Mechanism and proton activating factors in base-induced β-elimination reactions of 2-(2-chloroethyl)pyridine †

Sergio Alunni * and Alessandra Busti

Dipartimento di Chimica, Università di Perugia, 06100, Perugia, Italy

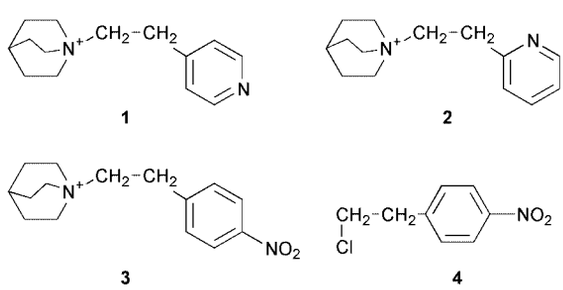
Received (in Cambridge, UK) 4th December 2000, Accepted 14th March 2001
First published as an Advance Article on the web 9th April 2001

The substrate 2-(2-chloroethyl)pyridine reacts in OH^-/H_2O, 50 °C, $\mu = 1$ M KCl by an elimination reaction with the formation of 2-vinylpyridine; the second order rate constant is $k^N_{OH} = 4.59 \times 10^{-4}$ dm^3 mol^{-1} s^{-1}. In acetohydroxamate–acetohydroxamic acid buffers, the elimination reaction competes with the S_N2 reaction of the acetohydroxamate nucleophile. Studies of acid–base catalysis at pH values ranging from 8.42 to 9.42 are in agreement with an E1cb irreversible mechanism, where carbon deprotonation occurs from the substrate protonated at the nitrogen of the pyridine ring (**NH$^+$**), even if it is present at very low concentrations with respect to the unprotonated substrate (**N**) under the reaction conditions. The value for the reactivity ratio between **NH$^+$** and **N** is of the order of 10^5. The strong reactivity of **NH$^+$** is attributed to the high stability of the carbanion intermediate formed; this intermediate has an enamine structure.

Introduction

β-Elimination reactions are processes of interest due to the various possible mechanisms that can operate.[1–3] It has been shown that with systems with high β-activation (with respect to the leaving group), such as *p*- or *o*-nitrophenyl groups, and with tertiary amines as the leaving group, an E1cb mechanism is followed, which involves a carbanion intermediate.[4–7]

In a previous paper[8] we showed that β-elimination reactions of *N*-[2-(4-pyridyl)ethyl]quinuclidinium (**1**) and *N*-[2-(2-pyridyl)-ethyl]quinuclidinium (**2**) salts in acetohydroxamate–acetohydroxamic acid‡ buffers at pHs ranging from 8.42 to 9.42, with the formation of 4- or 2-vinylpyridine, respectively, proceed by an E1cb mechanism. The pK_a values of the conjugate acid of the 4- and 2-isomers are 4.85 and 3.81 respectively[8] (50 °C, $\mu = 1$ M KCl). The concentration of the substrate protonated at the nitrogen of the pyridine ring (**NH$^+$**) is much lower than that of the unprotonated substrate (**N**) under the reaction conditions. However, it was demonstrated that carbon deprotonation occurs from **NH$^+$**, because it was ≈10^6 times more reactive than **N**. The greater reactivity of **NH$^+$** with respect to **N** (proton activating factor, PAF[9–11]) can be attributed to the strong stabilization of the intermediate carbanion formed from **NH$^+$** due to resonance; this carbanion has an enamine structure. With these two previously studied systems, a reversible E1cb mechanism, $(E1cb)_R$, was demonstrated, with the rate for the leaving group expulsion being comparable to the rate of carbanion reprotonation. In the present work, we have studied the same reaction with 2-(2-chloroethyl)pyridine (**5**) with two objectives. The first was to study the mechanistic implications of changing the leaving group from a charged tertiary amine to chlorine. This structural variation implies a lower barrier for leaving group expulsion. The same structural variation also implies a change from an $(E1cb)_R$ mechanism for *N*-[2-(*p*-nitrophenyl)ethyl]quinuclidinium (**3**) salt to an E2 concerted mechanism for 2-(*p*-nitrophenyl)ethyl chloride (**4**).[12] In this work we wanted to check whether the barrier for chlorine leaving group expulsion disappeared, with the process then becoming concerted, or if the intermediate carbanion had a significant lifetime,[13] such that the mechanism remains E1cb. The second objective is related to the fact that it is very difficult to distinguish between an E2 concerted and an E1cb irreversible $[(E1cb)_I]$ mechanism. In systems activated by heteroaromatic substrates with basic nitrogen atoms, we wanted to see if a study of acid–base catalysis and an evaluation of PAF would make it possible to distinguish between these two mechanisms.



