Kinetics and Mechanisms of Gas Phase Elimination of Ethyl 1-piperidine Carboxylate, Ethyl Pipecolinate, and (Revisited) Ethyl 1-methyl Pipecolinate

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ABSTRACT: The kinetics of the gas-phase elimination of the title compounds has been determined in a static reaction system over the temperature range of 340–420°C and pressure range of 45–96 Torr. The reactions proved to be homogeneous, unimolecular, and obey a first-order rate law. The estimated rate coefficients are represented by the following Arrhenius expressions: Ethyl 1-piperidine carboxylate

$$\log k_1(\mathrm{s}^{-1}) = (12.61 \pm 0.11) - (191.1 \pm 1.4)\,\mathrm{kJ\,mol}^{-1}(2.303\,RT)^{-1},\ r = 0.9999$$

Ethyl pipecolinate

$$\log k_1(\mathrm{s}^{-1}) = (12.87 \pm 0.16) - (204.3 \pm 2.1)\,\mathrm{kJ\,mol}^{-1}(2.303\,RT)^{-1},\ r = 0.9998$$

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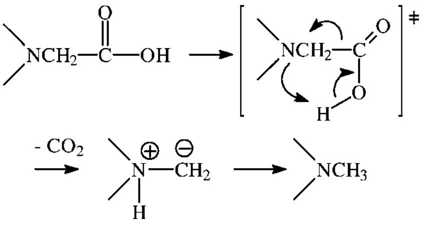
Ethyl 1-methyl pipecolinate

$$\log k_1(\mathrm{s}^{-1}) = (13.34 \pm 0.32) - (209.4 \pm 4.0)\ \mathrm{kJmol}^{-1}(2.303\,RT)^{-1},\ r = 0.9992$$

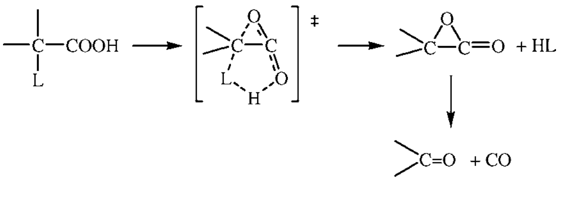
The first step of decomposition of these esters is the formation of the corresponding carboxylic acids and ethylene. The acid intermediate undergoes a very fast decarboxylation process. The mechanism of this elimination reactions is suggested on the basis of the kinetic and thermodynamic parameters. © 2005 Wiley Periodicals, Inc. Int J Chem Kinet 37: 383–389, 2005

INTRODUCTION

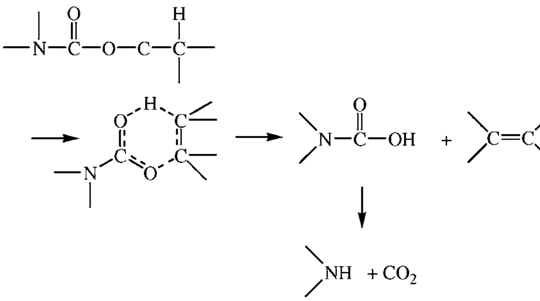
Low molecular weight amino acids are solids, and they are difficult to examine in gas phase elimination reactions. Moreover, these compounds on heating sinter or decompose into amorphous materials, and also are insoluble in most organic solvents. Their high solubility in water, forming zwitterions species, restricts their study as neutral molecules in the gas phase. In spite of these limitations, few recent works have reported the homogeneous, unimolecular gas phase elimination of *N*,*N*-dimethylglycine [1], picolinic acid [2], and *N*-phenylglycine [3]. These substrates as 2-substituted amino carboxylic acids undergo decarboxylation as shown in reaction (1).


