

Mechanistic Studies of the Solvolyses of Cyclohexanesulfonyl Chloride

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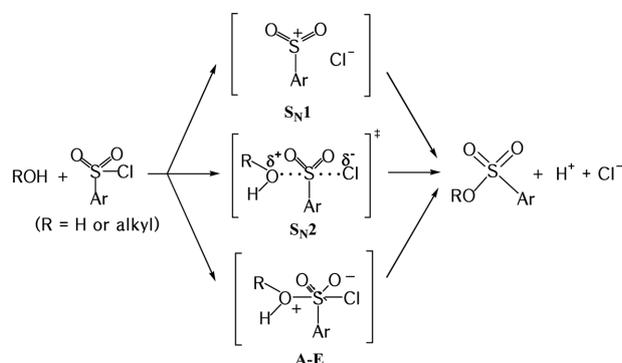
ABSTRACT. In this study, the solvolysis of cyclohexanesulfonyl chloride (**1**) was studied by kinetics in ethanol-water, methanol-water, acetone-water, and 2,2,2-trifluoroethanol (TFE)-water binary solvent systems. The rate constants were applied to the extended Grunwald-Winstein equation, to obtain the values of $m = 0.41$ and $l = 0.81$. These values suggested S_N2 mechanism in which bond formation is more important than bond breaking in the transition state (TS). Relatively small activation enthalpy values (11.6 to 14.8 kcal·mol⁻¹), the large negative activation entropy values (-29.7 to -38.7 cal·mol⁻¹·K⁻¹) and the solvent kinetic isotope effects (SKIE, 2.29, 2.30), the solvolyses of the cyclohexanesulfonyl chloride (**1**) proceeds via the S_N2 mechanism.

Key words: Cyclohexanesulfonyl chloride, Extended Grunwald-Winstein equation, S_N2 mechanism, Solvent kinetic isotope effect

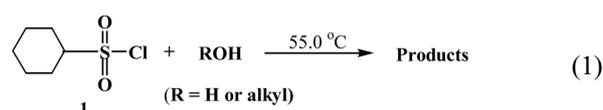
INTRODUCTION

The reaction mechanism for the nucleophilic substitution reaction at a halogenated sulfonyl has attracted considerable attention. It has been reported that the nucleophilic substitution reaction of halogenated sulfonyl having 4-coordination sulfur in a various binary solvents is an S_N2 reaction¹ or addition-elimination (A-E) reaction.² We reported that the solvolysis of methanesulfonyl chloride undergo a S_N2 reaction mechanism close to the A-E reaction.³ Also, it is generally known that the solvolysis of benzenesulfonyl chloride proceeds through three reaction mechanisms, *Scheme 1*.⁴

In this study, the solvolysis of cyclohexanesulfonyl chloride (**1**), which is not an aromatic ring, was studied kinetically in ethanol-water, methanol-water, acetone-water, and TFE-water binary solvent systems, (eq. 1).



Scheme 1. Reaction pathways for the solvolysis of benzenesulfonyl chloride.



The rate constants were applied to the extended Grunwald-Winstein equation to discuss the reaction mechanism. The reaction mechanism were also discussed through by determining the activation parameters (ΔH^\ddagger and ΔS^\ddagger) and solvent kinetic isotope effect (SKIE).

RESULTS AND DISCUSSION

Rate constants for the solvolysis of **1** are summarized in binary solvent systems (*Table 1*). The rate constant increases in the order of TFE-water < acetone-water < ethanol-water < methanol-water. The reaction rate also tends to increase as the water content increases (*i.e.*, more nucleophilic solvent). The fact that the reaction rate increases with increasing solvent ionization power means that the TS of this reaction is relatively sensitive to water. These results strongly imply that the solvolysis of **1** proceeds by a bimolecular reaction mechanism.⁴

In *Fig. 1*, we can see that the four solvent systems in the Grunwald-Winstein equation⁵ (eq. 2) for the solvolysis of **1** are dispersed. In addition, the TFE-water solvent shows a large dispersion phenomenon, which makes it difficult to quantitatively analyze the reaction mechanism for the solvolysis of the sulfonyl compound in a binary mixed solvent system. *Fig. 1* shows that such as the nucleophilicity of the solvent should be considered.⁶

Table 1. Rate constants for the solvolyses of **1**^a in binary solvent mixtures at 55.0 °C, and the N_T and the Y_{Cl} values for the solvents