Results and discussion

Kinetic study in OH^-/H_2O

The kinetics of elimination reactions with 2-(2-chloroethyl)-pyridine (**5**) in OH^-/H_2O, 50 °C, $\mu = 1$ M KCl, were followed by monitoring (initial rates) the formation of 2-vinylpyridine (**6**) at $\lambda = 290$ nm. The second order rate constant is $k^N_{OH} = 4.59 \times 10^{-4}$ dm^3 mol^{-1} s^{-1}. In this reaction medium, the reacting species is the unprotonated substrate, **N**, due to the high $[OH^-]$ used. This value can be compared with the rate constant for the related substrate *N*-[2-(2-pyridyl)ethyl]quinuclidinium (**2**), $k^N_{OH} = 2.71 \times 10^{-4}$ dm^3 mol^{-1} s^{-1}. The second order kinetic law for the elimination from **5** is in agreement with all three possible mechanisms: the concerted E2, the E1cb reversible $(E1cb)_R$ or the E1cb irreversible $(E1cb)_I$ mechanism. However a study of H/D exchange in OD^-/D_2O, 50 °C, $\mu = 1$ M KCl has shown the absence of deuterium incorporation into the reagent during the elimination reaction. This result excludes the $(E1cb)_R$ mechanism in this reaction medium.

Study in acetohydroxamate–acetohydroxamic acid buffer

In this reaction medium the products were either 2-vinyl-pyridine (**6**), indicated as E (elimination reaction) and 2-(2-

† Electronic supplementary information (ESI) available: pseudo-first order rate constants for β-elimination reactions. See http://www.rsc.org/suppdata/p2/b0/b009716k/

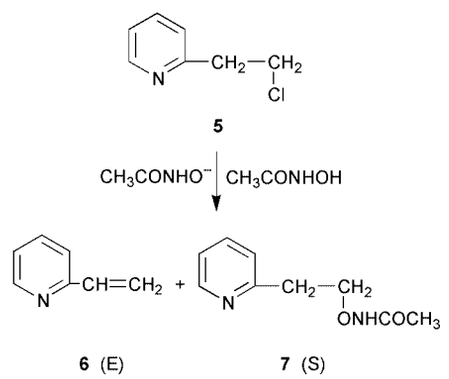
‡ *N*-Hydroxyacetamide.

 DOI: 10.1039/b009716k

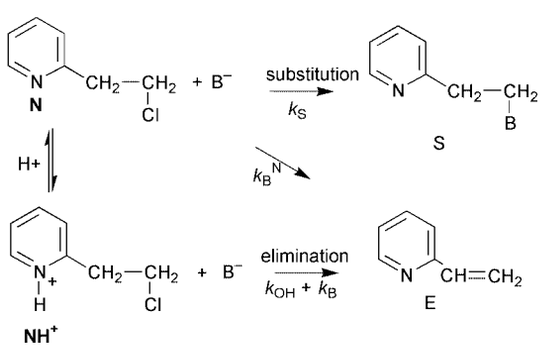
Table 1 Values of the ratio between the elimination and S_N2 reaction products, [E]/[S], obtained from **5** in an acetohydroxamate–acetohydroxamic acid buffer, 50 °C, $\mu = 1$ M KCl, at various pH, [B^-], [BH]

