http://dx.doi.org/10.5012/bkcs.2014.35.8.2410

Kinetic Study on Aminolysis of Y-Substituted-Phenyl Picolinates: Effect of H-Bonding Interaction on Reactivity and Transition-State Structure

Min-Young Kim, Tae-Ah Kang,† Jung Hwan Yoon,‡ and Ik-Hwan Um*

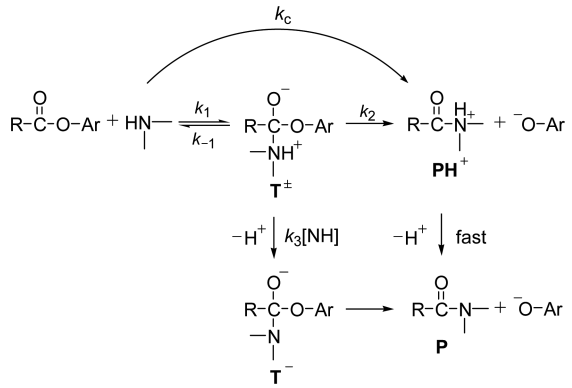
Department of Chemistry and †Department of Life Science, Ewha Womans University, Seoul 120-750, Korea
**E-mail: ihum@ewha.ac.kr*
‡Young-il High School, Seoul 157-836, Korea
Received April 9, 2014, Accepted April 23, 2014

A kinetic study is reported on nucleophilic substitution reactions of Y-substituted-phenyl picolinates (**7a-7h**) with a series of cyclic secondary amines in 80 mol % H_2O/20 mol % DMSO at 25.0 ± 0.1 °C. Comparison of the kinetic results with those reported previously for the corresponding reactions of Y-substituted-phenyl benzoates (**1a-1f**) reveals that **7a-7h** are significantly more reactive than **1a-1f**. The Brønsted-type plot for the aminolysis of 4-nitrophenyl picolinate (**7a**) is linear with β_{nuc} = 0.78, which is typical for reactions proceeding through a stepwise mechanism with expulsion of the leaving group being the rate-determining step. The Brønsted-type plots for the piperidinolysis of **7a-7h** and **1a-1f** are also linear with β_{lg} = –1.04 and –1.39, respectively, indicating that the more reactive **7a-7h** are less selective than the less reactive **1a-1f** to the leaving-group basicity. One might suggest that the enhanced reactivity of **7a-7h** is due to the inductive effect exerted by the electronegative N atom in the picolinyl moiety, while the decreased selectivity of the more reactive substrates is in accord with the reactivity-selectivity principle. However, the nature of intermediate (*e.g.*, a stabilized cyclic intermediate through the intramolecular H-bonding interaction for the reactions of **7a-7h**, which is structurally not possible for the reactions of **1a-1f**) is also responsible for the enhanced reactivity with a decreased selectivity.

Key Words : Aminolysis, Phenyl picolinate, H-bonding interaction, Intermediate, Reactivity-selectivity principle

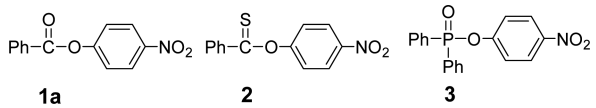
Introduction

Numerous studies on aminolysis of esters have been carried out due to their importance in organic syntheses and in biological processes (*e.g.*, peptide biosynthesis and enzyme action).[1,2] As shown in Scheme 1, aminolysis of esters has been reported to proceed either through a concerted mechanism or *via* a stepwise pathway with one or two intermediates (*e.g.*, a zwitterionic tetrahedral intermediate $T^{\pm}$ and its deprotonated form T^{-}), depending on the reaction conditions such as the nature of electrophilic center, reaction medium, stability of reaction intermediate, *etc.*[2-9]