(1)

The mechanism described in reaction (1) differs from the already reported both experimentally and theoretically the gas phase elimination of several types of 2-substituted carboxylic acids. The latter compounds are found to decarbonylate [4–10] as depicted in reaction (2)


L = Leaving Group: Cl, Br, OH, OR, OPh, OAc. (2)

The gas phase elimination of above-mentioned neutral amino acids [1–3] showed to be very reactive species in the gas phase. This fact was rationalized in terms of the N atom becoming more polarized when approaching to the acidic H of the COOH group, thus causing a lowering in the energy. Therefore, a very rapid decomposition may be expected. The fact that the neutral amino acids decompose rapidly in the gas phase is supported from the experimental results on the elimination kinetics of *N*,*N*-dimethylglycine [1], picolinic acid [2], and *N*-phenylglycine [3], when compared as product intermediates of their corresponding ethyl ester pyrolysis [1–3]. These results suggested the elimination kinetics of neutral amino acids in the gas phase may occur. An interesting fact is that when the N atom is adjacent to the acid side of carboxylic acid, that is carbamic acids, they are unstable molecules even at room temperature. Attempts to determine the kinetic and thermodynamic parameters from gas phase elimination of simple types of carbamic acid substrates are difficult. These organic acids have been described to be as intermediates of carbamates pyrolysis [11–20], according to the following general mechanistic consideration [reaction (3)].


(3)

In spite of the limitations to study the elimination of carbamic and α-amino acids in the gas phase, it is intended, if possible, to determine the kinetic and thermodynamic parameters of decarboxylation of these acid intermediates through a consecutive reaction from the corresponding ester decomposition. In addition to this fact, it was thought interesting to examine the extent to which nitrogen atom may influence decarboxylation process at the 1- and 2-position of the carboxylic acid intermediates. Consequently, this work aimed at examining the gas phase pyrolysis of ethyl 1-piperidine carboxylate, ethyl pipecolinate, and to revise ethyl 1-methylpipecolinate.

EXPERIMENTAL

The substrates ethyl 1-piperidine carboxylate (Aldrich), ethyl pipecolinate (Aldrich), and ethyl 1-methylpipecolinate (Aldrich) were distilled several times, and the fraction over 98.6% purity was used (GC-MS : Saturn 2000, Varian, with a DB-5MS capillary column 30 m × 0.53 mm. i.d., 0.53 μm film thickness). The quantitative chromatographic analysis of ethylene was determined by using a gas chromatograph HP 5710A with a Porapak Q (80-100 mesh). The identifications of the products piperidine and 1-methylpiperidine were made in a GC-MS (Saturn 2000, Varian with a DB-5MS capillary column 30 m × 0.25 mm. i.d., 0.25 μm).

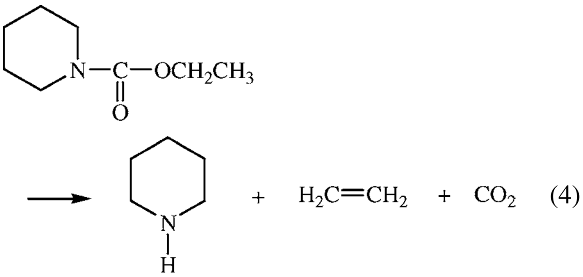
Kinetics

The kinetic determinations were carried out in a static reaction system as described before [21–23]. At each temperature, six to nine runs are carried out in our experiments. The rate coefficients were calculated from the pressure increase manometrically and/or by formation of ethylene product. The temperature was maintained within ±0.2°C through control with a Shinko DIC-PS 23TR resistance thermometer and was measured with a calibrated iron-Constantan type k thermocouple. No temperature gradient was observed along the reaction vessel. The starting materials were all injected directly into the reaction vessel with a syringe through a silicone rubber septum. The amount of substrate used for each reaction was ~0.05–0.1 mL.

RESULTS AND DISCUSSION

Ethyl 1-piperidine Carboxylate

The product of gas phase elimination of ethyl piperidine carboxylate are mainly piperidine, ethylene, and carbon dioxide [reaction (4)].


(4)

The experimental stoichiometry for the pyrolysis of this substrate [reaction (4)] requires $P_f/P_0 = 3.0$, where P_f and P_0 are the final and initial pressure, respectively. The average experimental P_f/P_0 at four different temperatures and 10 half-lives is 3.0 (Table I). Additional confirmation of stoichiometry (4) was obtained by comparing the pressure measurements with the quantitative analyses of ethylene formation (Table II).

