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# **Amine Catalyzed Intramolecular Imidization of Alkyl and Aryl Phthalamates. Kinetics and Mechanism in Deuterated Chloroform.**

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## **ABSTRACT**

The kinetics of the amine catalyzed intramolecular imidization of alkyl and phenyl phthalamates with a variety of amines were measured in deuterated chloroform at 40.1°C. An overall second-order kinetic rate law,  $\text{rate} = k_{\text{overall}} [\text{amine}][\text{phthalamate}]$ , was obtained from our experiments. Although pre-association between the amides and the amines through hydrogen bonding interaction was suggested by proton NMR spectroscopy, the catalytic ability of amines was found to be related to their basicity rather than to their hydrogen-bonding ability or nucleophilicity. This observation implies the involvement of proton transfer from the amide to the amine in the critical transition state. In addition, by changing the leaving group from phenoxy to *n*-butoxy group, the reaction rate constants decrease by a factor of 30 to 70. On the basis of these kinetic results, we propose that the intramolecular imidization proceeds through an amine assisted cyclization to a zwitterionic intermediate, followed by the expulsion of the alkoxy or phenoxy group to provide phthalimide and the corresponding alcohol.

## Introduction.

The study of catalytic principles has been of great importance in understanding the mechanisms of enzyme action<sup>1</sup>. During the past few decades, numerous model studies about intramolecular catalysis<sup>2</sup>, solvolysis mechanisms<sup>3</sup>, and molecular recognition<sup>4</sup> have been reported. Since most of the physiological reactions happen in a hydroxylic environment, early investigations were mainly concentrated on aqueous phase model studies.<sup>5</sup> However, the actual enzyme catalyzed reactions might occur in the hydrophobic portion of the enzymes. This concept is appealing because impaired ion solvation often leads to very large rate and equilibrium enhancements. In recent years a considerable amount of work has been carried out on hydrogen-bonded interactions<sup>6</sup>, proton transfer processes<sup>7</sup>, and the mechanism of transacylation reactions<sup>8</sup> in organic media. Because of the predominance of amide linkages in proteins, it is reasonable to anticipate that these amido groups also play an important role in enzyme reactivity. Since both neutral amides and their conjugate bases are effective nucleophiles, neighboring amido groups often facilitate solvolytic and redox reactions.<sup>9</sup> Early work by Hancock and Sondheimer clearly demonstrated that a neighboring amido group can effectively catalyze the alkaline hydrolysis of the adjacent ester through an imide intermediate.<sup>10</sup> In addition, on the basis of kinetic results, Shafer<sup>11</sup> proposed an amidate (1) formation during the imidization process (Scheme 1).

Our interest in the application of base-catalyzed chemistry to polymer systems has led us to investigate the possibility of using amines as catalysts in intramolecular imidizations.<sup>12</sup> Our ultimate target is the optimization of the design of polyamic acid and polyamic esters<sup>13</sup> in order to facilitate their transformation into polyimides under the influence of base generated photochemically *in situ*.<sup>14</sup> However, the mechanism of this base-catalyzed imidization reaction is not fully understood. Since the basicity of amines is too low for the direct deprotonation of the amido groups, we suspected that the amine-catalyzed imidization proceeds through a different mechanism. In this report, we

present our recent progress in the study of the mechanism of the amine-catalyzed intramolecular imidization of alkyl and aryl phthalamates.

## Results and Discussion

Amines are versatile reagents that may activate amido-esters through hydrogen-bonding interactions, proton abstraction, or nucleophilic addition to the carbonyl groups. In order to distinguish between these different effects, a wide range of amines having different hydrogen bonding abilities, basicities, and nucleophilicities were selected for this study. Since the intramolecular imidization involves the attack of a neighboring amido group onto the adjacent ester, the reaction has to proceed through a multi-step process that likely involves several nucleophilic additions and eliminations. In order to ascertain the rate determining step, a variety of leaving groups including phenoxy, 1,1,1-trifluoroethoxy, and *n*-butoxy groups were introduced into the substrate. If the rate determining step involves the expulsion of alkoxyl or phenoxy group, a significant effect on the imidization rate constants is expected for these different compounds.

*Synthesis of Alkyl and Phenyl Phthalamates.*- *n*-Butyl and 1,1,1-trifluoroethyl phthalamates (2) and (3) were prepared by a two-step synthetic sequence<sup>15</sup> from phthalic anhydride (Scheme 2). Because of the low conversion of phthalic anhydride into *mono* phenyl phthalate, phenyl phthalamate (4) was prepared by a one pot synthesis from phthaloyl dichloride as shown in Scheme 3.

*Hydrogen Bonding Complexation.*- It has been well documented that amines can be hydrogen-bonded to amides in two different ways (Type I and Type II)<sup>16</sup>. In the first case, the amine acts as an acceptor to receive a hydrogen from the amide nitrogen. In the second case, the amine acts as a donor to provide a hydrogen to the amide carbonyl oxygen. In our study, the formation of a hydrogen-bonded complex in deuterated chloroform is suggested on the basis of <sup>1</sup>H NMR observations. The spectrum of *n*-butyl phthalamate shows a broad singlet at 5.9 ppm which corresponds to two protons

(Figure 1) and is assigned to the amide protons. In the presence of piperidine, the broad singlet splits into two smaller broad signals, each of which corresponds to one proton. The width of this splitting depends on the piperidine concentration. Similar peak splitting was also observed by addition of 1,4-diazabicyclo[2.2.2]octane, a tertiary amine, to the phthalamate solution. These observations support the formation of hydrogen-bonded complexes between the amines and the amides. Since the amine proton is not a necessary requirement for the signal splitting, we believe that type I hydrogen bonding interaction is more significant than type II hydrogen bonding interaction in this case.

*Insert diagrams marked "Type I and Type II" here*

**Basicity of Amines and Mechanistic Aspects of the Imidization Process.**- The kinetics governing the imidization in  $\text{CDCl}_3$  were determined by  $^1\text{H}$  NMR spectroscopy. For amines listed in Table 1, the imidization obeys a second-order rate law which was determined under pseudo-first order conditions (Figure 2). By plotting the pseudo first-order rate constants,  $k_{\text{pseudo}}$  vs. [amine] and measuring the slope of the straight line (Figure 3), the overall rate constants,  $k_{\text{overall}}$  were evaluated. The deviation of the intercepts from the origin is within the experimental and least square errors (Figure 3). The overall kinetic rate law is shown in eqns. (1) and (2).

$$\text{Rate} = k_{\text{pseudo}}[\text{phthalamate}] \quad (1)$$

where

$$k_{\text{pseudo}} = k_{\text{overall}}[\text{amine}] \quad (2)$$

Instead of the observations of hydrogen-bonded complex formation, the kinetic data for phenyl phthalamate (Table 1) indicate that the catalytic ability of amines is not correlated to their hydrogen-bonding ability. Strong hydrogen-bonding acceptors<sup>8, 17</sup>

such as 4-(*N,N*-dimethylamino)pyridine (DMAP) and *N*-methylimidazole do not facilitate the imidization as effectively as some weaker hydrogen bond acceptors such as primary amines. On the other hand, the catalytic ability of amines follows the trend of their basicity. Rumeau and Balint Novotny reported that the relative basicity of amines in chloroform decreases from the tertiary to the primary ones.<sup>18</sup> Although 1,8-bis(dimethylamino)naphthalene (proton sponge) is a very strong base in aqueous phase, Alder and Benoit reported a dramatic basicity reversal for proton sponge when compared with monoamines in deuterated dimethylsulfoxide, chloroform, and dichloromethane.<sup>19</sup> These results explain the low catalytic ability of proton sponge in the imidization reaction. Except for sterically hindered diisopropylethylamine, a similar correlation between amine basicities and their catalytic reactivities was also observed for *n*-butyl phthalamate. These results strongly suggest that the mechanism involves a large extent of proton transfer from the amide to the amine in the imidization.