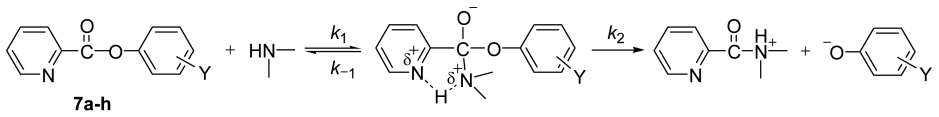


Scheme 1

Reactions of 4-nitrophenyl benzoate (**1a**) with a series of cyclic secondary amines have been reported to proceed through a stepwise mechanism, in which expulsion of the leaving group occurs in the rate-determining step (RDS) on the basis of a linear Brønsted-type plot with β_{nuc} = 0.81.[5] In contrast, the corresponding reactions of *O*-4-nitrophenyl thionobenzoate (**2**) have been suggested to proceed through a stepwise mechanism with two intermediates (*e.g.*, $T^{\pm}$ and T^{-}) since the plots of k_{obsd} *vs.* [amine] curved upward.[6] However, the reactions of 4-nitrophenyl diphenylphosphinate (**3**) have been concluded to proceed through a concerted mechanism on the basis of a linear Brønsted-type plot with β_{nuc} = 0.5 ± 0.1,[7] indicating that the nature of electrophilic center (*e.g.*, C=O, C=S and P=O) is an important factor that governs the reaction mechanism.



Aminolysis of 2,4-dinitrophenyl benzoate has been reported to proceed through a stepwise mechanism with a change in RDS in 80 mol % H_2O/20 mol % DMSO on the basis of a curved Brønsted-type plot with β_2 = 0.74 and β_1 = 0.34,[8a] but *via* a concerted mechanism in MeCN on the basis of a linear Brønsted-type plot with β_{nuc} = 0.40.[8b] Instability of $T^{\pm}$ in the aprotic solvent has been suggested to force the reaction to



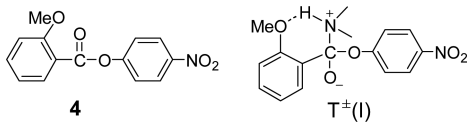
Y = 4-NO_2(**7a**), 4-CHO(**7b**), 4-COMe(**7c**), 4-COOEt(**7d**), 3-Cl(**7e**), 4-Cl(**7g**), H(**7h**).

HN— ; HN Z Z = CH_2, NH, NCH_2CH_2OH, O, NH_2^+.
R R = H or CH_3.

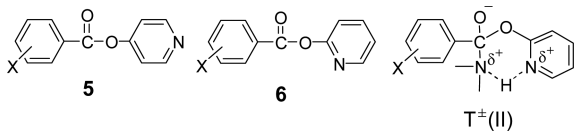
Scheme 2

proceed through a concerted mechanism.

However, aminolysis of 4-nitrophenyl 2-methoxybenzoate (**4**) in MeCN has been reported to proceed through a stepwise mechanism on the basis of a linear Brønsted-type plot with $\beta_{nuc} = 0.70$.[9a] The reaction has been proposed to proceed through a cyclic intermediate as modeled by $T^{\pm}$(I), which is stabilized through the intramolecular H-bonding interaction in the aprotic solvent.[9a]



We have also reported that aminolysis of 4-pyridyl X-substituted-benzoates (**5**) in MeCN proceeds through a stepwise mechanism with one or two intermediates depending on the electronic nature of the substituent X, *e.g.*, $T^{\pm}$ and T^{-} when X is a strong electron-withdrawing group (EWG) but $T^{\pm}$ only when X is a weak EWG or an electron-donating group (EDG).[9b] In contrast, the corresponding reaction of 2-pyridyl X-substituted-benzoates (**6**, the isomers of **5**) has been concluded to proceed through a concerted mechanism regardless of the electronic nature of the substituent X on the basis of a linear Brønsted-type plot with $\beta_{nuc} = 0.59$.[9c] This is contrary to the expectation that the aminolysis of **6** would proceed through a stepwise mechanism with a stable intermediate as modeled by $T^{\pm}$(II).[9c]



Scrutiny of the plausible intermediate $T^{\pm}$(II) reveals that the H-bonding interaction could decrease the leaving-group basicity by changing the highly basic 2-pyridyloxide (*e.g.*, $pK_a = 11.62$ in H_2O)[10] to the weakly basic 2-pyridiniumoxide (*e.g.*, $pK_a = 0.75$ in H_2O)[10] or its tautomer 2-pyridone. Apparently, the decreased leaving-group basicity would cause a significant increase in the nucleofugality of the leaving group. Thus, it has been concluded that the H-bonding interaction in the plausible intermediate $T^{\pm}$(II) shortens its lifetime and forces the reaction to proceed through a concerted mechanism.[9c]

Our study has now been extended to the reactions of Y-substituted-phenyl picolinates (**7a-7h**) with a series of cyclic secondary amines in 80 mol % H_2O/20 mol % DMSO at 25.0 ± 0.1 °C (Scheme 2). The kinetic results have been compared with those reported previously for the corresponding reactions of Y-substituted-phenyl benzoates (**1a-1f**) to investigate the effect of changing the nonleaving group from benzoyl to picolinyl on reactivity and reaction mechanism.