Ph	[B^-]/mol dm^{-3}	[BH]/mol dm^{-3}	[E]/[S]
8.42	0.05	0.269	8.47
8.42	0.02	0.108	8.33
9.15	0.2	0.2	1.82
9.15	0.2	0.2	2.04
9.15	0.05	0.05	2.46
9.38	0.2	0.118	1.19
9.38	0.048	0.028	1.66

pyridyl)ethyl acetohydroxamate (**7**) indicated as S (nucleophilic substitution reaction) (see Scheme 1). The ratio of the concentrations of the two products, [E] : [S], determined at various pH values and with different [B^-] and [BH] are reported in Table 1. The experimental data are in agreement with the process shown in Scheme 2.



Scheme 1



Scheme 2

Assuming that the elimination reaction follows an $(E1cb)_I$ mechanism, the k_{obs}(elimination) is expressed by eqn. (2) (see later), while k_{obs}(substitution) = k_s[B^-]. Eqn. (1) can then be

$$[B^-]\frac{[E]}{[S]} = \frac{k_0}{k_S} + \frac{k_B{}^N}{k_S}[B^-] + \frac{k_B K_a{}^T}{k_S K_a{}^N}[BH] \qquad (1)$$

derived (neglecting the term k^N_{OH} [OH^-] because its contribution is very small), where $K_a{}^T$ is the acid dissociation constant of acetohydroxamic acid,[8] $K_a{}^T = 0.71 \times 10^{-9}$ M, 50 °C, $\mu = 1$ M KCl; $k_0 = k_{OH}$ [OH^-][H^+]/$K_a{}^N$.

Multiple regression analysis with the dependent variable [B^-][E]/[S] and the independent variables [B^-] and [BH] gives the equation [B^-][E]/[S] = 0.011 + 0.36[B^-] + 1.47[BH] with values of $R = 0.9941$ and $R^2 = 0.9881$. The good correlation obtained supports the process shown in Scheme 2. Therefore the S_N2 reaction occurs from the unprotonated substrate, **N** (there is no nitrogen protonation required in this process), while the elimination reaction occurs from the protonated substrate, **NH^+**. The acid–base catalysis for the elimination reaction will be discussed in the next section; for the meaning of the rate constants, see the following section and Scheme 2.

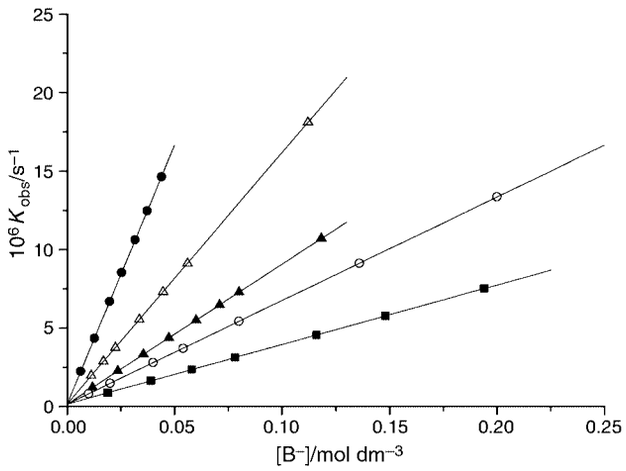


Fig. 1 Dependence of the k_{obs} (s^{-1}), on [acetohydroxamate] at various pH values for substrate **5**. Solid square pH = 9.42: $y = (0.18 \times 10^{-6}) + (4.52 \times 10^{-5})x$, $r = 0.9928$; open circle pH = 9.15: $y = (0.09918 \times 10^{-6}) + (6.9 \times 10^{-5})x$, $r = 0.9921$; solid triangle pH = 9.02: $y = (0.014 \times 10^{-6}) + (9.1 \times 10^{-5})x$, $r = 0.9940$; open triangle pH = 8.74: $y = (0.496 \times 10^{-6}) + (13.9 \times 10^{-5})x$, $r = 0.9978$; solid circle pH = 8.42: $y = (0.66 \times 10^{-6}) + (33.9 \times 10^{-5})x$, $r = 0.9971$.