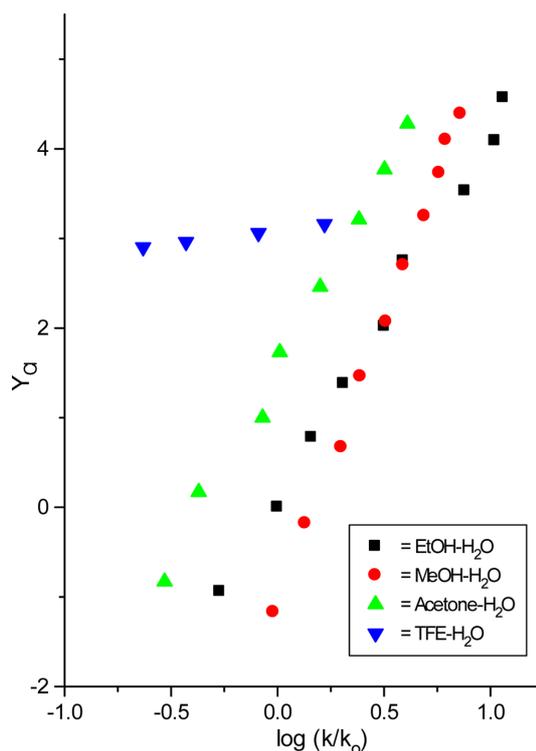
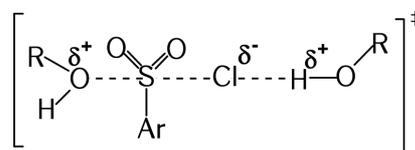
Solvent (%) ^b	N_T ^c	Y_{Cl} ^c	k (s ⁻¹)
90EtOH	0.16	-0.94	2.45×10^{-5}
80EtOH	0.00	0.00	4.57×10^{-5}
70EtOH	-0.20	0.78	6.61×10^{-5}
60EtOH	-0.39	1.38	9.33×10^{-5}
50EtOH	-0.58	2.02	1.45×10^{-4}
40EtOH	-0.74	2.75	1.78×10^{-4}
30EtOH	-0.93	3.53	3.47×10^{-4}
20EtOH	-1.16	4.09	4.79×10^{-4}
H ₂ O	-1.38	4.57	5.25×10^{-4}
100MeOH	0.17	-1.17	4.37×10^{-5}
90MeOH	-0.01	-0.18	6.17×10^{-5}
80MeOH	-0.06	0.67	9.12×10^{-5}
70MeOH	-0.40	1.46	1.12×10^{-4}
60MeOH	-0.54	2.07	1.48×10^{-4}
50MeOH	-0.57	2.70	1.78×10^{-4}
40MeOH	-0.87	3.25	2.24×10^{-4}
30MeOH	-1.06	3.73	2.63×10^{-4}
20MeOH	-1.23	4.10	2.82×10^{-4}
10MeOH	-1.36	4.39	3.31×10^{-4}
80Acetone	-0.37	-0.83	1.35×10^{-5}
70Acetone	-0.42	0.17	1.85×10^{-5}
60Acetone	-0.52	1.00	3.89×10^{-5}
50Acetone	-0.70	1.73	4.68×10^{-5}
40Acetone	-0.83	2.46	7.24×10^{-5}
30Acetone	-0.96	3.21	1.10×10^{-4}
20Acetone	-1.11	3.77	1.45×10^{-4}
10Acetone	-1.23	4.28	1.86×10^{-4}
80TFE ^d	-2.17	2.90	1.07×10^{-5}
70TFE	-1.98	2.96	1.70×10^{-5}
60TFE	-1.85	3.06	3.72×10^{-5}
50TFE	-1.73	3.16	7.59×10^{-5}

^aUnless otherwise indicated, a 1.0 mol dm⁻³ solution of the substrate in the indicated solvent, containing 0.1% CH₃CN. ^bOn a volume-volume content at 25.0 °C, and the other component is water. ^cValues from refs. 5. ^dSolvent prepared on a weight-weight basis at 25.0 °C, and the other component is water.