**Leaving Group Effect.**- Phenyl phthalamate cyclizes about 2 times faster than trifluoroethyl phthalamate and about 30-70 times faster than *n*-butyl phthalamate. This reactivity order of the leaving groups is consistent with that reported for the alkaline hydrolysis of phenyl  $\alpha$ -(2-imidazolyl)benzoate,<sup>20</sup> but their rate constant differences are two orders of magnitude smaller. The difference in the imidization rate constants implies an influence of the leaving group in the critical transition state. However, the extent of the negative charge located on the oxygen leaving groups may be smaller than that in the hydrolysis of phenyl  $\alpha$ -(2-imidazolyl)benzoate.

**Nucleophilicity and Catalytic Ability.**- Amines may act as nucleophiles to attack either the ester carbonyl group or the amide carbonyl group to promote the imidization. For example, tertiary amines and DMAP could conceivably attack the ester group to form an acylium salt intermediate **5**<sup>21</sup> that could further react with the adjacent amide to provide phthalimide (Scheme 4). Nevertheless, generalization of the mechanism to the cases of primary and secondary amines is unlikely because deprotonation of the corre-

sponding acylium salts, which is supposed to be a fast reaction in the basic reaction conditions, would lead to the bis-amides instead of phthalimide as the major products. If the nucleophilic addition of amines to the amide carbonyl group occurred, a zwitterionic tetrahedral intermediate 6 would be generated. In this situation, the lone-pair electrons of the amide nitrogen would no longer be conjugated to the carbonyl group and therefore they would become more nucleophilic. This tetrahedral intermediate would further attack the adjacent ester to induce imidization (Scheme 5). This type of amide activation through a nucleophilic attack was mentioned by Nagasawa and Elberling in the study of the Favorskii rearrangement of  $\alpha$ -halolactams.<sup>22</sup> If the nucleophile assisted mechanism operates for the imidization, a correlation between the nucleophilicity of amines and their catalytic ability would be observed. However, our kinetic results are inconsistent with this mechanism. DMAP which shows a very high catalytic activity in nucleophilic acylation reactions<sup>21</sup> is only a moderate catalyst just like the sterically hindered diisopropylethylamine, which is a poor nucleophile and is ineffective in the imidization of *n*-butyl phthalamate. In addition, the very poor nucleophile proton sponge shows a higher catalytic ability than the more nucleophilic *N,N*-dimethylaniline in the imidization of phenyl phthalamate.<sup>23</sup> These observations are contrary to the predictions based on the nucleophile assisted mechanism. Moreover, this mechanism cannot explain the particularly high catalytic ability of diisopropylethylamine in the imidization of phenyl and trifluoroethyl phthalamate.

*Mechanism of Amine Catalyzed Intramolecular Imidization of Alkyl and Phenyl Phthalamates.*- Based on all the information obtained from the kinetic studies, a mechanism for the imidization is proposed in Scheme 6. The first step of the reaction involves formation of a hydrogen-bonded complex between the amide and the amine to give intermediate 7. This assumption is in good agreement with our NMR observations and the results reported in the literature.<sup>24</sup> In general, complex formation results from a fast equilibrium with a low activation energy barrier. The second step involves a reversible



intramolecular cyclization during which the lone-pair electrons on the amide nitrogen attack the adjacent ester carbonyl group, along with a simultaneous proton transfer from the amide nitrogen to the hydrogen-bonded amine<sup>25</sup>. The amine molecule in this step functions by removing a proton from the tetrahedral intermediate **8**, thereby avoiding the formation of a high-energy *N*-protonated amide species **9** during the cyclization. Since the stability of the zwitterionic tetrahedral intermediate **8** is dependent on the extent of proton transfer, this explains the correlation between the amine basicities and their catalytic abilities. An interesting study by Kirby et al.<sup>25</sup> on the general base catalysed cyclization of hydantoic esters points out the stereoelectronic problems associated with these cyclizations.

The last step of the reaction sequence involves the expulsion of an oxygen-based leaving group from the tetrahedral intermediate **8**. However, there are two diastereomeric zwitterionic intermediates **10** and **11** that may be formed in the amine assisted cyclization (Scheme 7). Tetrahedral intermediate **10** has the leaving group *syn* to the hydrogen-bonded ammonium ion. When the tetrahedral intermediate collapses, the negative charge localized on the oxygen-based leaving group can be neutralized immediately by the adjacent ammonium ion, and therefore the charge separation involved in the transition state **12** is small. On the other hand, collapse of the *anti* intermediate **11** will inevitably lead to a transient charge separation in the transition state **13**. With relatively good leaving group such as phenolate or trifluoroethoxide, the negative charge localized on the oxygen atom can be stabilized by resonance or by an inductive effect. Therefore, the instability arising from the charge separation is reduced. In both of these cases, both the *syn* and *anti* eliminations, are feasible. However, with a poor leaving group such as *n*-butoxy group, the *anti*-elimination that creates a transient charge separation in a non-polar medium will be highly unfavorable. In this situation, the *syn* elimination through intermediate **10** is expected to be predominant.<sup>26</sup> Since the *syn* configuration of **10** is sterically more congested than the *anti* configuration of **11**, its

formation would be more sensitive to steric hindrance. For those amines bearing bulky substituents, formation of the *syn* intermediate **10** would be unfavorable and therefore the imidization would be retarded. These considerations explain the exceptionally low catalytic ability of diisopropylethylamine in the imidization of *n*-butyl phthalamate.

By applying the steady state conditions to our proposed mechanism, a rate expression for the kinetic law can be deduced and is shown in eqns. (3) and (4).

$$\text{Rate} = k_{\text{overall}} [\text{amine}] [\text{phthalamate}] \quad (3)$$

$$k_{\text{overall}} = k_1 k_2 k_3 / (k_{-1} k_3 + k_{-1} k_{-2} + k_2 k_3) \quad (4)$$

This expression is in good agreement with our kinetic results which show an overall second order kinetics, first order in amines and first order in phthalamates. If the expulsion of the leaving group is the rate determining step,  $k_3$  should be smaller than  $k_{-2}$ . Assuming that  $k_{-1} k_{-2} \gg k_3 (k_{-1} + k_2)$ , eqn. (4) can be simplified to eqn. (5).

$$k_{\text{overall}} = K' k_3 \quad (5)$$

$$\text{where } K' = k_1 k_2 / k_{-1} k_{-2} = [\mathbf{10} + \mathbf{11}] / [\text{phthalamate}][\text{amine}]$$

The term  $K'$  is the total equilibrium constant for the formation of the key intermediates **10** and **11**. From this simplified equation, we can understand that the basicity of amines affects the reaction rate by stabilizing the cyclic intermediates **10** and **11** and hence increases the equilibrium constant  $K'$ . According to our discussion and hypotheses, a reaction energy profile for the imidization is established in Scheme 8. Since the *anti* intermediate **11** has a smaller charge separation and less steric hindrance, a lower energy is assigned to this intermediate.

## Conclusion

Our experimental results demonstrate the importance of amine basicity in the imidiza-

tion of alkyl or aryl phthalamates. We may be able to elaborate these observations to other organic bases. In particular, in the context of our study of the photochemically induced base-catalyzed preparation of polyimides<sup>12</sup>, we are developing new photoprecursors<sup>14</sup> of bases that are expected to further enhance the imidization step. Similarly, considering the significant roles of carboxylates in enzyme action and their strong basicities in nonpolar solvents,<sup>27</sup> the carboxylate catalyzed intramolecular imidization may be another interesting target to study. Since we predict an involvement of the cyclic zwitterionic intermediate **8** in the reaction, factors governing the equilibrium of ring-chain tautomerism, such as steric assistance effects,<sup>28</sup> may also be pronounced on the imidization reactions. Some of our results concerning these effects will be reported in the near future.

