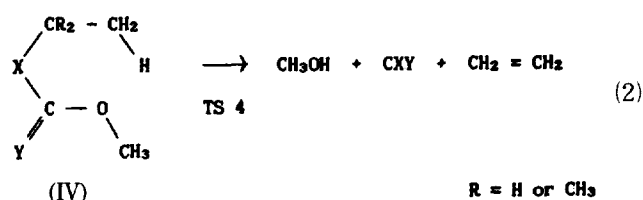


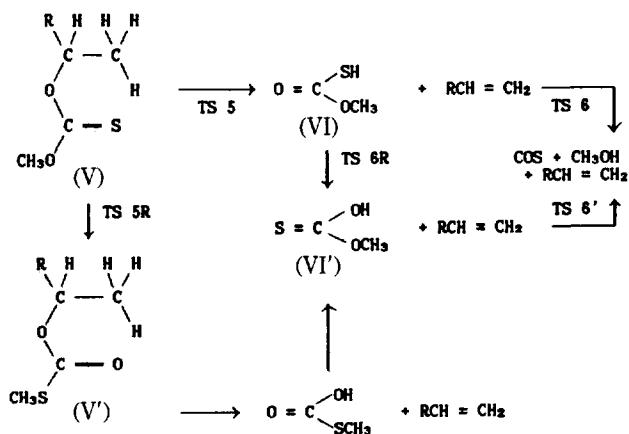
Figure 1. The TS structures for decomposition of carbonate esters (TS 2, TS 3 and TS 4 for X=Y=O).



general, in addition to the decompositions involving rearranged reactants and intermediates depending on X or Y. In both reaction pathways, the TSs had a six-membered cyclic structure, TS 2 and TS 4 but in pathway 1 a four-membered cyclic TS, TS 3, appeared in the second stage of the process after the intermediate formation of  $\text{CH}_3\text{-OCXYH}$ . The representative TS structures are shown for the  $\text{O-C=O}$  compound in Figure 1. The heats of formation of the GS and TS, and the enthalpies of activation are summarized in Table 1 for ethyl ( $\text{R}=\text{H}$ ) and isopropyl ( $\text{R}=\text{CH}_3$ ) carbonate esters. We note that the rate determining step in pathway 1 is the second stage, TS 3, and the reactivity decreases in the order,  $\text{O-C=S} > \text{O-C=O} > \text{S-C=S} > \text{S-C=O}$ ; the reactivity of the  $\text{S-C=S}$  derivative tends to decrease for TS 3 in contrast to TS 2 and the relative reactivity is seen to decrease more for TS 4 becoming the least reactive in the series. Both the TSs, 3 and 4, proceed to form CXY as a product, but the product  $\text{CS}_2$  ( $\text{X}=\text{Y}=\text{S}$ ) is the least stable,<sup>11</sup> so that the TSs leading to this compound ( $\text{CS}_2$ ) are elevated accordingly as shown in Table 1. Thus, even though the barrier heights of the first step, TS 2, predict the reactivity order of  $\text{O-C=S} > \text{S-C=S} > \text{O-C=O} > \text{S-C=O}$ , similarly with as other esters reported previously<sup>2</sup>, the overall reactivity order changes to  $\text{O-C=S} > \text{O-C=O} > \text{S-C=S} > \text{S-C=O}$ . For both carbonate esters ( $\text{R}=\text{H}$  and  $\text{CH}_3$ ), the barrier heights corresponding

Table 1. Heats of Formation ( $\Delta H_f$ ) of Ground (GS) and Transition States (TS) and Activation Enthalpies ( $\Delta H^*$ ) (kcal/mol) for Alkyl Carbonates Decomposition by AM1

R	X	Y		GS	TS2	TS3	TS4
isopro- pyl	O	S	$\Delta H_f$	-68.06	-32.63	-22.48	-3.54
			$\Delta H^*$		35.43	45.58	64.52
	S	S	$\Delta H_f$	-16.70	30.25	50.45	65.66
			$\Delta H^*$		46.95	67.15	82.36
	O	O	$\Delta H_f$	-147.16	-94.31	-81.44	-80.90
			$\Delta H^*$		52.85	65.72	66.26
ethyl	S	O	$\Delta H_f$	-91.33	-31.55	-6.66	-12.12
			$\Delta H^*$		59.78	84.67	79.21
	O	S	$\Delta H_f$	-63.84	-24.02	-12.06	7.57
			$\Delta H^*$		39.82	51.78	71.41
	S	S	$\Delta H_f$	-13.63	36.23	60.87	72.09
			$\Delta H^*$		49.86	74.50	85.72
	O	O	$\Delta H_f$	-143.30	-86.39	-71.02	-71.44
			$\Delta H^*$		56.91	72.28	71.86
	S	O	$\Delta H_f$	-87.65	-26.35	3.76	-6.60
			$\Delta H^*$		61.30	91.41	81.05



Scheme 1.

to the two TSs, TS 3 and TS 4, for  $\text{O-C=O}$  differ little so that the two pathways, 1 and 2, should become competitive. For  $\text{S-C=S}$ , reaction pathway 1 is always favored.