The reaction can be said to be homogeneous since no significant effects on the rates were obtained on using both clean Pyrex and seasoned Pyrex vessels with a surface-to-volume ratio of 6.0 relative to the normal clean and seasoned vessels in these experiments (Table III). The presence of different proportions of toluene, a free radical suppressor, had no effect on the rates and no induction period was obtained (Table IV). The rates are reproducible with a relative standard deviation of not greater that 5% at a given temperature.

The rate coefficients for elimination, calculated from $k_1 = (2.303/t)\log[2P_0/(3P_0 - P_t)]$, are invariable to initial pressures (Table V), and the first-order plots of $\log(3P_0 - P_t)]$ against time t gave a good straight line for up to 60% decomposition. The variation of the rate coefficients with temperature is shown in Table VI. The experimental data were fitted to the Arrhenius equation shown in Table VI (Fig. 1), where 90% confidence limits from a least-squares procedure are given.

Table I Ratio of Final (P_f) to Initial (P_0) Pressure

Compound	Temperature (°C)	P_0 (Torr)	P_f (Torr)	P_f/P_0	Aver.
Ethyl 1-piperidine carboxylate	360.4	54.5	163.5	3.0	3.0
	370.5	59.5	178.5	3.0	
	380.8	60	174.0	2.9	
	391.0	59	177.5	3.0	
Ethyl pipecolinate	400.2	56	165	3.0	3.0
	410.4	64	184	2.9	
	420.0	59	173	2.9	
	430.5	64	203	3.0	

Table II Stoichiometry of the Reaction

Compound	Temperatures (°C)	Parameter	Value				
Ethyl 1-piperidine carboxylate	370.5	Time (min)	3	5	7	9	12
		Reaction (%) (pressure)	18.3	29.3	39.7	46.0	58.0
		Ethylene (%) (GC)	17.8	29.4	40.0	45.8	57.7
Ethyl pipecolinate	410.0	Time (min)	3	5	7	9	12
		Reaction (%) (pressure)	25.7	39.2	50.3	61.8	71.8
		Ethylene (%) (GC)	25.3	39.9	49.5	60.8	70.6

Table III Homogeneity of Pyrolysis Reactions

Compound	S/V (cm^{-1})[a]	$10^4 k_1$ (s^{-1})[b]	$10^4 k_1$ (s^{-1})[c]
Ethyl 1-piperidine carboxylate at 370.5°C	1	12.5 (±0.1)	12.8 (±0.1)
	6	12.5 (±0.2)	12.4 (±0.1)
Ethyl pipecolinate at 420.3°C	1	30.2 (±0.1)	30.9 (±0.1)
	6	29.6 (±0.2)	31.7 (±0.1)

[a] S = Surface area; V = volume.

[b] Clean Pyrex vessel.

[c] Vessel seasoned with allyl bromide.

Table IV Effect of Free Radical Inhibitor Toluene on the Reactions

Substrate	Temperature (°C)	P_s (Torr)	P_i (Torr)	P_i/P_s	$10^4\ k_1$ (s^{-1})
Ethyl 1-piperidine carboxylate	370.5	90	–	–	11.5
		66	117	1.8	12.6
		39	49	1.3	12.6
		33	51	1.6	12.4
Ethyl pipecolinate	420.0	64.5	–	–	30.1
		74.5	117	1.6	30.1
		94	190.5	2.0	30.3
		59	163	2.8	30.2

P_s = pressure substrate. P_i = pressure inhibitor.

Table V Invariability of the Rate Coefficients with Initial Pressure

Compound	Temp. (°C)	Parameters					
Ethyl 1-piperidine carboxylate	370.5	P_0 (Torr)	49.5	64	71	85	95.5
		$10^4\ k_1$ (s^{-1})	12.4	12.6	12.6	12.6	12.5
Ethyl pipecolinate	420.0	P_0 (Torr)	45	59	68	74.5	94.0
		$10^4\ k_1$ (s^{-1})	30.1	30.2	30.3	30.1	30.3