## Experimental

*General Directions.*-Melting points were measured on a Gallenkamp melting point apparatus. IR spectra were recorded on a Nicolet IR/44 spectrophotometer. <sup>1</sup>H and <sup>13</sup>C NMR spectra were recorded on solutions in CDCl<sub>3</sub>, or [<sup>2</sup>H<sub>6</sub>]-acetone on an IBM-Bruker AF300 (300 MHz) spectrometer using the solvent proton signal or the solvent carbon signal as an internal standard. Mass Spectra were obtained on a Hewlett Packard MSD-5971A GC/MS.

*Synthesis of mono n-Butyl Phthalate.*- A mixture of phthalic anhydride (16.9 mmol) and *n*-butanol (5 equiv.) was heated at reflux for 4 h, after which the reaction mixture was cooled to room temperature, washed with water, extracted with CHCl<sub>3</sub>, dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>, and rotary evaporated to dryness to afford a colorless solid in 80% yield (13.5 mmol): m.p. 72-74°C;  $\nu_{\text{max}}/\text{cm}^{-1}$  3373-2700 (COOH), 1716, 1650 (C=O);  $\delta_{\text{H}}$  (CDCl<sub>3</sub>) 0.91 (3H, t, *J* 7.3), 1.35-1.47 (2H, m), 1.67-1.74 (2H, m), 4.31 (2H, t, *J* 6.6), 7.40-7.59 (2H, m), 7.66 (1H, d, *J* 7.0), 7.86 (1H, d, *J* 7.4), 11.9 (1H, br s);  $\delta_{\text{C}}$  (CDCl<sub>3</sub>) 172.66, 168.12, 133.48, 132.07, 130.64, 129.90, 129.61, 128.62, 65.75,

30.30, 19.05, 13.55. (Found: C, 65.0; H, 6.4. Calc. for  $C_{12}H_{14}O_4$ : C, 64.9; H, 6.4; O, 28.8 %)

**Synthesis of *n*-Butyl Phthalamate (2).**- To a solution of *mono n*-butyl phthalate (2.25 mmol) in benzene (10 cm<sup>3</sup>) was added a solution of oxalyl chloride (3 equiv.) in benzene (3 cm<sup>3</sup>) followed by a few drops of *N,N*-dimethylformamide. The reaction mixture was stirred for 2h, after which the solvent and unreacted oxalyl chloride was removed under reduced pressure. The residue was taken up into benzene (5 cm<sup>3</sup>), filtered, and concentrated to provide a crude acid chloride. The crude acid chloride was redissolved in  $CH_2Cl_2$  (10 cm<sup>3</sup>) and a solution of 1,1,1,3,3,3-hexamethyldisilazane (3 equiv.) in  $CH_2Cl_2$  (5 cm<sup>3</sup>) was added at 0°C. The mixture was gradually warmed up and stirred at ambient temperature for 8h after which the mixture was quenched by addition of methanol (20 cm<sup>3</sup>) at 0 °C. Stirring was continued for an additional 2 h. The organic phase was washed with dilute  $H_2SO_4$ , extracted with ethylacetate, dried over anhydrous  $Na_2SO_4$ , and rotary evaporated to dryness to provide a crude solid. Recrystallization of the crude solid from  $CHCl_3$ /hexanes gave **2** as colorless crystals in 84% yield (1.89 mmol): m.p. 64-66°C (*lit.*<sup>13</sup> m.p. 64-65 °C);  $\nu_{max}/cm^{-1}$  3373, 3175 ( $CONH_2$ ), 1717, 1650 ( $C=O$ ); 1401, 1259, 1136;  $\delta_H(CDCl_3)$  0.94 (3H, t, *J* 7.4), 1.36-1.49 (2H, m), 1.65-1.75 (2H, m), 4.27 (2H, t, *J* 6.7), 5.90-5.05 (2H, bs), 7.43-7.52 (3H, m), 7.84 (1H, d, *J* 7.2);  $\delta_C(CDCl_3)$  171.78, 167.13, 137.41, 131.78, 129.89, 129.83, 129.74, 127.58, 65.61, 30.52, 19.25, 13.81. (Found C, 65.3; H, 6.8; N, 6.4. Calc. for  $C_{12}H_{15}NO_3$ : C, 65.1; H, 6.8; N, 6.3; O, 21.7 %).

**Synthesis of mono 1,1,1,-Trifluoroethyl Phthalate.**- A mixture of phthalic anhydride (0.1 mol) and 1,1,1-trifluoroethanol (2 equiv.) was heated at reflux for 6 h, after which the mixture was cooled to room temperature, taken up into chloroform, and washed twice with water to remove any unreacted trifluoroethanol. The desired acid was extracted into dilute  $K_2CO_3$  solution, separated, and regenerated by acidifying the basic aqueous extracts to provide a white solid. Recrystallization the white solid from

chloroform/hexanes gave *mono* 1,1,1-trifluoroethyl phthalate in 25 % yield (0.025 mol): m.p. 80-82 °C;  $\nu_{\max}/\text{cm}^{-1}$  3300-2400 (COOH), 1758, 1693 (C=O);  $\delta_{\text{H}}(\text{CDCl}_3)$  4.68 (2H, q,  $J_{\text{HF}}$  8.4), 7.60-7.71 (3H, m), 7.93-7.96 (1H, m), 10.84 (1H, br s);  $\delta_{\text{C}}(\text{CDCl}_3)$  172.65, 166.66, 132.72, 131.86, 131.73, 130.23, 130.01, 129.09, [128.58, 124.91, 121.24, 117.50 (q,  $J_{\text{CF}}$  274)], [62.33, 61.83, 61.35, 60.86 (q,  $J_{\text{CF}}$  37)]. (Found: C, 48.6; H, 2.7. Calc. for  $\text{C}_{10}\text{H}_7\text{O}_4\text{F}_3$ : C, 48.4; H, 2.8; O, 25.8; F, 23.0 %).

*Synthesis of 1,1,1-Trifluoroethyl phthalamate(3).*- Following the procedure for *n*-butyl phthalamate (2) above, *mono* 1,1,1-trifluoroethyl phthalate (12.9 mmol) was converted to the corresponding acid chloride, followed by aminolysis with 1,1,1,3,3,3-hexamethyldisilazane (3 equiv.). Since the final phthalamate is sensitive to basic conditions, the reaction mixture was first washed with ice-cooled aqueous sulfuric acid before methanolysis. The organic phase was then separated, dried over anhydrous  $\text{Na}_2\text{SO}_4$  and concentrated under vacuum to provide a viscous oil. The oil was redissolved in methanol (30  $\text{cm}^3$ ) and allowed to stand at room temperature for 2h. Rotary evaporation of the methanol gave a white solid which was recrystallized from chloroform to provide 3 as colorless crystals in 73% yield: m.p. 138-140 °C;  $\nu_{\max}/\text{cm}^{-1}$  3374, 3183 (amide  $\text{NH}_2$ ), 1739, 1650 (C=O);  $\delta_{\text{H}}([\text{C}_2\text{H}_6]_2\text{-acetone})$  4.74 (2H, q,  $J_{\text{HF}}$  8.8), 6.83 (1H, bs), 7.39 (1H, bs), 7.52-7.65 (3H, m), 7.75 (1H, d,  $J$  7.2);  $\delta_{\text{C}}(\text{CDCl}_3)$  170.18, 166.77, 138.72, 132.63, 130.72, 130.51, 129.99, 128.50, [130.0 (overlapping with 129.99), 126.32, 122.66, 116.99 (q,  $J_{\text{CF}}$  271)], [62.31, 61.83, 61.36, 60.88 (q,  $J_{\text{CF}}$  35)]; (Found: C, 48.5; H, 3.0; N, 5.7. Calc. for  $\text{C}_{10}\text{H}_8\text{NO}_3\text{F}_3$ : C, 48.6; H, 3.3; N, 5.7; O, 19.4; F, 23.1 %).

