

Imidazo[1,5-*a*]pyridinium Salts from Phenylchlorocarbene and 2-Pyridyl Schiff Bases: Synthesis, Reaction Mechanism and Effect of Rotamerism

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3-Phenylimidazo[1,5-*a*]pyridinium salts are easily prepared in excellent yield by thermolysis of phenylchlorodiazirine in the presence of 2-pyridyl Schiff bases (2-Pyr-CH=NR, where R is an aromatic or alkyl group). When the reaction is conducted in an alkane solvent, the salts precipitate and are easily obtained with a high level of purity after filtration and repeated washing of the precipitate with a nonpolar solvent. A laser-flash photolysis study of the reaction mechanism reveals that the phenylchlorocarbene produced by decomposition of the diazirine reacts with the Schiff base to give two different ylides. The intramolecular cyclization of these two ylides yields the same intermediate product, which rapidly

eliminates a chlorine anion. Neither semi-empirical calculations of the energy barriers for the formation and cyclization of the various possible ylides, nor comparison of their calculated and experimental absorption spectra, allow us to determine whether the two ylides are rotamers of a pyridinium ylide or a pyridinium ylide and an iminium ylide. Only the comparison of systems where R is a cyclohexyl or a *tert*-butyl group indicates that the two ylides are rotamers of a pyridinium ylide.

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Introduction

Carbenes and metal carbenoids are useful intermediates in the synthesis of nitrogen-containing heterocyclic compounds as they react with azomethines to give oxazolidines, aziridines, pyrrolidines, and β -lactams.^[1] They also react with 1-azabuta-1,3-dienes to give pyrroles by intramolecular cyclization of an intermediate ylide and elimination of HCl.^[2] The same mechanism accounts for the formation of phenylindolizine from phenylchlorocarbene (PCC) and 2-vinylpyridine (VP).^[3] In the latter case, the pyridinium ylide was shown to be a mixture of two rotamers that give a single product after cyclization and HCl elimination. There are also two rotamers for the ylide resulting from the attack of 2,2'-bis(pyridyl) (BiPy) on PCC.^[4] They give a dipyr-ido[1,2-*c*;2',1'-*e*]imidazolium salt as a single product in nonpolar solvents but two products in polar solvents, the second being a pyrido[2,3-*a*]indolizinium salt.

In light of these results, the reaction of PCC with 2-pyridylimines (2-Pyr-CH=NR) is expected to give the imidazo[1,5-*a*]pyridinium salt **III** and/or the pyrrolo[3,4-*b*]pyridine derivatives **IV** and **V**, as shown in Scheme 1. These

products are orally effective hypoglycemic agents that are used as antidiabetics.^[5]

According to semi-empirical calculations,^[6] the two most stable geometries of the 2-pyridylimines have a *trans* imine double bond and the *anti* rotamer is slightly more stable than the *syn* rotamer. It should therefore be largely predominant in photolysis experiments at 20 °C as well as in thermolysis experiments at 80 °C. Considering only the *anti* rotamer, it may react with PCC to give either *anti*-PyY, a pyridinium ylide, or *anti*-ImY, an iminium ylide. The *syn* rotamers of both of these ylides may give CP1 and then **III** after elimination of Cl[−], whereas only the *anti* rotamer of ImY can cyclize to CP2, which would then yield the product(s) **IV** and/or **V**.

Here we report a study of this system: the nature of the products was determined and the mechanism of their formation investigated, with special attention being paid to the nature of the intermediate ylide species.