Table VI Variation of the Rate Coefficients with Temperatures

Substrate	Parameters	Values						
Ethyl 1-piperidine carboxylate	Temp. (°C)	341.0	350.9	360.4	370.5	380.8	391.0	
	$10^4\ k_1$ (s^{-1})	2.33	4.06	7.13	12.5	22.1	38.8	
	Rate equation $\log k_1$ (s^{-1}) = (12.61 ±0.11) – (191.1 ±1.4) kJ mol^{-1} (2.303 RT)$^{-1}$, $r = 0.9999$							
Ethyl pipecolinate	Temp. (°C)	380.2	390.1	400.2	410.4	420.3	430.5	
	$10^4\ k_1$ (s^{-1})	3.51	5.98	10.2	17.7	30.2	51.6	
	Rate equation $\log k_1$ (s^{-1}) = (12.87 ±0.16) – (204.3 ±2.1) kJ mol^{-1} (2.303 RT)$^{-1}$, $r = 0.9998$							
Ethyl 1-methyl pipecolinate	Temp. (°C)	361.8	371.2	380.5	390.5	398.5	410.5	419.7
	$10^4\ k_1$ (s^{-1})	1.35	2.36	4.05	6.90	12.6	21.6	38.0
	Rate equation $\log k_1$ (s^{-1}) = (13.34 ±0.32) – (209.4 ±4.0) kJ mol^{-1} (2.303 RT)$^{-1}$, $r = 0.9992$							

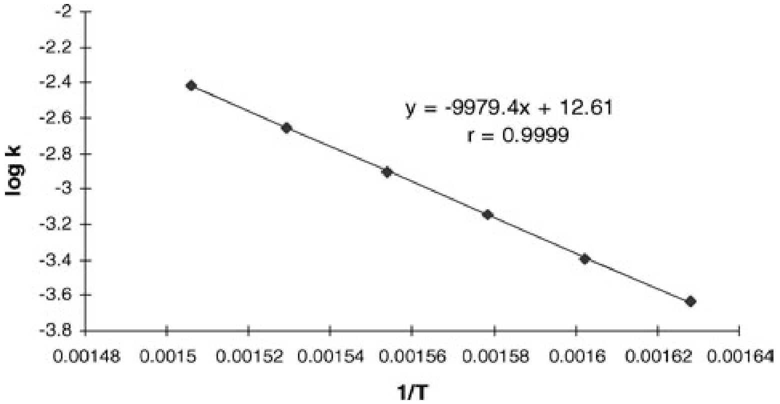
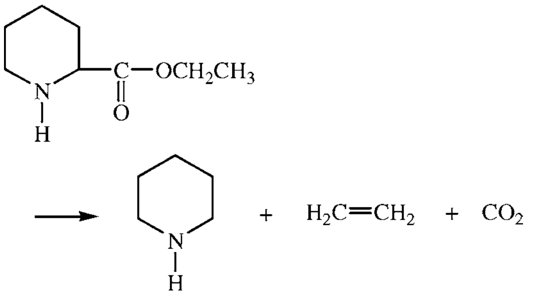


Figure 1 Graphic representation of the Arrhenius plot for the gas phase elimination of the ethyl-1-piperidine carboxylate.

Ethyl Pipecolinate

The elimination products of ethyl pipecolinate are piperidine, ethylene, and carbon dioxide [reaction (5)].



(5)

The theoretical stoichiometry (5) demands $P_f/P_0 = 3.0$. The average experimental P_f/P_0 obtained at four different temperatures and 10 half-lives is 3.0 (Table I). To verify stoichiometry (5), up to 70% decomposition, it was made by comparing the pressure measurements with those obtained by the quantitative GC analysis of the product ethylene (Table II). The effect of the surface area in the rate of elimination was examined by employing a vessel with a surface-to-volume ratio of six times greater than that of the normal vessel. The rate coefficient for product formation was unaffected on using both clean Pyrex and seasoned Pyrex vessels in these experiments (Table III). The reaction can be said to be homogeneous. Toluene inhibitor does not appear to have effect on the rates (Table IV), and no induction period was observed. The rates are reproducible with a relative standard deviation of not greater than 5% at a given temperature.