*Synthesis of Phenyl Phthalamate (4).*- To a solution of phenol (11.4 mmol) and phthaloyl dichloride (1.2 equiv.) in  $\text{CH}_2\text{Cl}_2$  (25  $\text{cm}^3$ ) was added a solution of DMAP (1.2 equiv.) and pyridine (5  $\text{cm}^3$ ) in  $\text{CH}_2\text{Cl}_2$  (10  $\text{cm}^3$ ). The mixture was stirred at room temperature for 3 h after which the mixture was chilled in an ice bath and subsequently added dropwise a solution of 1,1,1,3,3,3-hexamethyldisilazane (3 equiv.) in  $\text{CH}_2\text{Cl}_2$  (10  $\text{cm}^3$ ). The reaction mixture was stirred for an additional 6 h and quenched with ice-

cooled dilute  $\text{H}_2\text{SO}_4$  (5 %, 100  $\text{cm}^3$ ). The organic phase was taken up into  $\text{CH}_2\text{Cl}_2$ , washed with saturated aqueous NaCl solution, dried over anhydrous  $\text{Na}_2\text{SO}_4$ , and rotary evaporated to dryness to give a crude oil, which is essentially a silylated amide. The crude oil was then dissolved in MeOH (30  $\text{cm}^3$ ) and allowed to stand at room temperature for 2 h. Removal of the MeOH under reduced pressure gave a slightly yellowish solid. Flash chromatography of the solid on silica gel, eluting with hexanes/ethyl acetate (1:1.5) led to a white solid. Recrystallization of the solid from chloroform/hexanes (1:2) provided **4** as colorless crystals in 50 % yield: m.p. 118-119  $^\circ\text{C}$ ;  $\nu_{\text{max}}/\text{cm}^{-1}$  3382, 3188 (amide  $\text{NH}_2$ ), 1743, 1662 ( $\text{C}=\text{O}$ );  $\delta_{\text{H}}(\text{CDCl}_3)$  6.09 (1H, br s), 6.23 (1H, br s), 7.21-7.24 (3H, m), 7.35-7.40 (2H, m), 7.51-7.57 (3H, m), 7.98-8.01 (1H, m);  $\delta_{\text{C}}(\text{CDCl}_3)$  171.13, 166.00, 150.96, 137.59, 132.45, 130.53, 130.32, 129.64, 129.36, 127.67, 126.21, 121.65; (Found: C, 69.5; H, 4.7; N, 5.8. Calc. for  $\text{C}_{14}\text{H}_{11}\text{NO}_3$ : C, 69.7; H, 4.6; N, 5.8; O, 19.9 %).

*Kinetic Procedures.*- Deuterated chloroform was stirred over anhydrous potassium carbonate overnight and freshly distilled from  $\text{P}_2\text{O}_5$  before use. Amines were purified by distillation from  $\text{CaH}_2$  or recrystallization from an appropriate solvent according to literature procedures. Kinetics were measured by proton NMR spectroscopy at  $40.1 \pm 0.05$   $^\circ\text{C}$  in deuterated chloroform. In order to avoid any possible interference arising from the reaction between strong amine bases and  $\text{CDCl}_3$ , blank experiments were carried out under similar conditions. These experiments confirmed that under the conditions used for this work no reaction between the amines and  $\text{CDCl}_3$  occurred. The rate of decrease of *n*-butyl phthalamate was monitored by the disappearance of the triplet at 4.27 ppm ( $\text{COOCH}_2$ -) and the appearance of the triplet at 3.60 ppm ( $\text{HOCH}_2$ -) with the concentrations of amines ranging from 0.05 M to 0.5 M and the substrate concentration varied from 0.04M to 0.06M. The rate of decrease of phenyl phthalamate was monitored by the disappearance of the multiplet at 7.98-8.01 ppm (ArH of the phthalamate, 1H) and the appearance of the doublet at 6.79 ppm (*o*-H of Phenol, 2H) with the concentra-

tions of amines ranging from 0.002 M to 0.02 M and the concentration of the substrate varied from 0.04 to 0.06M . The reaction rate of trifluoroethyl phthalamate was monitored by the disappearance of the quartet at 4.68 ppm ( $\text{COOCH}_2\text{CF}_3$ ) and the appearance of the quartet at 3.90 ppm ( $\text{CF}_3\text{CH}_2\text{OH}$ ) with the concentrations of amines ranging from 0.005M to 0.02 M while the substrate concentration was 0.01M. According to eqn. (6) which is an integral form of eqn. (1), pseudo-first-order rate constants,  $k_{\text{pseudo}}$ , were obtained from the slope of a plot of  $-\ln [\text{phthalamate}]_t / [\text{phthalamate}]_0$  vs. reaction time. Second-order rate constants,  $k_{\text{overall}}$ , were obtained from the slope of a plot of  $k_{\text{pseudo}}$  vs. [amine], shown in eqn. (2).

$$-\ln [\text{phthalamate}]_t / [\text{phthalamate}]_0 = k_{\text{pseudo}} \times \text{reaction time} \quad (6)$$

### Acknowledgements

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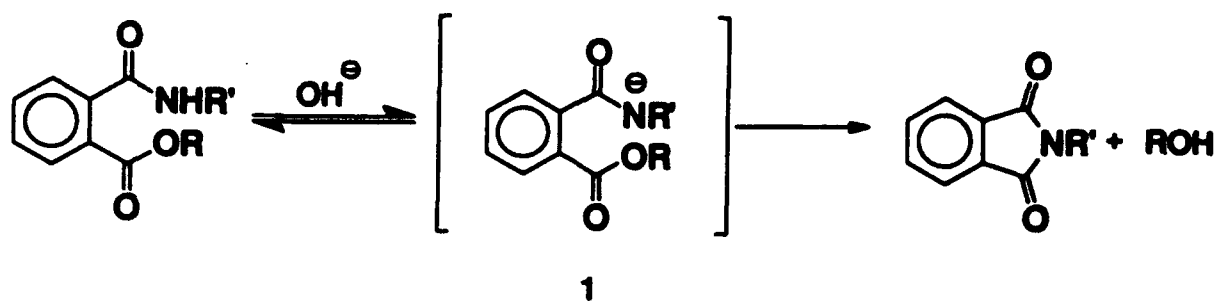
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## FIGURE CAPTIONS

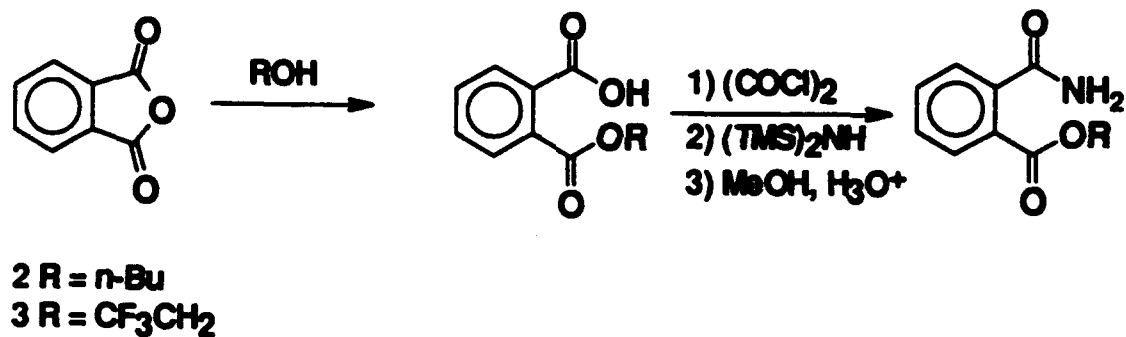
**Figure 1**  $^1\text{H}$  NMR spectra of *n*-butyl phthalamate ( $3.2 \times 10^{-2}$  M) in  $\text{CDCl}_3$ : (a) without piperidine; (b) [piperidine] =  $9.4 \times 10^{-2}$  M; (c) [piperidine] =  $1.9 \times 10^{-1}$  M. The broad singlet at 5.9 ppm is assigned to the amide proton. In the presence of piperidine, the broad singlet splits into two smaller signals. The down field shift signal is assigned to the proton that is hydrogen-bonded to piperidine through Type I interaction.