Results

Synthesis of the Imidazopyridinium Salts by Thermolysis

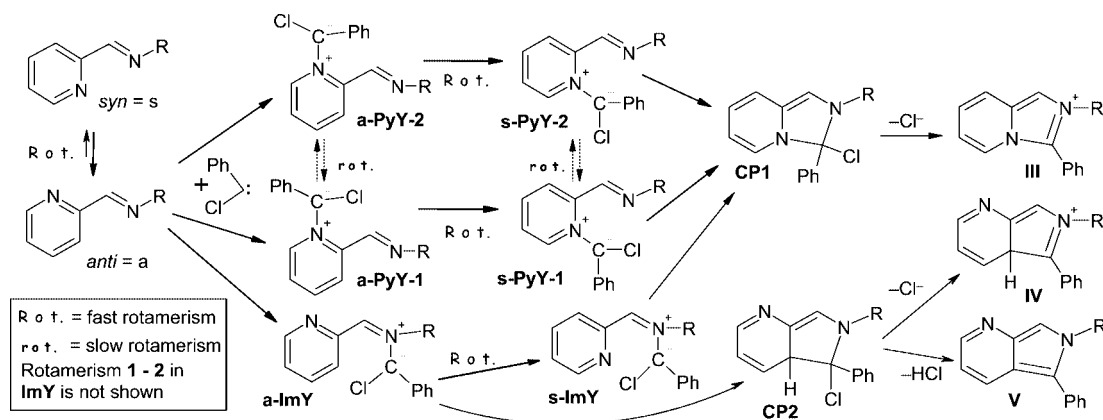
With R = Cyclohexyl (Schiff Base 1)

This compound was synthesized as described in the Exp. Sect. Its UV spectrum in water is shown in Figure 1. Slow evaporation of a solution of this product in 1,2-dichloroethane gave colorless crystals which were submitted to X-ray diffraction analysis.^[7] The results indicated unambigu-

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Scheme 1.

ously that the product is 2-cyclohexyl-3-phenylimidazo-[1,5-*a*]pyridin-2-ium chloride (**III-1**). Details of the molecular structure reveal alternatively short and long C–C bonds from C¹ to C⁶ [1.343(2) and 1.431(2) Å], in agreement with the three mesomeric structures that can be drawn for this compound. The length of both the C⁷–N¹ and C⁷–N² bonds is around 1.35 Å, which indicates a strong double bond character. The former is slightly shorter [1.344(2) Å] than the latter [1.354(2) Å], thus indicating a predominance of structure 1 over structure 2. This was confirmed by the fact that the chloride anion is located closer to N¹ [3.08(1) Å] than to N² [3.46(1) Å], in the crystal (Figure 2).

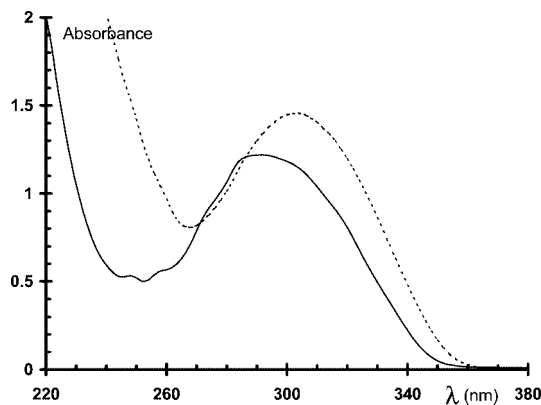


Figure 1. Absorption spectrum of the products obtained by thermolysis of chlorophenyldiazirine in isoctane in the presence of 2-pyridyl Schiff bases **1** (—) and **2** (----).

With R = Phenyl (Schiff Base 2)

A similar procedure was used for the thermolysis of chlorophenyldiazirine in the presence of **2**. The light-brown precipitate formed during the photolysis was filtered, washed with hexane, and dried under vacuum. As in the case of **1**, the mother isoctane solution did not contain any nonionic cycloaddition product. Assuming that the precipitate is the chloride of **III-2**, as suggested by its UV absorption spectrum, which is very similar to that of **III-1** (see Figure 1), the chemical yield is greater than 80% with respect to the initial amount of diazirine. The ¹H NMR spectrum is consistent with the structure **III-2** as a single product. The chlo-

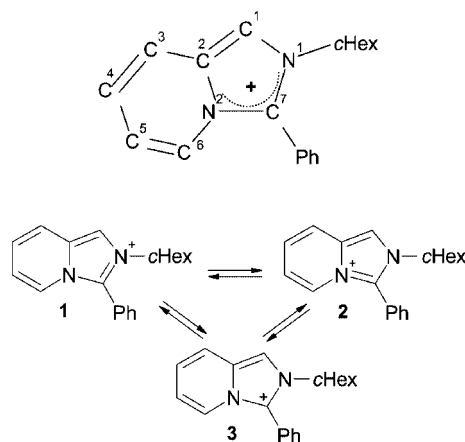


Figure 2. Atom numbering and mesomeric structures of **III-1**.

ride of **III-2** did not give single crystals, contrary to the perchlorate of **III-2**. However, X-ray diffraction experiments performed with the latter were not completely successful in solving the crystal structure (see Exp. Sect.). However, preliminary results are clearly in line with the crystallization of **III-2** together with perchlorate moieties.