The first-order rate coefficients for ethyl pipecolinate, calculated from $k_1 = (2.303/t)$ log $[2P_0/(3P_0 - P_t)]$, were found to be independent of the initial pressure (Table V). The k-value, at a given temperature, is measured at each reaction time, and the average k-value is estimated within ±5% standard deviation. A plot of $\log(3P_0 - P_t)$ against time t gave a good straight line up to 70% decomposition. The temperature dependence of the rate coefficients and the corresponding Arrhenius equation are given in Table VI (Fig. 2) (90% confidence coefficients from a least-squares procedure).

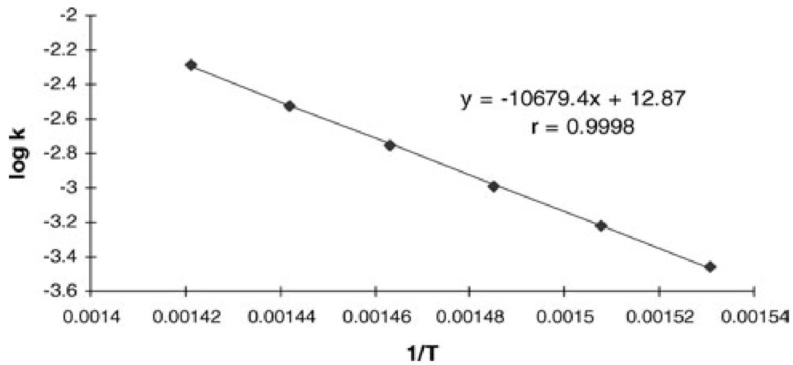


Figure 2 Graphic representation of the Arrhenius plot for the gas phase elimination of the ethyl pipecolinate.

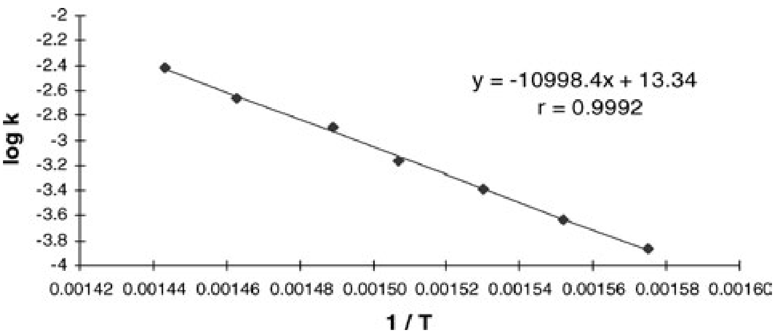
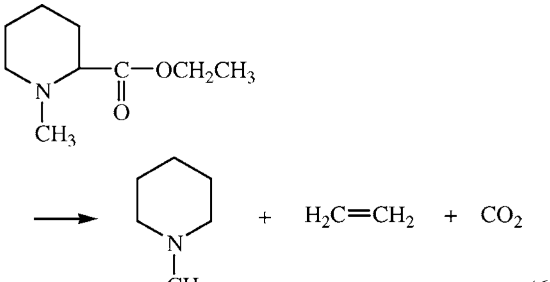


Figure 3 Graphic representation of the Arrhenius plot for the gas phase elimination of the ethyl-1-methylpipecolinate.

Ethyl 1-methylpipecolinate

In view of the small differences in rates of ethyl pipecolinate elimination (Table VI) when compared to the already reported data of ethyl 1-methylpipecolinate [2], led to us to reexamine the elimination kinetics of the latter compound. This verification is to assure an adequate argument relative to both substrates.



(6)

The stoichiometry for the reaction (6), the effect of the inhibitor, the examination of homogeneity of the reaction, and the invariability of the k-values with initial pressure were carried out in the same manner as described for the above-mentioned esters. However, the experimental variation of the rate coefficients with temperature and the corresponding Arrhenius equation are reported and given in Table VI (Fig. 3) (90% confidence limits from a least-squares procedure). The actual result was found to be quite similar to that described in the previous investigation [2].