$$\log(k/k_0) = mY_{Cl} + c \quad (2)$$

The bimolecular nucleophilic substitution reaction proceeds to a push-pull reaction mechanism in which the solvent acts simultaneously with the nucleophile and the electrophile such as *Scheme 2*.⁶ Therefore, the bimolecular solvolysis reaction can be applied to the extended Grunwald-Winstein equation⁷ (eq. 3), which is also dependent on the sensitivity to the nucleophilicity (N_T) of the solvent. *Fig. 2*

$$\log(k/k_0) = lN_T + mY_{Cl} + c \quad (3)$$

**Figure 1.** Plot of $\log(k/k_0)$ for solvolyses cyclohexanesulfonyl chloride (**1**) in 31 solvents at 55.0 °C against Y_{Cl} .**Scheme 2.** Push-pull reaction.

shows an extended Grunwald-Winstein equation plot with the nucleophilicity term of the solvent added to investigate the dispersion phenomenon depending on the nucleophilicity of the solvent. The dispersion phenomenon is greatly reduced in the extended Grunwald-Winstein equation plot.⁷

The m value indicating the sensitivity of the ionization power of the solvent was 0.41 and the l value indicating the sensitivity to the nucleophilicity of the solvent was 0.81. The l and m values for solvolyses of **1** are similar to those for the other solvolyses listed in *Table 2*, and can be expected an S_N2 mechanism in which bond formation is important than bond breaking. According to the results previously reported, l/m values of 1.2 to 3.5 leads to the bimolecular pathway. In this studies, value l/m of 2.0 was obtained (*Table 2*), and this gives a strong support for a bimolecular reaction mechanism in the solvolysis of **1**.⁷

The activation parameter (ΔH^\ddagger and ΔS^\ddagger) values provide

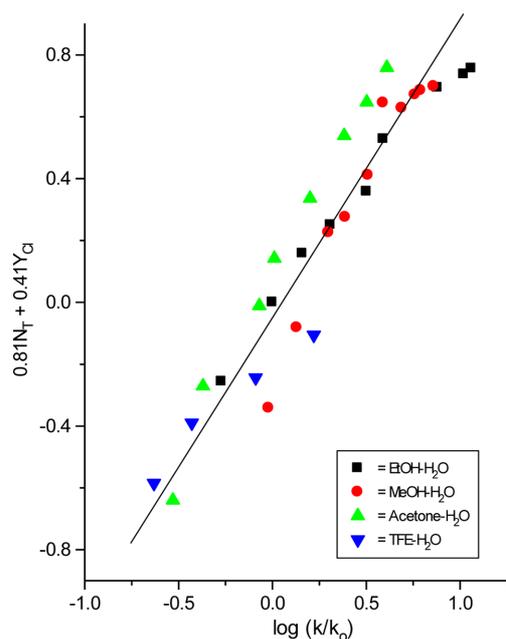


Figure 2. Plot of $\log(k/k_0)$ for solvolyses of cyclohexanesulfonyl chloride (**1**) in 31 solvents at 55.0 °C against $(0.81NT + 0.41Y_{Cl})$.

Table 2. Extended Grunwald-Winstein correlation of the kinetics of solvolytic displacement of chloride

Substrate	r^a	ρ^b	m^b	l/m	R^c
$C_6H_5CH_2SO_2Cl^d$	30	0.61	0.34	1.8	0.954
$C_{13}H_9CH_2OCOCl^e$	30	0.95	0.39	2.4	0.941
$C_6H_5SO_2Cl^f$	37	1.10	0.61	1.6	0.959
$(C_6H_5)_2PSCl^g$	25	1.00	0.64	1.8	0.983
$(CH_3)_2NC_{10}H_6SO_2Cl^h$	31	0.96	0.53	1.8	0.955
$4-CH_3OC_6H_4SO_2Cl^i$	38	1.07	0.60	2.3	0.967
$CH_2=CHCH_2OCOCl^j$	30	0.93	0.41	2.2	0.964
$(C_6H_5)_2CHCOCl^k$	34	0.76	0.34	2.2	0.932
Cyclo- $C_6H_{11}SO_2Cl^l$	31	0.81	0.41	2.0	0.949

^aNumber of solvents. ^bFrom eq. (3). ^cMultiple correlation coefficient. ^dRef. 8. ^eRef. 9. ^fRef. 4. ^gRef. 10. ^hRef. 11. ⁱRef. 12. ^jRef. 13. ^kRef. 14. ^lThis work.