Results and Discussion

The reactions of **7a-7h** with amines were followed spectrophotometrically by monitoring the appearance of Y-substituted-phenoxide ions under pseudo-first-order conditions. All of the reactions in this study obeyed first-order kinetics with quantitative liberation of Y-substituted-phenoxide ion. Pseudo-first-order rate constants (k_{obsd}) were calculated from the equation, $\ln (A_\infty - A_t) = -k_{obsd}t + C$. The plots of k_{obsd} *vs.* [amine] were linear with excellent correlation coefficients (*e.g.*, $R^2 \geq 0.9995$) and passed through the origin, indicating that general-base catalysis by a second amine molecule is absent and the contribution of H_2O and/or the OH^- ion from hydrolysis of amines to the k_{obsd} value is negligible. Accordingly, the second-order rate constants (k_N) were calculated from the slope of the linear plots and are summarized in Tables 1 for the reactions of 4-nitrophenyl picolinate (**7a**) with a series of cyclic secondary amines, and in Table 2 for the reactions of Y-substituted-phenyl picolinates (**7a-7h**) with piperidine together with those reported previously for the corresponding reactions of Y-substituted-phenyl benzoates (**1a-1f**)[11] to investigate the effect of changing the nonleaving group from benzoyl to picolinyl on reactivity and reaction

Table 1. Summary of Kinetic Data for the Reactions of 4-Nitrophenyl Benzoate (**1a**) and 4-Nitrophenyl Picolinate (**7a**) with Cyclic Secondary Amines in 80 mol % H_2O/20 mol % DMSO at 25.0 ± 0.1 °C[a]

	amines	pK_a	$k_N/M^{-1}s^{-1}$	
			1a	**7a**
1	piperidine	11.02	5.94	211
2	3-methylpiperidine	10.80	-	162
3	piperazine	9.85	0.851	50.5
4	1-(2-hydroxyethyl)piperidine	9.38	0.195	11.2
5	morpholine	8.65	0.0876	5.63
6	1-formylpiperazine	7.98	0.0100	-
7	piperazinium ion	5.95	-	0.0417

[a]The pK_a values and the kinetic data for the reaction of **1a** in 80 mol % H_2O/20 mol % DMSO were taken from ref. 5.

mechanism.

Effect of Nonleaving-Group Structure on Reactivity and Reaction Mechanism. As shown in Table 1, the k_N value for the aminolysis of **7a** decreases as the basicity of the incoming amine decreases, *e.g.*, it decreases from 211 $M^{-1}s^{-1}$ to 11.2 and 0.0417 $M^{-1}s^{-1}$ as the pK_a of the conjugate acid of the amine decreases from 11.02 to 9.38 and 5.95, in turn. A similar result is demonstrated for the corresponding reaction of **1a**, although the benzoate ester is much less reactive than the picolinate ester. The pyridine ring in **7a** is considered as an analogue of a benzene ring that carries a strong EWG due to the presence of an electronegative N atom. Thus, one might suggest that the inductive effect exerted by the electronegative N atom in the picolinyl moiety is responsible for the kinetic result that **7a** is more reactive than **1a**. However, we propose that the enhanced reactivity of **7a** is not solely due to the inductive effect. Because **7a** is *ca.* 10 times more reactive than 4-nitrophenyl 4-nitrobenzoate,[5] which possesses a strong EWG in the benzoyl moiety (*e.g.*, k_N = 21.0 $M^{-1}s^{-1}$ for the reaction with piperidine). Besides, many factors could affect reactivity of esters, *e.g.*, reaction mechanism, stability of transition state (TS), *etc.*

To investigate the reaction mechanism, Brønsted-type plot for the aminolysis of **7a** has been constructed. As shown in Figure 1, the plot exhibits an excellent linear correlation with β_{nuc} = 0.78. This is almost identical to the β_{nuc} value of 0.81 reported for the corresponding reaction of **1a**, which has been suggested to proceed through a stepwise mechanism.[5] However, it is much larger than the β_{nuc} value for reactions proceeding through a concerted mechanism (*e.g.*, β_{nuc} = 0.5 ± 0.1 for the aminolysis of 4-nitrophenyl diphenylphosphinate and phosphinothioate).[7] Thus, one can suggest that the aminolysis of **7a** also proceeds through a stepwise mechanism in which expulsion of the leaving group occurs in RDS.