Of the two mixed derivatives, only in the  $\text{O-C=S}$  derivative  $\text{CH}_3$  of the methoxy group on the  $\text{C}_\gamma$  can migrate to form a new rearranged form, ( $\text{V}'$ ), to the carbonyl S atom (Scheme 1). This type of 1,3-methyl group migration makes the decomposition more complex. For  $\text{O-C=S}$ , the following complications can arise (Scheme 1).

We have considered every possibilities and the overall energy profile is shown in Figure 2. The one step mechanism, i.e., pathway 2 through TS 4 is seen to be disfavored by a high activation energy barrier of 64.6 kcal/mol. The 1,3-methyl group rearrangement ( $\text{V} \rightarrow \text{V}'$ ) for  $\text{O-C=S}$  with  $\text{R}=\text{CH}_3$  (i.e., isopropyl derivative) had the activation enthalpy (TS 5R) of 62.5 kcal/mol, which is higher by 17 and 27 kcal/mol than TS 2 and TS 3 respectively, so that the reaction is not likely to proceed through this pathway involving the 1,3-methyl shift. We therefore disregarded the reaction path leading to the products from this rearrange form. Refe-

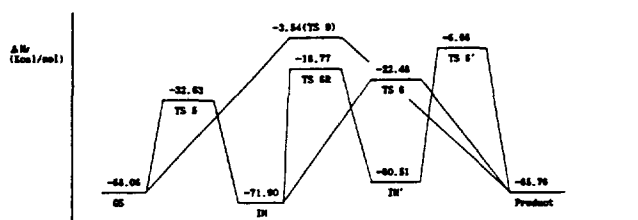
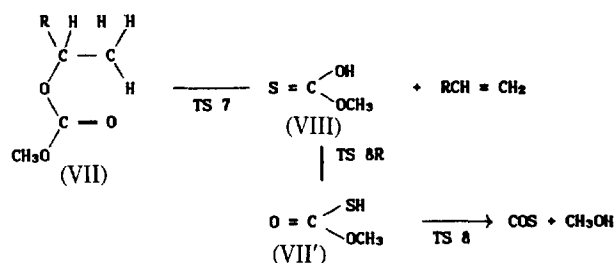


Figure 2. Energy profile of O-isopropyl thiocarbonate decomposition.

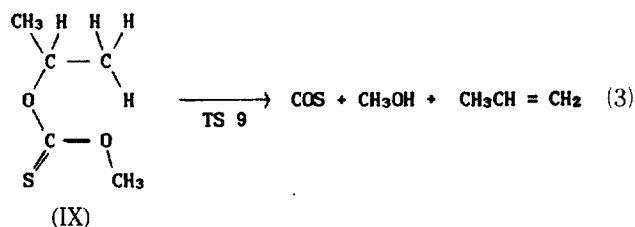


Scheme 2.

reference to Figure 2 reveals that despite the conceivable complexities due to rearrangements, reaction pathway 1 through intermediate VI with TSs 2 and 3 are most favored with the activation barrier of only 45.6 kcal/mol. The decomposition *via* the 1,3-hydrogen shift of VI to VI' has a higher barrier (TS 6' has  $\Delta H^*$  of 61.4 kcal/mol) in the decomposition of the rearranged species (VI').

For the S-C=O derivative of carbonate ester, the 1,3-migration of  $\text{CH}_3$  to the carbonyl oxygen does not give different form. However, the 1,3-hydrogen shift in the intermediate can result in a new form as shown in Scheme 2.

The energy profile is presented in Figure 3. We note that both the pathways, 1 and 2, are unfavorable compared to the reaction proceeding through the intermediate rearrangement in Scheme 2. The barrier height is the highest with TS 6 ( $\Delta H^* = 84.6$  kcal/mol), which is higher by 5.4 and 12.1 kcal/mol than TS 9 for direct decomposition, eq. (3) and the barrier height through 1,3-hydrogen rearrangement of the intermediate (Scheme 2) respectively.