Photolysis under Continuous Irradiation

Continuous irradiation experiments were performed in CH₂Cl₂ to avoid the spectroscopic problems arising from the precipitation of the product and with the Schiff base **1** because the absorption of **2** extends up to 400 nm and prevents both the irradiation of the diazirine and spectroscopic measurements below 360 nm.

Figure 3 (graph 1) shows a set of UV absorption spectra recorded during irradiation of a solution of phenylchlorodiazirine alone and with 5 mM of **1** at 366 nm. In the absence of **1**, one can see an isosbestic point at 345 nm where the absorbance increase due to the formation of azine compensates the absorbance decrease due to the loss of diazirine. In the presence of **1**, at concentrations of 2.5, 5, or 10 mM, the evolution of the spectra is different, thus indicating the formation of a reaction product in addition to azine. The increase of the absorbance at 345 nm reflects the formation

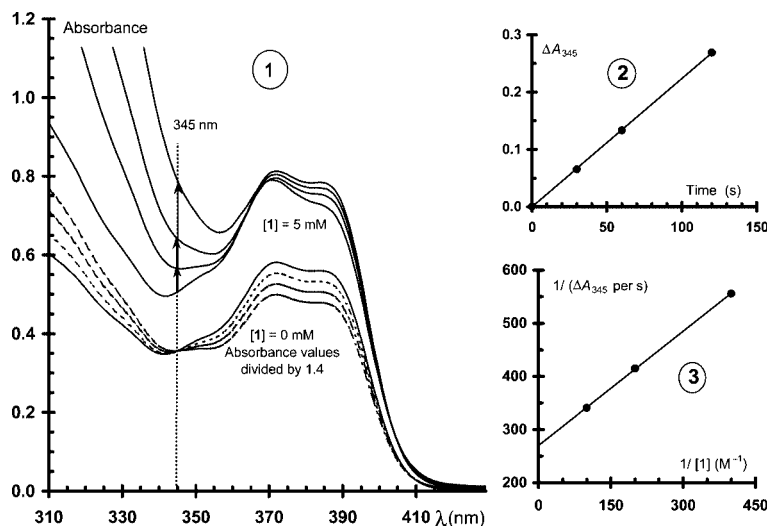


Figure 3. Graph (1) shows the evolution of the absorption spectrum of an isooctane solution of chlorophenyldiazirine with 0 and 5 mM of the Schiff base **1** as a function of irradiation time (0, 30, 60, and 120 seconds). The slope of the linear plot of the increase of the absorbance at 345 nm as a function of the time of irradiation, graph (2), is proportional to the yield of the reaction for $[1] = 5$ mM. Similar experiments conducted with $[1] = 2.5$ and 10 mM gave two other slope values. The slope/intercept ratio of the line in graph (3), which is a plot of $[1/\text{slope of graphs (2)}]$ vs. $[1]^{-1}$, gives the value of the product $k_q \tau_0$ (see text).

of the product. For each of the concentrations of **1**, a plot of ΔA_{345} as a function of time is linear [see Figure 3 (graph 2)]. The slope of these lines, ΔA_{345} per second, is proportional to the rate of formation of the product. This rate is itself proportional to the yield of conversion of the carbene into the intermediate ylide, $\phi = k_r[1]/(k_r[1] + 1/\tau_0)$ so that $(\Delta A_{345} \text{ per second}) = P k_r \tau_0 [1]/(k_r \tau_0 [1] + 1)$, where P is a proportionality factor.

A Stern–Volmer plot of $1/(\Delta A_{345} \text{ per second})$ as a function of $1/[1]$ is linear and the slope/intercept ratio gives $k_r \tau_0 \approx 380$ [Figure 3 (graph 3)]. The lifetime of the PCC carbene in the absence of **1** is limited by reactions with the diazirine, oxygen, and solvent,^[8] and in our experimental conditions $\tau_0 \approx 1 \mu\text{s}$. The rate constant for the reaction between PCC and **1**, k_p , should thus be around $4 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$, which means that the reaction of PCC with **1** would be faster than with BiPy or 2-VP. This was confirmed by laser flash photolysis measurements (see below).