**Figure 2** Plot of  $-\ln [\text{phthalamate}]_t / [\text{phthalamate}]_0$  against reaction time for 1,3-diaminopropane (DAP) catalyzed imidization of phenyl phthalamate at  $40.1^\circ\text{C}$ : (a) [DAP] =  $1.78 \times 10^{-2}$  M; (b) [DAP] =  $8.90 \times 10^{-3}$  M; (c) [DAP] =  $4.45 \times 10^{-3}$  M; (d) [DAP] =  $2.23 \times 10^{-3}$  M. The solid lines are the least square fits to the points. The linearity of the linear least square fits indicates that the imidization is in pseudo first order to phenyl phthalamate. The pseudo first order rate constants are obtained from the slopes of the solid lines.

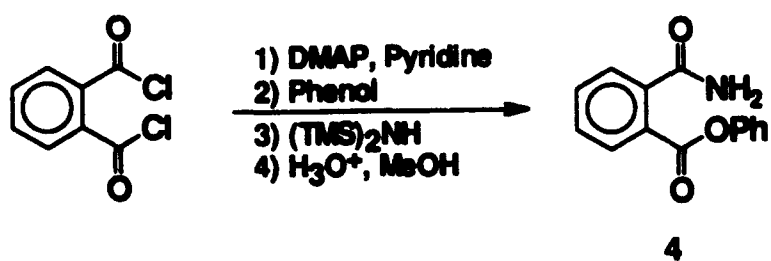
**Figure 3** Plot of  $k_{\text{pseudo}}$  against the concentrations of amines for the imidization of phenyl phthalamate: (a) piperidine; (b) diisopropylethylamine; (c) *N,N*-dimethyl-1,2-ethylenediamine; (d) 1,8-bis(dimethylamino)naphthalene (proton sponge). The linearity of the least square fits indicates that the imidization is in first order to amines.



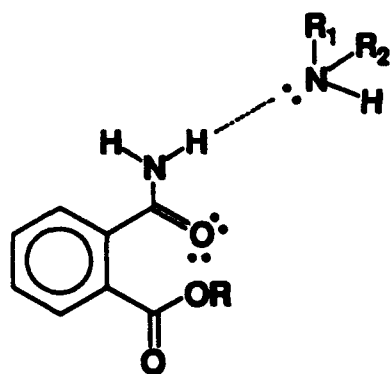
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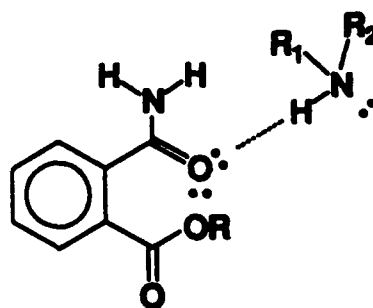
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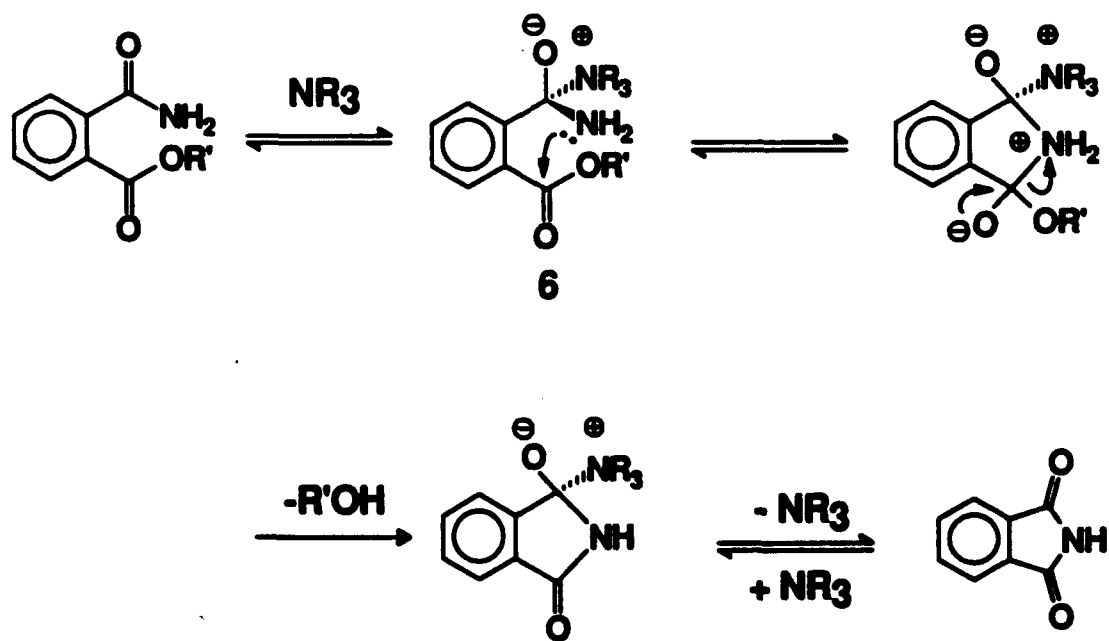
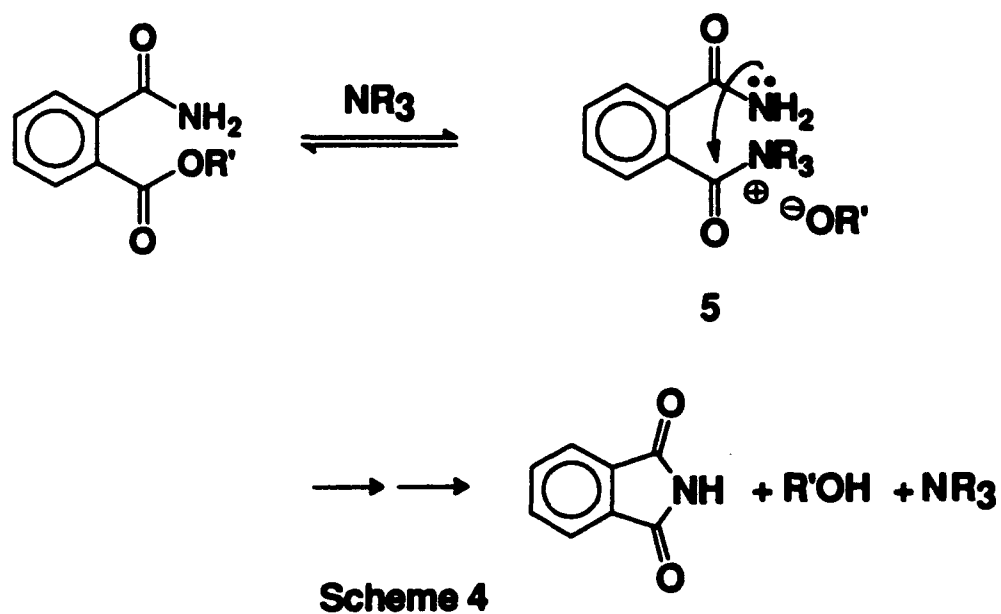
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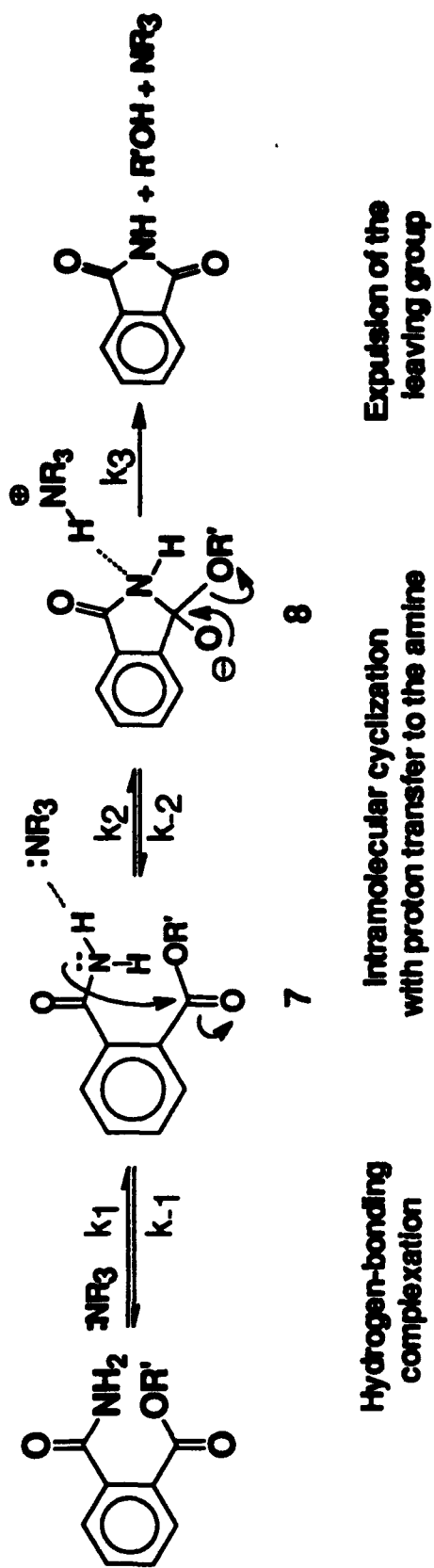