**$\alpha$ -Hydroxy Esters.** We have carried out calculations on the  $\alpha$ -hydroxy esters (X) with  $\text{R}^1, \text{R}^2, \text{R}^3 = \text{H}$  or  $\text{CH}_3$ . The

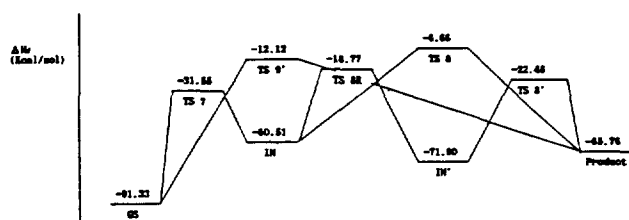
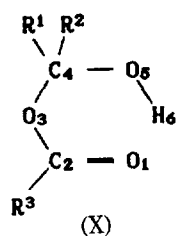


Figure 3. Energy profile of S-isopropyl thiocarbonate decomposition.

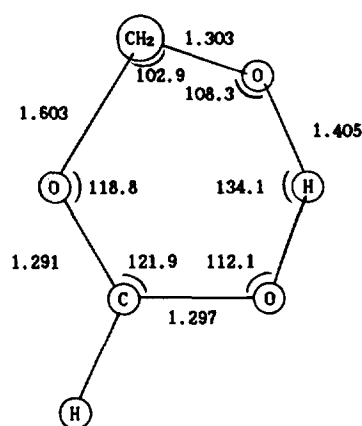
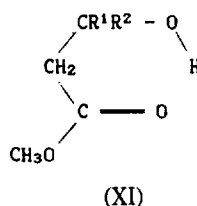
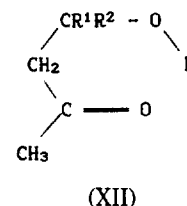


Figure 4. The TS structures for decomposition of  $\alpha$ -hydroxy ester ( $\text{R}^1 = \text{R}^2 = \text{R}^3 = \text{H}$ ).

enthalpies of activation are relatively low ( $\sim 44$  kcal/mol) compared with those corresponding compounds of ethyl formate ( $\Delta H^* = 63.5$  kcal/mol) and ethyl acetate ( $\Delta H^* = 62.3$  kcal/mol).<sup>2a</sup> A representative TS structure (for  $\text{R}^1, \text{R}^2$  and  $\text{R}^3 = \text{H}$ ) is shown in Figure 4. The activation enthalpies and relevant FMOs are summarized in Table 2. The reactivity of  $\alpha$ -hydroxy ester is seen to increase with successive methylation on the  $\text{C}_4$  and  $\text{C}_2$  carbons, the lower heats of formation of the TSs being responsible for the lowering of  $\Delta H^*$ . As we have discussed in great detail in our previous papers,<sup>2</sup> the lowering of  $\Delta H^*$  is mainly due to the higher  $\pi$ -HOMO of the  $\text{O}_1$ - $\text{C}_2$  bond and the lower  $\sigma^*$ -LUMO of the  $\text{O}_5$ - $\text{H}_6$  bond, *i.e.*, the unoleophilicity of  $\text{O}_1$  toward the migrating hydrogen,  $\text{H}_6$ , is the most important factor controlling the reactivity. The lower  $\sigma^*$ -LUMO ( $\text{O}_5$ - $\text{H}_6$ ) requires less extension,  $\Delta d = d_{\text{TS}} - d_{\text{GS}}$ , and hence less polarization,  $\Delta q = q_{\text{TS}} - q_{\text{GS}}$ , of the cleaving  $\text{O}_5$ - $\text{H}_6$  bond:  $\Delta d = 0.437, 0.444, 0.407$  and  $0.246$ ;  $\Delta q (\text{O}-\text{H}) = (-0.238) - (+0.137), (-0.238) - (+0.134), (-0.216) - (+0.131)$  and  $(-0.102) - (+0.127)$ , for  $\text{R}^1 \text{ R}^2 \text{ R}^3 = \text{H}, \text{H}, \text{H}; \text{H}, \text{H}, \text{CH}_3; \text{H}, \text{CH}_3, \text{CH}_3$  and  $\text{CH}_3, \text{CH}_3, \text{CH}_3$ , respectively.  $\beta$ -Hydroxy Esters, (XI), and  $\beta$ -Hydroxy Ketones, (XII)



(XI)



(XII)