Acid–base catalysis

Pseudo-first order rate constants (k_{obs}, s^{-1}, initial rates) were determined for the elimination reaction in acetohydroxamate–acetohydroxamic acid buffer at different pH values by following the formation of 2-vinylpyridine (**6**) at $\lambda = 290$ nm, H_2O, 50 °C, $\mu = 1$ M KCl ($\varepsilon = 3584$ dm^3 mol^{-1} cm^{-1} in the reaction conditions[8]). The pK_a of acetohydroxamic acid[8] is 9.15 at 50 °C, H_2O, $\mu = 1$ M KCl. It should be noted that the presence of the competing substitution reaction is irrelevant in the kinetic studies by initial rates (≈3% of the reaction), because the product of the S_N2 reaction, 2-(2-pyridyl)ethyl acetohydroxamate (**7**) does not absorb significantly at $\lambda = 290$ nm at its concentration in the kinetic experiments. In the following discussion we call the substrate unprotonated at the basic nitrogen of the pyridine ring **N**, and its conjugated acid, **NH^+**. The pK_a of **NH^+** is 4.91, H_2O, 50 °C, $\mu = 1$ M KCl. The plot of k_{obs} s^{-1} *vs.* acetohydroxamate concentration, [B^-], at five pH values (8.42, 8.74, 9.02, 9.15, 9.42) is shown in Fig. 1.

As can be seen in Fig. 1, there is a linear dependence of k_{obs} on [B^-], while the slope of the plots is directly dependent on the [H^+]. This indicates that the reacting species which undergoes carbon deprotonation is **NH^+**, as will be demonstrated in the kinetic analysis. Two possible mechanisms are in agreement with this result: a concerted E2 mechanism from **NH^+** or an E1cb irreversible mechanism from **NH^+**. The greater reactivity of **NH^+** with respect to **N** (proton activating factor, PAF) is in agreement with the E1cb mechanism. This mechanism is shown in Scheme 3.

In the case of the $(E1cb)_I$ mechanism, $k_2 > k_{BH}$[BH] and eqn. (2) holds when the competition with the unprotonated substrate, **N**, is also taken into account.

$$k_{obs} = k_0 + k_{OH}{}^N[OH^-] + k_B{}^N[B^-] + k_B[B^-][H^+]/K_a{}^N \qquad (2)$$

In eqn. (2) where k_0 is the first order rate constant for the reaction of **NH^+** at [buffer] = 0; it represents the reaction of **NH^+** with OH^-: $k_0 = k_{OH}[OH^-][H^+]/K_a{}^N$. $k^N_{OH} = 4.59 \times 10^{-4}$ dm^3 mol^{-1} s^{-1}; k^N_B is the second order rate constant for carbon

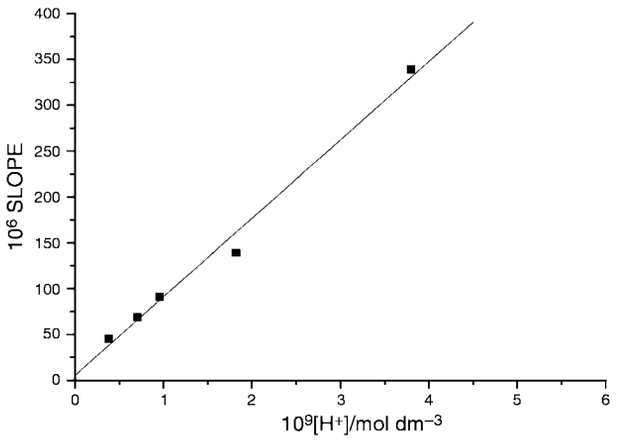
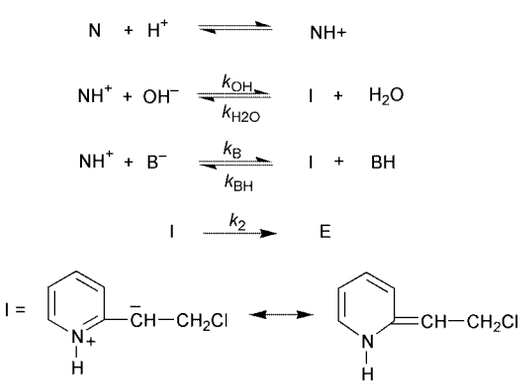


Fig. 2 Plot of the slopes obtained from eqn. (1) and Fig. 1 *versus* [H^+]. Linear regression analysis gives the equation: $y = (5.51 \times 10^{-6}) + (85.54 \times 10^3)x$, $r = 0.9941$.