Type I

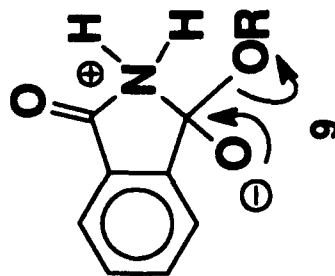


Type II

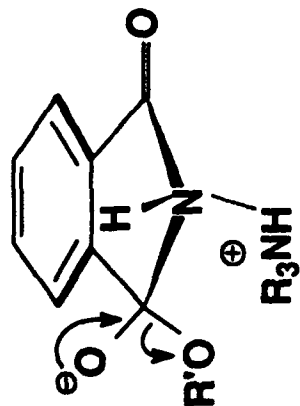




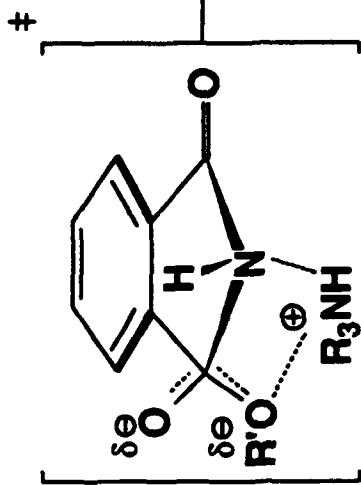
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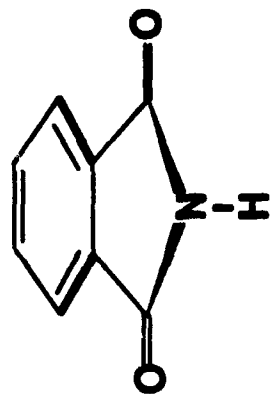
Charge separation decreases  
in the transition state



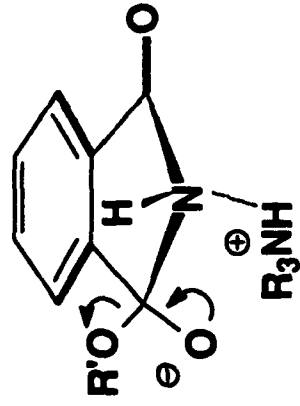
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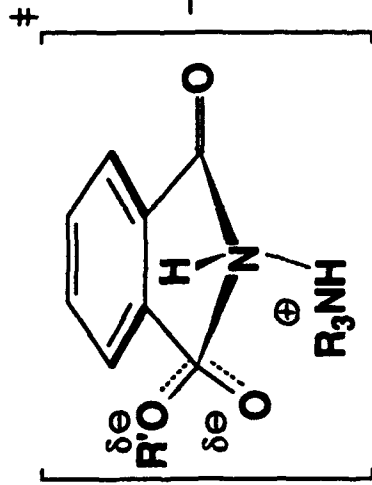
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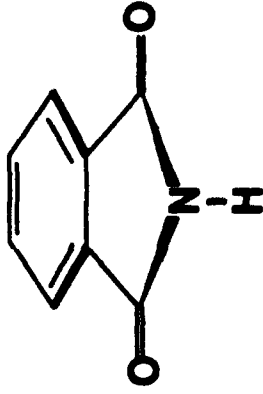
Charge separation increases  
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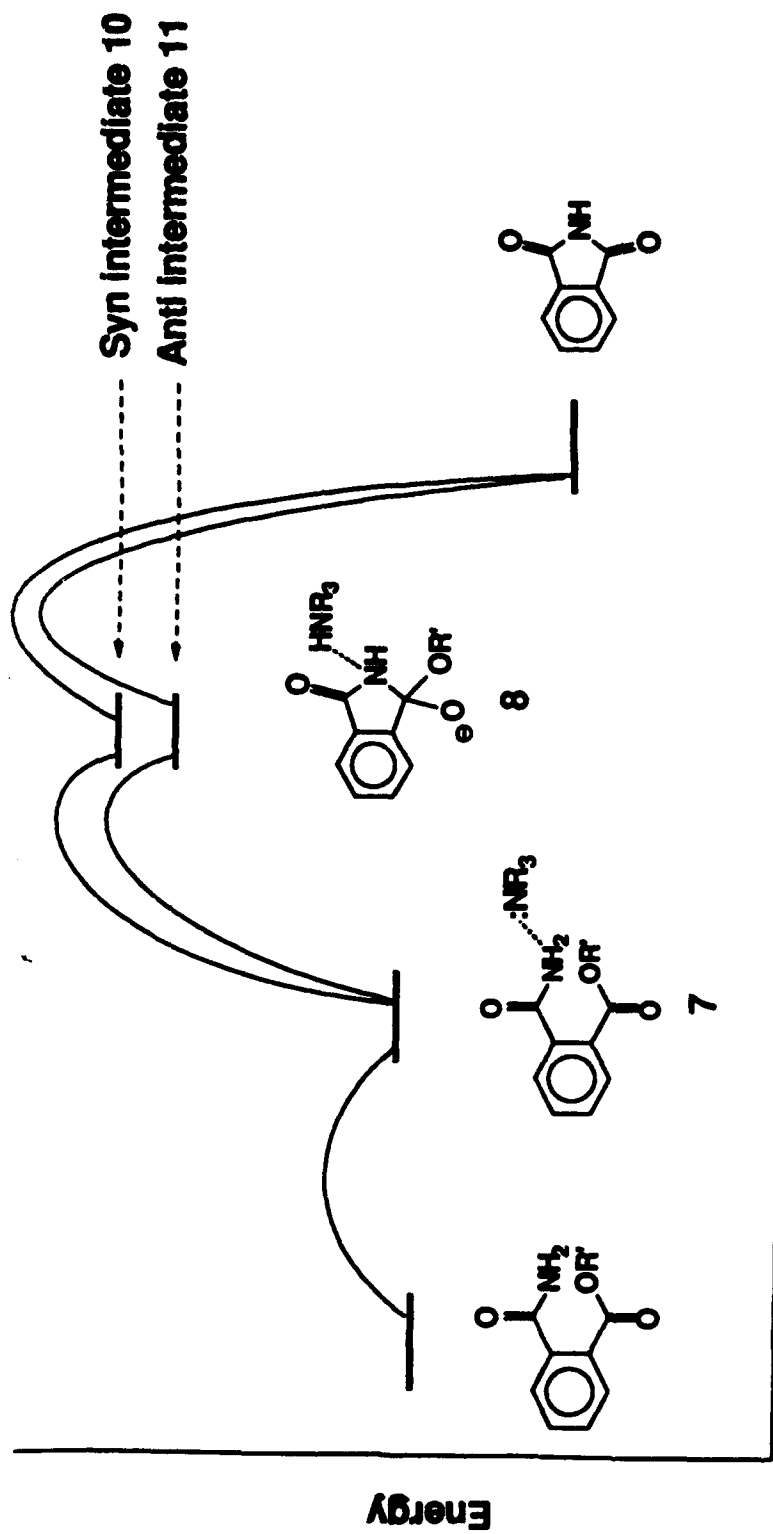
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13