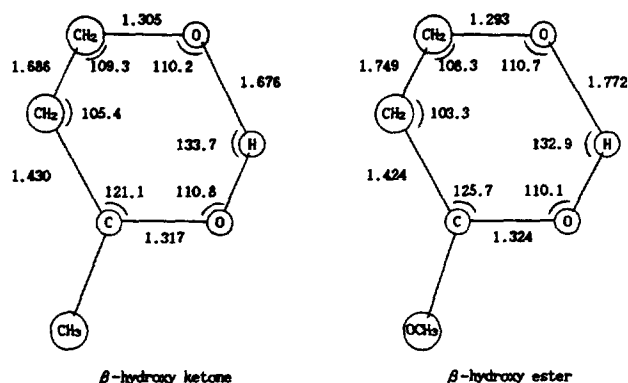
The AM1 activation enthalpies and free energies (XII) are collected together with the experimental rate constants,<sup>12</sup>  $k$ ,

**Table 2.** Activation Enthalpies ( $\Delta H^\ddagger$ ) (kcal/mol) and Relevant Frontier Orbital Levels (eV) for  $\alpha$ -Hydroxy Ester Decomposition by AM1

R <sup>1</sup>	R <sup>2</sup>	R <sup>3</sup>	GS	TS	$\Delta H^\ddagger$	$\pi$ -HOMO (O <sub>1</sub> -C <sub>2</sub> )	$\sigma^*$ -LUMO (O <sub>3</sub> -C <sub>4</sub> )	$\sigma^*$ -LUMO (O <sub>5</sub> -H <sub>6</sub> )
H	H	H	-146.34	-101.88	44.46	-11.872 (-13.387) <sup>a</sup>	1.901	3.353
H	H	CH <sub>3</sub>	-151.98	-108.34	43.64	-11.757 (-12.273) <sup>a</sup>	1.928	3.418
H	CH <sub>3</sub>	CH <sub>3</sub>	-155.90	-113.12	42.78	-11.700 (-12.951) <sup>a</sup>	1.924	3.355
CH <sub>3</sub>	CH <sub>3</sub>	CH <sub>3</sub>	-156.68	-117.10	39.58	-11.573 (-12.695) <sup>a</sup>	1.878	3.282

<sup>a</sup>The levels in parenthesis are for the (HO-1)th  $\pi$ -orbital.**Table 3.** Experimental Rate Constants,  $k$ (s<sup>-1</sup>) and Activation Enthalpies and Free Energies (kcal/mol) for Decomposition of  $\beta$ -hydroxy Esters and  $\beta$ -Hydroxy Ketones

	R <sup>1</sup>	R <sup>2</sup>	R <sup>3</sup>	$k$ (600 K)/s <sup>-1</sup>	$\Delta H^\ddagger$	$\Delta G^\ddagger$ (600K)
ester	H	H	CH <sub>3</sub>	$0.412 \times 10^{-4}$	60.62	59.18
	H	CH <sub>3</sub>	CH <sub>3</sub>	$3.84 \times 10^{-4}$	60.71	58.73
	CH <sub>3</sub>	CH <sub>3</sub>	CH <sub>3</sub>	$18.4 \times 10^{-4}$	59.88	58.14
ketone	H	H	CH <sub>3</sub>	$13.6 \times 10^{-3}$	62.42	61.10
	H	CH <sub>3</sub>	CH <sub>3</sub>	$95.0 \times 10^{-3}$	62.60	60.44
	CH <sub>3</sub>	CH <sub>3</sub>	CH <sub>3</sub>	$294 \times 10^{-3}$	61.75	59.89

**Figure 5.** The TS structures for decomposition of  $\beta$ -hydroxy ester and ketone ( $R^1=R^2=H$ ).

in Table 3, and TS structures for  $R^1=R^2=H$  are shown in Figure 5. In general esters have higher activation barriers than ketones in agreement with the experimental rate data.<sup>12</sup> There are some ambiguities in the reactivity order based on the calculated  $\Delta H^\ddagger$  values between  $R^1=R^2=H$  and  $R^1=H$  with  $R^2=CH_3$ , but when the activation entropies are taken into consideration the reactivity order with  $\Delta G^\ddagger$  conforms to that of the experimental one.