Scheme 3

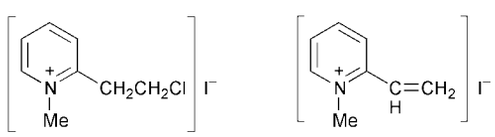
deprotonation from **N**; $K_a^N = 1.23 \times 10^{-5}$ mol dm^{-3} s^{-1} is the acid dissociation constant of the conjugate acid of **5** (nitrogen deprotonation). It should be noted that the alternative mechanism that involves carbon deprotonation from **N** to give the related carbanion, followed by nitrogen protonation to give the intermediate **I**, independent of the rate determining step, would follow a kinetic law different from that of eqn. (2). It would be a general base catalysis without the term which contains [H^+]. This reaction path can therefore be excluded.

Eqn. (2) predicts that a plot of k_{obs} *vs.* [B^-] at constant pH is linear with intercept $k_0 + k_{OH}^N[OH^-]$ and slope $k_B^N + k_B[H^+]/K_a^N$. Even though the intercepts of the plots are low and the standard deviations high, it is possible to calculate the value of k_B from the values of the slope. In fact, the plot of slope *versus* [H^+] is shown in Fig. 2. Linearity is observed, as expected from eqn. (2). From the slope of this plot a value of $k_B = 1.05$ dm^3 mol^{-1} s^{-1} was calculated. The value of the intercept is $k_B^N = 5.5 \times 10^{-6}$ dm^3 mol^{-1} s^{-1}. The contribution of **N** to the reaction is therefore very limited. The k_B value, the second order rate constant for carbon deprotonation from $\mathbf{NH}^+$ in H_2O, 50 °C, $\mu = 1$ M KCl, induced by acetohydroxamate base, can be compared with $k_B = 20$ dm^3 mol^{-1} s^{-1} previously[8] determined for the related substrate *N*-[2-(2-pyridyl)ethyl]quinuclidinium (**2**). The larger k_B value for the system with the charged tertiary amine leaving group could be related to the greater stabilization of the negative charge in the carbanion intermediate by the charged leaving group relative to the chlorine leaving group. In order to compare the reactivity of $\mathbf{NH}^+$ with that of **N**, the proton activating factor, an estimate of k_B^N for 2-(2-chloroethyl)-pyridine (**5**) with acetohydroxamate, can be made by extending the previously[8] proposed correlation to our system: $\log k_B^N = -1.4 + 1.1 \log k_{OH}^N$. From the known value of $k_{OH}^N = 4.59 \times 10^{-4}$ dm^3 mol^{-1} s^{-1}, a value of $k_B^N = 8.5 \times 10^{-6}$ dm^3 mol^{-1} s^{-1} is obtained. The value of $k_B^N = 5.5 \times 10^{-6}$ dm^3 mol^{-1} s^{-1} calculated from the intercept of the plot in Fig. 2 is associated with a high standard deviation (SD = 10.4×10^{-6}); however this value is close to that obtained by the linear free energy correlation and we have taken the average of two values in order to estimate $k_B^N = 7.6 \times 10^{-6}$ dm^3 mol^{-1} s^{-1}. The ratio k_B/k_B^N is then equal to 1.38×10^5. This PAF value can be compared with those determined[8] in the same reaction for *N*-[2-(2-pyridyl)-ethyl]quinuclidinium (**2**), PAF = 5.2×10^6 and *N*-[2-(4-pyridyl)-ethyl]quinuclidinium (**1**), PAF = 2.7×10^5. For these two substrates an E1cb mechanism has been demonstrated. The similarity of the PAF values for the three substrates suggests the same mechanism involving a carbanion intermediate; the large increase in reactivity due to the protonation of the nitrogen of the pyridine ring, can be explained by the presence of an intermediate carbanion with enamine structure[8] (**I** in Scheme 3).