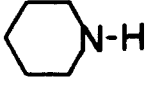
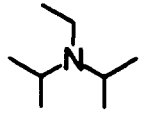
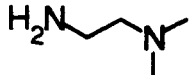
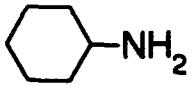
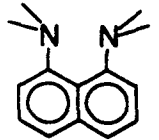
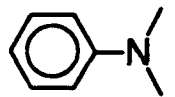
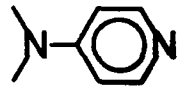


Scheme 7



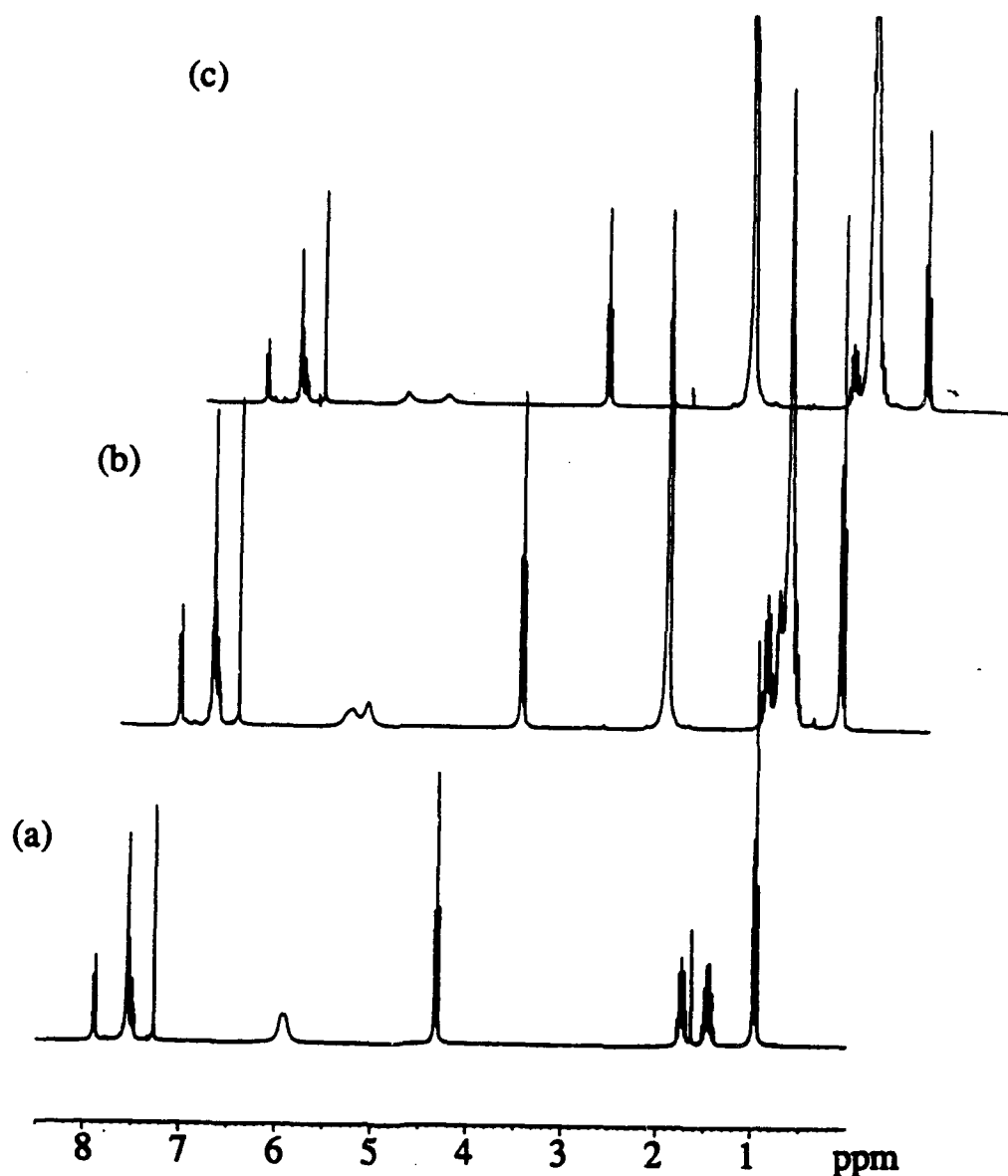
Scheme 8



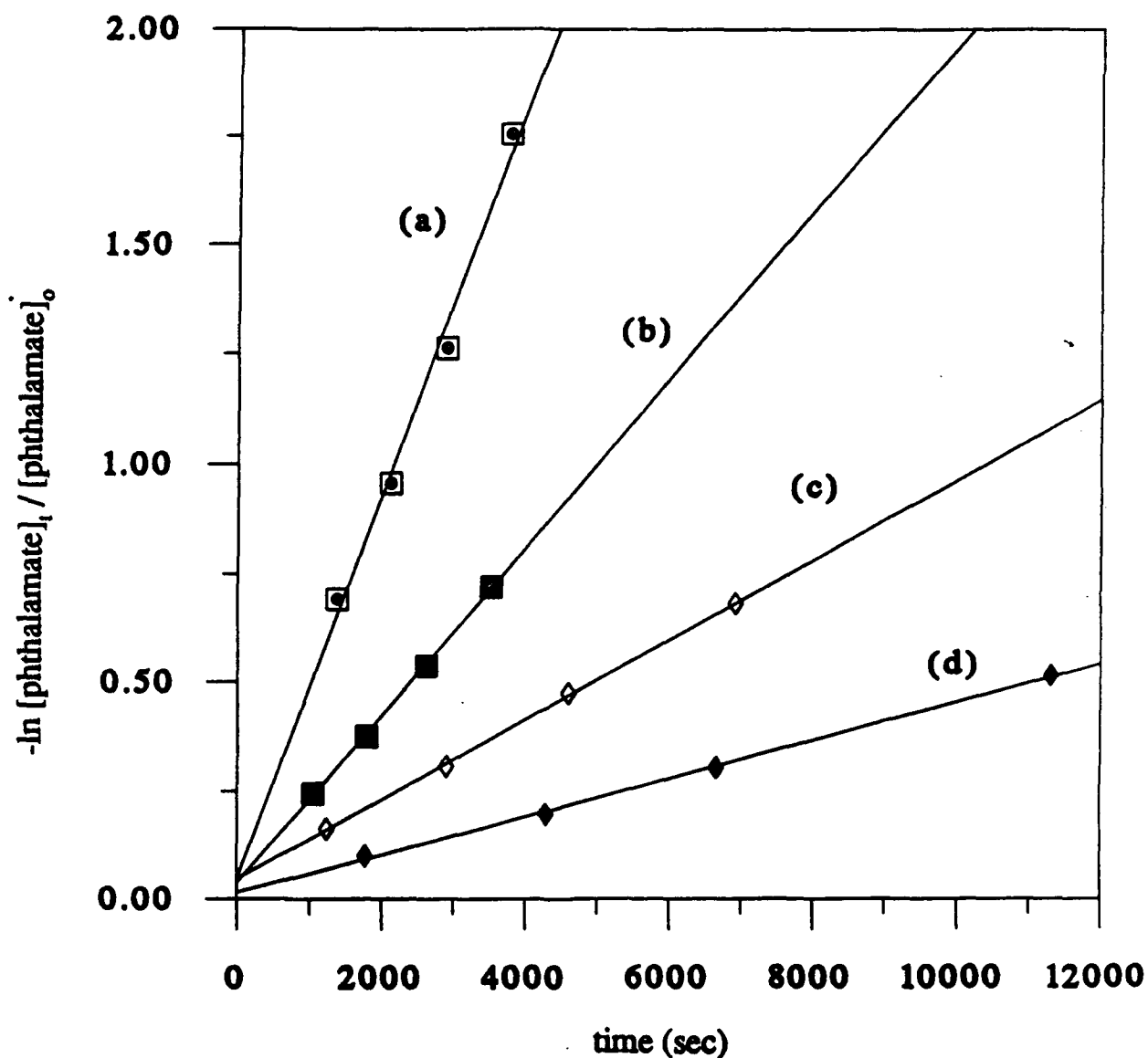
Table 1. Reaction Rate Constants for the Amine-Catalysed Imidization of Phenyl (Ph), 1,1,1-Trifluoroethyl (TFE), and *n*-Butyl (Bu) Phthalalamates at 40.1 °C in CDCl<sub>3</sub>.