It is also experimentally known that  $\beta$ -hydroxy ketone (XII) is more reactive than the corresponding acetate ester,<sup>12,13</sup> in contrast  $\beta$ -hydroxy ester is less reactive than the corresponding carbonate ester.<sup>12</sup> For  $R^1=R^2=H$ , acetate ester (O-C=O) has  $\Delta H^\ddagger=62.3$  kcal/mol which is higher than 60.6 kcal/mol for (XII), but for  $R^1=H$  and  $R^2=CH_3$  (XI) has  $\Delta H^\ddagger$

$=62.6$  kcal/mol, which is higher than 52.8 kcal/mol for carbonate ester of O-C=O. These are in good agreement with the experimentally known facts. An increasing reactivity, obtained by the AM1 calculations as well as by experiments,<sup>12</sup> with successive substitution of methyl groups for  $R^1$  and  $R^2$  is also seen to be a consequence of an elevation of  $\pi$ -HOMO (C=O) and lowering of  $\sigma^*$ -LUMO (O-H), as shown in Table 4.

Thus we concluded that in the gas-phase pyrolysis of alkanolic esters, carbonate esters,  $\alpha$ - and  $\beta$ -hydroxy esters and ketones, the most important factor controlling the reactivity in a six-membered cyclic TS is the ease of nucleophilic attack of carbonyl oxygen or sulfur upon  $\beta$ -hydrogen, which in turn is facilitated by a greater ability of the (*i.e.*, higher)  $\pi$ -HOMO of the donor (C=Y) and the accepting ability of the (*i.e.*, lower)  $\sigma^*$ -LUMO of the acceptor (C $\beta$ -H or O-H).

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## Kinetic Isotope Effects Involving Deuterated Benzylamine Nucleophiles

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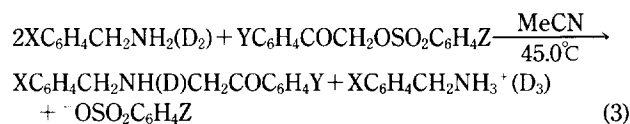
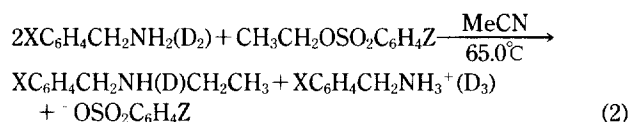
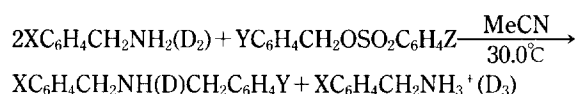
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The kinetic isotope effects (KIE) are determined for the reactions of benzyl benzenesulfonates (BBS), ethyl benzenesulfonates (EBS) and phenacyl benzenesulfonates (PAB) with deuterated benzylamine nucleophiles. The inverse secondary  $\alpha$ -deuterium KIE observed were somewhat smaller than those for the corresponding reactions with aniline nucleophiles. The primary KIEs obtained with PAB were slightly greater than those for the corresponding reactions with anilines, which suggested that the inverse secondary KIE is decreased due to a relatively earlier transition state for bond-making with little change in the hydrogen bonding strength to the carbonyl oxygen.

### Introduction

Primary and secondary deuterium kinetic isotope effects (KIE) have been widely used in characterizing the transition state (TS) structure in studies of substitution<sup>1</sup> and elimination<sup>2</sup> reactions. Normally, however, deuterium is incorporated into the substrate molecules.<sup>3</sup> In the studies of secondary  $\alpha$ -deuterium KIE in an S<sub>N</sub>2 process, however, there are some ambiguities as to which of the two concurrent changes of bond-making and -breaking is reflected mainly in the observed secondary KIE. This type of ambiguities can, however, be prevented by incorporating deuterium into the nucleophile or into the leaving group (LG) so that the secondary KIE reflects only a change in the degree of bond-making or-breaking. We have carried out such KIE studies with deuterated aniline nucleophiles<sup>4</sup> in the S<sub>N</sub>2 reactions and successfully applied to determine the TS structure and how the TSs vary with the substituents in the nucleophile (X) or in the LG (Z). In this work, we have extended our KIE studies to reactions 1-3, with deuterated benzylamine nucleophiles.



### Results and Discussion

Kinetic isotope effects observed with deuterated benzylamine nucleophiles for reactions 1-3 are summarized in Tables 1-3. The results in Tables 1 and 2 show that the  $k_H/k_D$  values are smaller than one; replacements of both amine hydrogens, H<sub>a</sub> and H<sub>b</sub>, on N in the benzylamine nucleophile leads to an inverse secondary  $\alpha$ -deuterium KIE, TS (I), since the N-H and N-D bending vibrations are hindered in the TS relative to the initial state.<sup>5</sup> Reactions of benzyl benzenesulfonates (BBS) with anilines<sup>6</sup> are known to proceed by a dissociative S<sub>N</sub>2 mechanism with a relatively loose TS. The