The E2 concerted process does not require nitrogen protonation. It can be concluded that in these systems, it is useful to determine the PAF because this technique distinguishes an $(E1cb)_I$ or E2 mechanism. The lower PAF value for 2-(2-chloroethyl)pyridine (**5**) with respect to that of *N*-[2-(2-pyridyl)ethyl]-quinuclidinium (**2**) could indicate that a smaller negative charge develops in the transition state at the carbon atom which is deprotonated.

Reactivity ratio k_{OH}[1-methyl-2-(2-chloroethyl)pyridinium iodide)]/k_{OH}^N[2-(2-chloroethyl)pyridine]

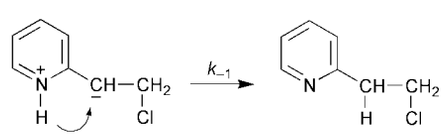
The second order rate constant for the elimination reaction of 1-methyl-2-(2-chloroethyl)pyridinium iodide (**8**) in OH^-/H_2O, 25 °C, $\mu = 1$ M KCl is $k_{OH} = 17.9$ dm^3 mol^{-1} s^{-1}. The k_{OH}^N value (initial rates) in OH^-/H_2O, 25 °C, $\mu = 1$ M KCl with 2-(2-chloroethyl)pyridine (**5**) is $k_{OH}^N = 2.6 \times 10^{-5}$ dm^3 mol^{-1} s^{-1}. The ratio between the rate constant for the methylated substrate and the non-methylated one is 6.88×10^5. This value is similar to the PAF value previously discussed, $k_B/k_B^N = 1.38 \times 10^5$. This similarity supports the proposed interpretation.



8 **9**

H/D exchange

NMR studies of H/D exchange with 2-(2-chloroethyl)pyridine (**5**) in acetohydroxamate–acetohydroxamic acid buffer, D_2O, 50 °C, $\mu = 1$ M KCl, showed no incorporation of deuterium in the β position of the substrate (with respect to the chlorine leaving group) during the elimination reaction. As an example, at [B^-] = [BD] = 0.15 M, when the olefin formed reached 42%, no deuterium incorporation on the remaining 2-(2-chloroethyl)pyridine (**5**) was observed. This result is in agreement with the $(E1cb)_I$ mechanism. Also, the significance of an intramolecular proton-transfer, Scheme 4, in the intermediate



Scheme 4

carbanion can be excluded; in fact, the significance of k_{-1} competing with the elimination reaction would imply the presence of H/D exchange.

Conclusion

2-(2-Chloroethyl)pyridine (**5**) in acetohydroxamate–aceto-

hydroxamic acid buffers at pHs ranging from 8.42 to 9.42 at 50 °C, $\mu = 1$ M KCl gives an elimination reaction with the formation of 2-vinylpyridine (**6**). Studies of acid–base catalysis are in agreement with an E1cb irreversible mechanism, with carbon deprotonation occurring from $\mathbf{NH^+}$, the conjugate acid of **5**, even if the concentration of this species is much lower than that of **N**. The reactivity of $\mathbf{NH^+}$ is much greater than that of **N** in the elimination reaction, with a value of $k_B/k_B^N = 1.38 \times 10^5$. This greater reactivity of $\mathbf{NH^+}$ with respect to **N** can be explained by the large stability by resonance of the intermediate carbanion (**I**), which has an enamine structure. The system consistently showed an absence of H/D exchange in acetohydroxamate–acetohydroxamic acid buffer, D_2O, 50 °C, $\mu = 1$ M KCl.

Experimental

Materials

Glass distilled and freshly boiled water was used throughout. Reagent grade potassium chloride, acetohydroxamic acid, 2-(2-hydroxyethyl)pyridine and 2-vinylpyridine were purchased from Aldrich.