Amine	M <sup>-1</sup> s <sup>-1</sup>			k(Ph)/k(Bu)
	10 <sup>4</sup> x k(Ph)	10 <sup>4</sup> x k(TFE)	10 <sup>4</sup> x k(Bu)	
	360 ± 25	250 ± 3	10.8 ± 0.1	33
H <sub>2</sub> N(CH <sub>2</sub> ) <sub>3</sub> NH <sub>2</sub>	260 ± 10	104 ± 10	3.5 ± 0.1	73
	230 ± 7	104 ± 10	0.11 ± 0.002	2100
H <sub>2</sub> N(CH <sub>2</sub> ) <sub>10</sub> NH <sub>2</sub>	44 ± 2	----	2.8 ± 0.1	16
	35 ± 1	----	0.98 ± 0.06	47
	32 ± 3	----	----	----
	3.1 ± 0.2	< 1.0	No reaction <sup>a</sup>	----
	No reaction <sup>a</sup>	----	----	----
	----	----	0.21 ± 0.02	----
	----	----	No reaction <sup>b</sup>	----
CH <sub>3</sub> -N 	----	----	No reaction <sup>b</sup>	----

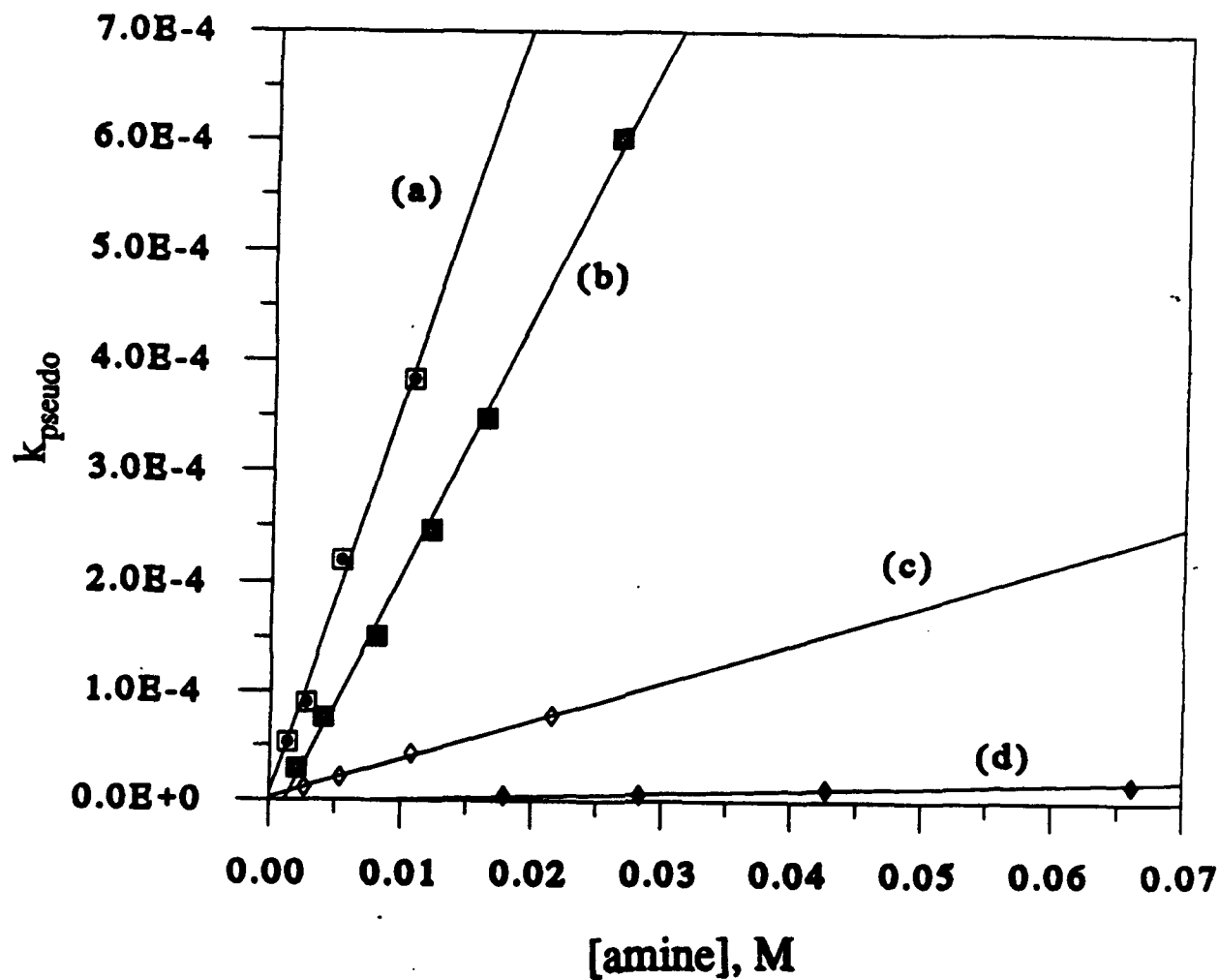
(a) [amine] = 0.15 M for 24 h. (b) [amine] = 0.7 M for 24 h.



**Figure 1**  $^1\text{H}$  NMR spectra of *n*-butyl phthalamate ( $3.2 \times 10^{-2} \text{ M}$ ) in  $\text{CDCl}_3$ : (a) without piperidine; (b) [piperidine] =  $9.4 \times 10^{-2} \text{ M}$ ; (c) [piperidine] =  $1.9 \times 10^{-1} \text{ M}$ . The broad singlet at 5.9 ppm is assigned to the amide proton. In the presence of piperidine, the broad singlet splits into two smaller signals. The down field shift signal is assigned to the proton that is hydrogen-bonded to piperidine through Type I interaction.



**Figure 2** Plot of  $-\ln [phthalamate]_t / [phthalamate]_0$  against reaction time for 1,3-diaminopropane (DAP) catalyzed imidization of phenyl phthalamate at 40.1 °C: (a)  $[DAP] = 1.78 \times 10^{-2} \text{ M}$ ; (b)  $[DAP] = 8.90 \times 10^{-3} \text{ M}$ ; (c)  $[DAP] = 4.45 \times 10^{-3} \text{ M}$ ; (d)  $[DAP] = 2.23 \times 10^{-3} \text{ M}$ . The solid lines are the least square fits to the points. The linearity of the linear least square fits indicates that the imidization is in pseudo first order to phenyl phthalamate. The pseudo first order rate constants are obtained from the slopes of the solid lines.



**Figure 3** Plot of  $k_{\text{pseudo}}$  against the concentrations of amines for the imidization of phenyl phthalamate: (a) piperidine; (b) diisopropylethylamine; (c) *N,N*-dimethyl-1,2-ethylenediamine; (d) 1,8-bis(dimethylamino)naphthalene (proton sponge). The linearity of the least square fits indicates that the imidization is in first order to amines.