According to Table VII, the electron-withdrawing effect of the nitrogen atom at the 1-position of ethyl piperidine carboxylate shows a faster rate of ethylene formation than when the N atom is at the 2-position as in ethyl pipecolinate. It is rather unfortunate that under the working reaction temperature, the kinetic parameters of the corresponding acids intermediates could not be estimated. It is well known that carbamic acids are more unstable and decarboxylate more rapidly than α-amino acids in the gas phase. The rate of the gas phase pyrolysis of ethyl 1-methylpipecolinate [2] was found to be a little faster in rate than ethyl pipecolinate. Because of this, the former substrate was revisited in order to verify their previous reported kinetic and thermodynamic data. The reexamination of ethyl 1-methylpipecolinate gave similar parameters reported before [2]. The apparent very small difference in rate between ethyl pipecolinate and ethyl 1-methylpipecolinate implies, from ring structure, steric acceleration of the methyl group of the latter compound. From products elimination and the results given in Table VII, ethyl piperidine carboxylate appears to proceed via a mechanism similar to carboxylic esters in the gas phase [24,25], while the carbamic acid intermediate decarboxylates through a four-membered cyclic transition state [reaction (7)]. Ethyl pipecolinate and ethyl 1-methylpipecolinate decompose, as expected, to ethylene and the corresponding neutral amino acid derivatives. These acid intermediates are unstable under the experimental condition and proceed to decarboxylate through a five-membered

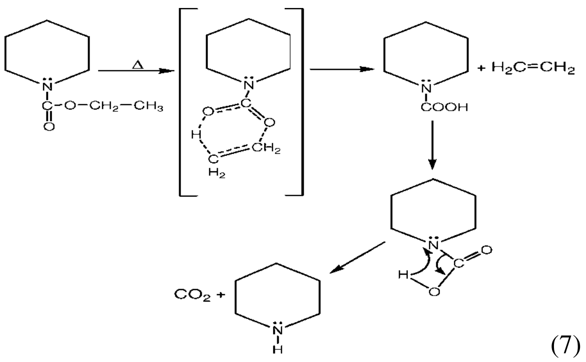
Table VII Kinetic and Thermodynamic Parameters at 390°C

Compound	$10^4\ k_1$ (s^{-1})	E_a (kJ/mol)	log A (s^{-1})	$\Delta S^{\neq}$ (J/mol K)	$\Delta H^{\neq}$ (kJ/mol)	$\Delta G^{\neq}$ (kJ/mol)
Ethyl 1-piperidine carboxylate	35.85	191.1 ± 1.4	12.61 ± 0.11	−18.4	185.6	197.8
Ethyl pipecolinate	5.95	204.3 ± 2.1	12.87 ± 0.16	−13.4	198.8	207.7
Ethyl 1-methylpipecolinate[a]	7.16	209.5 ± 3.9	13.36 ± 0.31	−4.1	204.0	206.7
Ethyl 1-methylpipecolinate[b]	6.96	209.4 ± 4.0	13.34 ± 0.32	−4.4	203.9	206.8

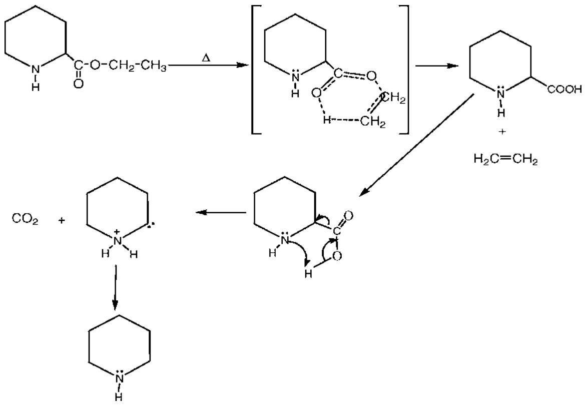
[a] After [2].

[b] This work.

cyclic transition state as depicted in reaction (8).



(7)



(8)

The gas phase pyrolysis of pure samples of the acid intermediates of reaction (8), i.e. pipecolinic acid (Aldrich) and 1-methylpipecolinic acid (from hydrolysis of ethyl 1-methylpipecolinate) were difficult to work in the reaction static system. These acids are solids with high melting point and could not be dissolved in most organic solvents. To prepare the pure acid from hydrolysis of ethyl 1-piperidine carboxylate was also unsuccessful, because the carbamic acid intermediate is unstable and leads to the formation of piperidine as the final product.

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