It is well known that stability of reaction intermediate or TS is an important factor that controls reactivity. Aminolysis of 4-nitrophenyl 2-methoxybenzoate (**4**) has been reported to be 20 and 74 times more reactive than its isomers 4-nitrophenyl 3-methoxybenzoate and 4-methoxybenzoate, respectively.[9a] Thus, stabilization of $T^{\pm}$(I) through the H-bonding interaction, which is structurally not possible for the reactions of 4-nitrophenyl 3- and 4-methoxybenzoates, has been suggested to be responsible for the enhanced reactivity of **4**.[9a]

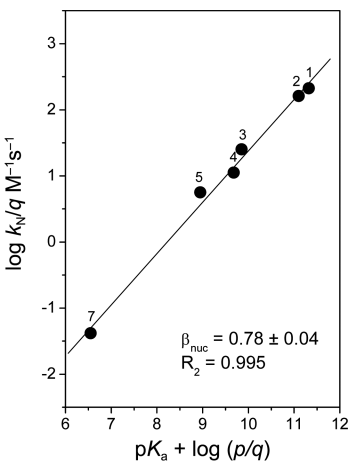
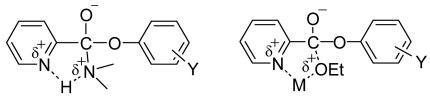


Figure 1. Brønsted-type plot for the reaction of 4-nitrophenyl picolinate (**7a**) with cyclic secondary amines in 80 mol % H_2O/20 mol % DMSO at 25.0 ± 0.1 °C. The identity of points is given in Table 1.

One might expect that aminolysis of **7a** proceeds also through a stepwise mechanism with a stabilized intermediate, *e.g.*, $T^{\pm}$(III). Since such a cyclic intermediate is structurally not possible for the reaction of **1a**, one can suggest that the enhanced stability of $T^{\pm}$(III) through the H-bonding interaction is mainly responsible for the kinetic result that **7a** is much more reactive than **1a**. This idea can be further supported by the report that nucleophilic substitution reaction of **7a** with ion-paired $CH_3CH_2O^-M^+$ (M = Na or K) proceeds through a cyclic intermediate $T^{\pm}$(IV).[12] It is notable that $T^{\pm}$(IV) is structurally similar to $T^{\pm}$(III). Furthermore, the enhanced stability of $T^{\pm}$(IV) through M^+ ion complexation is responsible for the kinetic result that the ion-paired $CH_3CH_2O^-Na^+$ or $CH_3CH_2O^-K^+$ is up to 17 times more reactive than the dissociated $CH_3CH_2O^-$.[12]



$T^{\pm}$(III) $T^{\pm}$(IV)

Effect of Leaving-Group Basicity on Reactivity and Reaction Mechanism. To obtain further information on the reaction mechanism including the TS structure, the k_N values for the reactions of Y-substituted-phenyl picolinates (**7a-7h**) with piperidine have been measured and are summarized in Table 2. The the k_N values reported previously for the corresponding reactions of Y-substituted-phenyl benzoates (**1a-1f**)[11] are also included for comparison. Table 2 shows that the k_N value for the reactions of **7a-7h** decreases as the leaving group basicity increases, *e.g.*, it decreases from 211 $M^{-1}s^{-1}$ to 12.7 and 0.230 $M^{-1}s^{-1}$ as the pK_a of the conjugate

Table 2. Summary of Kinetic Data for the Reactions of Y-Substituted-Phenyl Benzoates (**1a-1f**) and Picolinates (**7a-7h**) with Piperidine in 80 mol % H_2O/20 mol % DMSO at 25.0 ± 0.1 °C[a]

	Y	p$K_a^{Y\text{-}PhOH}$	$k_N/M^{-1}s^{-1}$	
			1[b]	**7**
a	4-NO_2	7.14	5.94	211
b	4-CHO	7.66	0.852	49.5
c	4-COMe	8.05	0.236	18.0
d	4-COOEt	8.50	-	12.7
e	3-Cl	9.02	0.0159	2.34
f	3-COMe	9.19	0.00650	-
g	4-Cl	9.38	-	0.783
h	H	9.95	-	0.230

[a]The pK_a data for the Y-substituted-phenols were taken from ref. 10. [b]The kinetic data for the reactions of **1a-1f** were taken from ref. 11.