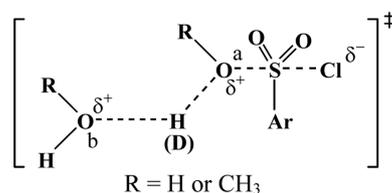
information on the reaction mechanism of the nucleophilic substitution reaction and the solvolysis reaction. *Table 3* summarizes the rate constants and the activation parameter values in 80% ethanol-water, methanol, and 50% TFE-water solvent systems. In the present study, it is shown that the enthalpy change is relatively small and negative entropy change value is large, which means a bimolecular reaction that the disorder state of the transition state is greatly reduced.¹⁵

The solvent kinetic isotope effect (SKIE) also provides important information for predicting the reaction mechanism. A reaction in which an alcohol or water molecule solvent acts as a general base catalyst can be shown in *Scheme 3*.¹⁶ When O-H bond dissociation of the nucleophile alco-

Table 3. Rate constants and activation parameters for the solvolyses of **1**^a at various temperatures

Solvent (%) ^b	T (°C)	k (s ⁻¹) ^c	ΔH^\ddagger (kcal/mol) ^d	$-\Delta S^\ddagger$ (cal/mol·K) ^d
80EtOH	35	1.30×10^{-5}	12.1±0.7	38.7±1.8
	45	2.41×10^{-5}		
	55	4.57×10^{-5}		
100MeOH	35	1.28×10^{-5}	11.60.5	40.1±1.7
	45	2.43×10^{-5}		
	55	4.37×10^{-5}		
50TFE ^e	35	1.64×10^{-5}	14.80.2	29.7±0.6
	45	3.45×10^{-5}		
	55	7.59×10^{-5}		

^aA 1.0 mol·dm⁻³ solution of the substrate in the indicated solvent, also containing 0.1% CH₃CN. ^bOn a volume-volume content at 25.0 °C, and the other component is water. ^cAverages of three or more runs. ^dThe activation parameters are accompanied by the standard error. ^eSolvent prepared on a weight-weight basis at 25.0 °C, and the other component is water.



Scheme 3. Solvent kinetic isotope effect.

Table 4. Solvent kinetic isotope effects (SKIEs) for the solvolyses of **1** at 55.0 °C.

Solvent	k_H (s)	k_D (s)	SKIE
MeOH	4.37×10^{-5}	1.89×10^{-5}	2.30
H ₂ O	5.25×10^{-4}	2.29×10^{-4}	2.29

hol or water molecule is performed in the determination step of the TS, the difference of reaction rate is shown when the nucleophile is R-O-H and R-O-D, and thus the SKIE is exhibited.¹⁷

The solvent kinetic isotope effects of the solvolysis of **1** are summarized in *Table 4*. SKIEs provide information for the mechanism of the reaction.

The SKIE values in the solvolysis of **1** were 2.29 and 2.30, respectively. According to the previous studies, it is known that the SKIE value is 1.7 or more for the normal base catalytic reaction, whereas the value is as small as 1.2 to 1.5 for the S_N2 reaction. The reaction of this study has a relatively large SKIE value, which support to a bimolecular reaction that proceeds with a general base catalytic reaction.¹⁸

CONCLUSION

A kinetic study was carried out to investigate the mech-

anism of the solvolysis of **1** and the following conclusions were obtained. The dispersion of Grunwald-Winstein equation⁵ plot was shown in several solvent systems, and the dispersion was greatly improved extended Grunwald-Winstein equation plot.⁷

The rate constants were applied to the extended Grunwald-Winstein equation, and the results were $m = 0.41$ and $l = 0.81$. These values suggested the S_N2 mechanism in which bond formation is more important than bond breaking in the TS. In addition, based on the relatively small activation enthalpy values, the large negative activation entropy values, and the SKIE values, the reaction of this study is expected to proceed through the S_N2 mechanism.

EXPERIMENTAL

Ethanol, methanol, acetone and 2,2,2-trifluoroethanol (TFE) solvents were GR grade. Water was used after the third distillation. The substrate, cyclohexanesulfonyl chloride (**1**), was purchased. The solvolysis of **1** produces hydrogen ions and chloride ions. The reaction rate was measured by the electric conductivity method using the first-order proportionality of the conductivity with the change of the amounts of hydrogen ions and chloride ions. The reaction was carried out with a substrate concentration of about 10⁻³ M and a similar first-order reaction, in which the concentration of the nucleophile was much larger than that of the substrate. The uncertainty in the k_{obsd} values was estimated to be less than $\pm 3\%$ from replicate runs.

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