2-(2-Chloroethyl)pyridine (5). A mixture of 2-(2-hydroxyethyl)pyridine, (6 g, 48.2 mmol), $P(Ph)_3$ (11 g, 40 mmol) and 17 ml of $CHCl_3$ were left to react at room temperature for 72 h. The solution was hydrolyzed and extracted with $CHCl_3$. The solvent was removed by rotary evaporation and the residue treated with *n*-hexane. The mixture was filtered, the solution taken to dryness and the residue again treated with *n*-hexane. Evaporation of the solvent by rotary evaporation gave 1.5 g of oil which was chromatographed on silica gel (Et_2O–*n*-hexane 70 : 30), to give 1.1 g of **5**. Found: C, 59.4; N, 9.7; H, 5.8. Calc. for C_7H_8NCl: C, 59.4; N, 9.9; H, 5.7%. (200 MHz, D_2O) δ_H 3.2 (2H, t, CH_2), 3.9 (2H, t, CH_2), 7.1–7.4 (2H, m, Ar), 7.6 (1H, t, Ar), 8.5 (1H, d, Ar). *m*/*z* 140 [$(M - 1)^+$, 9%], 142(3), 106(100), 79(28).

2-(2-Pyridyl)ethyl acetohydroxamate (7). A mixture of 2-vinylpyridine (0.7 g, 6.66 mmol), acetohydroxamic acid (1.5 g, 20 mmol), 3.3 M KOH (3.3 ml) in 3 ml of CH_3CN was left to react for 24 h at room temperature and for 24 h at 50 °C. The solvent was removed by rotary evaporation and the residue extracted three times with $CHCl_3$. The solvent was removed under reduced pressure and the remaining oil purified by column chromatography with silica gel ($CHCl_3$) to give 110 mg of **7**. (200 MHz, CD_3OD) δ_H 1.6 (3H, s, CH_3), 2.9–3.0 (2H, m, CH_2), 3.9–4 (2H, m, CH_2), 7.0–7.2 (2H, m, Ar), 7.5–7.6 (1H, m, Ar), 8.2 (1H, d, Ar). *m*/*z* 180 (M^+, 2%), 138(1), 122(41), 106(100).

1-Methyl-2-(2-chloroethyl)pyridinium iodide (8). A mixture of 2-(2-chloroethyl)pyridine (300 mg, 2.1 mmol), CH_3I (3.4 g, 24 mmol) and 6 ml of CH_3COCH_3 was left to react at room temperature for 24 h with magnetic stirring. The solvent was removed under rotary evaporation and the solid washed three times with Et_2O. The residue was washed with CH_3COCH_3 and the solid obtained was dried under vacuum to give 120 mg of **8**. Mp 95 –99 °C. (200 MHz, D_2O) δ_H 3.4 (2H, t, CH_2), 3.9 (2H, t, CH_2), 4.1 (3H, s, CH_3), 7.7–8.6 (4H, m, Ar).

1-Methyl-2-vinylpyridinium iodide (9). A mixture of 2-vinylpyridine (700 mg, 6.66 mmol), CH_3I (4.5 g, 31 mmol) in 10 ml of CH_3OH was left to react under magnetic stirring for 48 h at room temperature. The solvent was removed under rotary evaporation and the solid washed three times with Et_2O. After drying under vacuum a pale solid (400 mg) **9**, was recovered. Mp 221–226 °C (dec.). (200 MHz, D_2O) δ_H 4.1 (3H, s, CH_3), 5.8–6.2 (2H, m, CH_2), 6.9 (1H, d, CH), 7.7 (1H, t, Ar), 8.0 (1H, d, Ar), 8.3 (1H, t, Ar), 8.5 (1H, d, Ar).