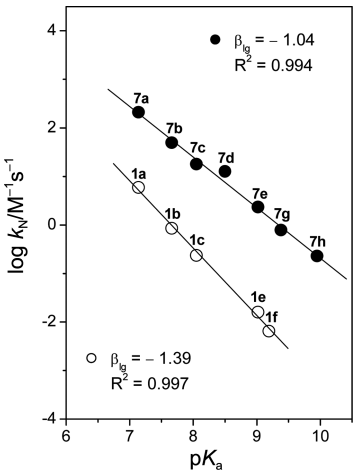


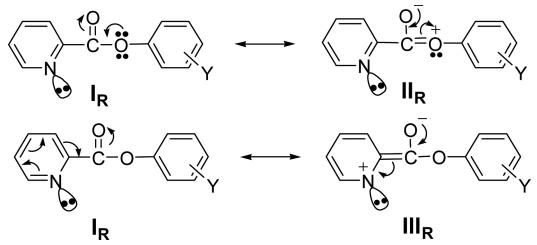
Figure 2. Brønsted-type plots for the reactions of Y-substituted-phenyl benzoates **1a-1f** (○) and picolinates **7a-7h** (●) with piperidine in 80 mol % H_2O/20 mol % DMSO at 25.0 ± 0.1 °C. The identity of points is given in Table 2.

acid of the leaving group increases from 7.14 to 8.50 and 9.95, in turn. A similar result is demonstrated for the corresponding reactions of **1a-1f**. However, the benzoate esters are much less reactive than the picolinate esters regardless of the leaving group basicity.

The effect of the leaving-group basicity on reactivity is illustrated in Figure 2 for the reactions of **1a-1f** and **7a-7h**. The Brønsted-type plots exhibit excellent linear correlations with $\beta_{lg} = -1.39$ and -1.04 for the reactions of **1a-1f** and for those of **7a-7h**, respectively. It is notable that the reactions of **7a-7h** result in a little smaller β_{lg} value than the reactions of **1a-1f**. However, the β_{lg} value of -1.04 is much larger than that reported for reactions which proceed through a concerted mechanism (*e.g.*, $\beta_{lg} = -0.5 \pm 0.1$ for aminolysis of Y-substituted-phenyl diphenylphosphinates and phosphinothioates).[7] A linear Brønsted-type plot with $\beta_{lg} = -1.5 \pm 0.3$ is typical for reactions reported to proceed through a stepwise mechanism with expulsion of the leaving group being the RDS.[2] In fact, the aminolysis of **1a-1f** has been reported to proceed through a stepwise mechanism.[11] Thus, one can suggest that the reactions of **7a-7h** also proceed through a stepwise mechanism with expulsion of the leaving group being the RDS. This is consistent with the preceding proposal that the reactions of both **1a** and **7a** proceed through a stepwise mechanism on the basis of the linear Brønsted-type plots with $\beta_{nuc} = 0.8 \pm 0.1$.

It is well known that the magnitude of β_{lg} value represents a selectivity or a sensitivity parameter. Since the picolinate esters are more reactive than the benzoate esters, one might suggest that the smaller β_{lg} value obtained for the reactions of **7a-7h** is in accord with the Reactivity-Selectivity Principle (RSP). However, we propose that the RSP is not solely responsible for the small β_{lg} value obtained for the reactions of **7a-7h**.

Substrates **7a-7h** can be represented by three different resonance structures as illustrated in the resonance structures I_R, II_R and III_R. One might expect that the resonance structure II_R becomes the major contributor when the substituent Y is a strong EDG. In contrast, the contribution of the resonance structure III_R would increase as the substituent Y becomes a stronger EWG. It is apparent that the positively charged N atom in III_R would inhibit formation of the intermediate $T^{\pm}$(III). Furthermore, such inhibition would be stronger as the substituent Y becomes a stronger EWG due to the increasing resonance contribution of III_R. This is consistent with the kinetic result that the rate enhancement decreases as the substituent Y becomes a stronger EWG. Thus, one can suggest that contribution of the resonance structure III_R is mainly responsible for the smaller β_{lg} value found for the reactions of **7a-7h**.



Conclusions

The current study has led us to conclude the following: (1) The Brønsted-type plot for the aminolysis of **7a** is linear with $\beta_{nuc} = 0.78$, indicating that the reaction proceeds through a stepwise mechanism with expulsion of the leaving group being the RDS. (2) The picolinate esters **7a-7h** are more reactive than the corresponding benzoate esters **1a-1f**. (3) The Brønsted-type plots for the piperidinolysis of **7a-7h** and **1a-1f** exhibit excellent linear correlations with $\beta_{lg} = -1.04$ and -1.39, respectively. (4) The inductive effect of the electronegative N atom in the picolinyl moiety of **7a-7h** and the RSP could be a possible explanation for the enhanced reactivity and the decreased selectivity shown by substrates **7a-7h**. (5) However, the stability of intermediate $T^{\pm}$(III) through H-bonding interaction, which is not possible for the reactions of **1a-1f**, is more responsible for the increased reactivity with a decreased selectivity.

Experimental Section

Materials. Substrates **7a-7h** were prepared through the reaction of picolinyl chloride with the respective phenols in anhydrous ether under the presence of triethylamine as reported previously.[13] The crude products were purified by short pathway silica gel column chromatography or recrystallization. Their purity was checked by their melting point, ^{1}H and ^{13}C NMR spectra. Amines and other chemicals were of the highest quality available.

Kinetics. Kinetic study was carried out by using a UV-Vis spectrophotometer for slow reactions (*e.g.*, $t_{1/2} \geq 10$ s) or a stopped-flow spectrophotometer for fast reactions (*e.g.*, $t_{1/2} < 10$ s) equipped with a constant-temperature circulating bath to maintain the reaction temperature at 25.0 ± 0.1 °C. All reactions were performed under pseudo-first-order conditions

in which the concentration of amines was kept at least 20 times greater than that of the substrate. Typically, the reaction was initiated by adding 5 μL of a 0.01 M of substrate stock solution in MeCN by a 10 μL syringe to a 10 mm UV cell containing 2.50 mL of the reaction medium and the amine nucleophile. Reactions were followed generally up to 9 half-lives and k_{obsd} were calculated using the equation, ln $(A_\infty - A_t)$ *vs*. *t*.

Acknowledgments. This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2012-R1A1B-3001637). JHY is also grateful for the Intensive Science Program of Young-il High School.