Kinetic measurements

The kinetic studies with **5** were carried out following the formation of 2-vinylpyridine (**6**) in OH^-/H_2O or acetohydroxamate–acetohydroxamic acid buffers at 50 °C, $\mu = 1$ M KCl. The procedure followed was the same as that previously described.[8] Kinetics in OH^-/H_2O with **8** were studied under pseudo-first order conditions at $[OH^-] = 0.01$ M, 25 °C, $\mu = 1$ M KCl, by following to completion the formation of 1-methyl-2-vinylpyridinium iodide (**9**) at $\lambda = 287$ nm. Pseudo-first order k_{obs}, s^{-1} was evaluated from a plot of $\ln[(A_\infty - A_0)/(A_\infty - A_t)]$ *versus* time. The absorption coefficient of **9** is $\varepsilon = 10274$ dm^3 mol^{-1} cm^{-1} at $\lambda = 287$ nm, 25 °C, H_2O, $\mu = 1$ M KCl.

Product analysis

Reactions of **5** in OH^-/H_2O, 50 °C, $\mu = 1$ M KCl were shown to be complete elimination reactions with the formation of 2-vinylpyridine (**6**) by UV analysis at the end of the kinetic experiments. Experiments carried out with **5** in acetohydroxamate–acetohydroxamic acid buffers at 50 °C, $\mu = 1$ M KCl, after extraction with $CHCl_3$ and VPC analysis, showed the presence of the two products, 2-vinylpyridine (E) and 2-(2-pyridyl)ethyl hydroxamate (S). The [E] : [S] ratio at different pH values and various $[B^-]$ and [BH] was determined by VPC analysis with bibenzyl as internal standard. The two products were shown to be stable in the VPC analysis. VPC analyses were performed through the HP 5890 GC equipped with an HP 5 capillary column (30 m length, 0.25 mm ID, 0.25 mm phase thickness).

pK_a determination

The pK_a of the conjugate acid of **5** was determined by titration of **5** at 50 °C, H_2O, $\mu = 1$ M KCl.

H/D exchange

Compound **5** was left to react in acetohydroxamate–acetohydroxamic acid buffers, D_2O, 50 °C, $\mu = 1$ M KCl in an NMR tube. The signals of the system CH_2–CH_2 of the reagent at 50% of elimination reaction remained unchanged. As a control, the solution was extracted with $CHCl_3$ and GC-MS analysis confirmed the absence of deuterium incorporation in the substrate.

Acknowledgements

Thanks are due to the CNR (Rome) and the Ministero dell'Università e della Ricerca Scientifica e Tecnologica (MURST) for financial support.

References

1 W. H. Saunders and A. F. Cockerill, *Mechanism of Elimination Reactions*, Wiley Interscience, New York, 1973.
2 E. Baciocchi, *The Chemistry of Halides*, *Pseudo Halides and Azides*, *Supplement D*, ed. S. Patai and Z. Rappoport, Wiley, Chichester, UK, 1983.
3 J. R. Gandler, *The Chemistry of Double Bonded Functional Groups*, ed. S. Patai, Wiley, Chichester, UK, 1989.
4 S. Alunni and W. P. Jencks, *J. Am. Chem. Soc.*, 1980, **102**, 2052.
5 J. R. Keefe and W. P. Jencks, *J. Am. Chem. Soc.*, 1983, **105**, 265.
6 S. Alunni and P. Tijskens, *J. Org. Chem.*, 1995, **60**, 8371.
7 S. Alunni, R. Ruzziconi and O. Teofrasti, *Res. Chem. Intermed.*, 1999, **25**, 483.
8 S. Alunni, A. Conti and R. Palmizio Errico, *J. Chem. Soc.*, *Perkin Trans. 2*, 2000, 453.
9 R. Stewart and R. Srinivasan, *Acc. Chem. Res.*, 1978, **11**, 271.
10 G. M. McCann, R. A. More O'Ferrall and S. M. Walsh, *J. Chem. Soc.*, *Perkin Trans. 2*, 1997, 2761.
11 G. M. McCann, R. A. More O'Ferrall, M. G. Murphy, B. A. Murray and S. M. Walsh, *J. Phys. Org. Chem.*, 1998, **11**, 519.
12 J. R. Gandler and W. P. Jencks, *J. Am. Chem. Soc.*, **1982**, 104, 1937.
13 W. P. Jencks, *Acc. Chem. Res.*, 1980, **13**, 16.