References

1. (a) Anslyn, E. V.; Dougherty, D. A. *Mordern Physical Organic Chemistry*; University Science Books: California, 2006; Chapt. 10. (b) Page, M. I.; Williams, A. *Organic and Bio-organic Mechanisms*; Longman: Singapore, 1997; Chapt. 7. (c) Lowry, T. H.; Richardson, K. S. *Mechanism and Theory in Organic Chemistry*, 3rd ed.; Harper Collins Publishers: New York, 1987; Chapt. 8.5. (d) Jencks, W. P. *Catalysis in Chemistry and Enzymology*; McGraw Hill: New York, 1969; Chapt. 10.
2. Reviews: (a) Castro, E. A. *Pure Appl. Chem.* **2009**, *81*, 685-696. (b) Castro, E. A. *J. Sulfur Chem.* **2007**, *28*, 401-429. (c) Castro, E. A. *Chem. Rev.* **1999**, *99*, 3505-3524. (d) Jencks, W. P. *Chem. Rev.* **1985**, *85*, 511-527. (e) Jencks, W. P. *Chem. Soc. Rev.* **1981**, *10*, 345-375.
3. (a) Castro, E. A.; Aliaga, M. E.; Gazitua, M.; Pavez, P.; Santos, J. G. *J. Phys. Org. Chem.* **2014**, *27*, 265-268. (b) Pavez, P.; Millan, D.; Morales, J. I.; Castro, E. A. *J. Org. Chem.* **2013**, *78*, 9670-9676. (c) Aguayo, R.; Arias, F.; Canete, A.; Zuniga, C.; Castro, E. A.; Pavez, P.; Santos, J. G. *Int. J. Chem. Kinet.* **2013**, *45*, 202-211. (d) Castro, E. A.; Ugarte, D.; Rojas, M. F.; Pavez, P.; Santos, J. G. *Int. J. Chem. Kinet.* **2011**, *43*, 708-714. (e) Castro, E.; Aliaga, M.; Campodonico, P. R.; Cepeda, M.; Contreras, R.; Santos, J. G. *J. Org. Chem.* **2009**, *74*, 9173-9179. (f) Castro, E. A.; Ramos, M.; Santos, J. G. *J. Org. Chem.* **2009**, *74*, 6374-6377.
4. (a) Ilieva, S.; Nalbantova, D.; Hadjieva, B.; Galabov, B. *J. Org. Chem.* **2013**, *78*, 6440-6449. (b) Swiderek, K.; Tunon, I.; Marti, S.; Moliner, V.; Bertran, J. *J. Am. Chem. Soc.* **2013**, *135*, 8708-8719. (c) Swiderek, K.; Tunon, I.; Marti, S.; Moliner, V.; Bertran, J. *Chem. Commun.* **2012**, 11253-11255. (d) Oh, H. K.; Oh, J. Y.; Sung, D. D.; Lee, I. *J. Org. Chem.* **2005**, *70*, 5624-5629. (e) Oh, H. K.; Jin, Y. C.; Sung, D. D.; Lee, I. *Org. Biomol. Chem.* **2005**, *3*, 1240-1244. (f) Llinas, A.; Page, M. I. *Org. Biomol. Chem.* **2004**, *2*, 651-654. (g) Perreux, L.; Loupy, A.; Delmotte, M. *Tetrahedron* **2003**, *59*, 2185-2189. (h) Ilieva, S.; Galabov, B.; Musaev, D. G.; Moroluma, K.; Schaefer III, H. F. *J. Org. Chem.* **2003**, *68*, 1496-1502.
5. Um, I. H.; Min, J. S.; Ahn, J. A.; Hahn, H. J. *J. Org. Chem.* **2000**, *65*, 5659-5663.
6. (a) Um, I. H.; Hwang, S. J.; Yoon, S. R.; Jeon, S. E.; Bae, S. K. *J. Org. Chem.* **2008**, *73*, 7671-7677. (b) Um, I. H.; Seok, J. A.; Kim, H. T.; Bae, S. K. *J. Org. Chem.* **2003**, *68*, 7742-7746. (c) Um, I. H.; Lee, S. E.; Kwon, H. J. *J. Org. Chem.* **2002**, *67*, 8999-9005.
7. (a) Um, I. H.; Han, J. Y.; Shin, Y. H. *J. Org. Chem.* **2009**, *74*, 3073-3078. (b) Um, I. H.; Akhtar, K.; Shin, Y. H.; Han, J. Y. *J. Org. Chem.* **2007**, *72*, 3823-3829.
8. (a) Um, I. H.; Kim, K. H.; Park, H. R.; Fujio, M.; Tsuno, Y. *J. Org. Chem.* **2004**, *69*, 3937-3942. (b) Um, I. H.; Jeon, S. E.; Seok, J. A. *Chem. Eur. J.* **2006**, *12*, 1237-1243.
9. (a) Um, I. H.; Bea, A. R. *J. Org. Chem.* **2011**, *76*, 7510-7515. (b) Um, I. H.; Bea, A. R. *J. Org. Chem.* **2012**, *77*, 5781-5787. (c) Um, I. H.; Bae, A. R.; Um, T. I. *J. Org. Chem.* **2014**, *79*, 1206-1212.
10. Jencks, W. P.; Regenstein, J. In *Handbook of Biochemistry*, 2nd ed.; Sober, H. A., Ed.; Chemical Rubber Publishing Co.: Cleveland, OH, 1970; p J-195.
11. Um, I. H.; Lee, J. Y.; Ko, S. H.; Bae, S. K. *J. Org. Chem.* **2006**, *71*, 5800-5803.
12. Hong, Y. J.; Kim, S. I.; Um, I. H. *Bull. Korean Chem. Soc.* **2010**, *31*, 2483-2487.
13. (a) Menger, F. M.; Smith, J. H. *J. Am. Chem. Soc.* **1972**, *94*, 3824-3829. (b) Maude, A. B.; Williams, A. *J. Chem. Soc., Perkin Trans. 2* **1997**, 179-183. (c) Maude, A. B.; Williams, A. *J. Chem. Soc., Perkin Trans. 2* **1995**, 691-696. (d) Menger, F. M.; Brian, J.; Azov, V. A. *Angew. Chem. Int. Ed.* **2002**, *41*, 2581-2584.