Laser Flash Photolysis Measurements

After excitation of an isooctane solution containing the diazirine (0.7 mM) and **1** (10 to 60 mM) by a laser pulse at 355 nm, a transient absorption appears in the 400–700-nm wavelength range. This absorption is assigned to an ylide species and grows according to first-order kinetics. The plot of $1/\tau_{\text{growth}}$ vs. $[1]$, shown in Figure 4, follows the linear relationship $1/\tau_{\text{growth}} = 1/\tau_0 + k_{y1}[1]$. The intercept of the straight line yields the lifetime of the carbene in the absence of **1** ($\tau_0 = 0.9 \mu\text{s}$) and its slope gives the rate constant for ylide formation ($k_{y1} = 3.23 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$). The product $k_{y1} \tau_0 = 300$ is in good agreement with the value (ca. 380) obtained from the Stern–Volmer plot of the continuous irradiation data. The small difference is easily explained by the difference in solvents (k_r increases as the viscosity of the

solvent decreases) and the difference in diazirine concentrations (due to the reaction between carbene and diazirine, the lower concentration used in continuous irradiation experiments results in a larger value of τ_0).

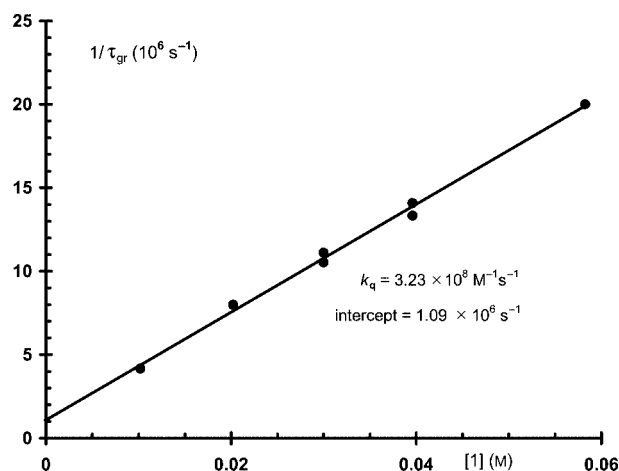


Figure 4. Rate of growth of the ylide absorption vs. the concentration of 2-Pyr-CH=Nc-hexyl (monitored at 500 nm in isooctane).

In isooctane, the absorption spectrum of the ylide species, shown in Figure 5, is time-dependent: unusually broad when it is recorded 1 μs after excitation, it becomes noticeably narrower after 25 μs . When monitored at 500 nm, the decay of the ylide follows first-order kinetics with a decay time of around 450 μs at room temperature, whereas in the red part of the transient absorption spectrum (600–700 nm), the decay is complex, as shown in Figure 6. The absorption appears to be the sum of two components: the first one decays with a lifetime of 7.5 μs (at 23 °C) and the second with a lifetime of 450 μs , identical to the value measured in the 450–550-nm region.

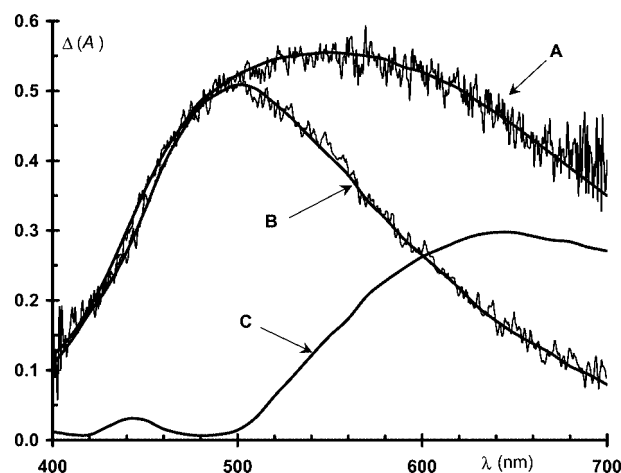


Figure 5. Transient absorption spectra recorded 1 (trace A) and 25 μs (trace B) after excitation of an isooctane solution of chlorophenyldiazirine in the presence of **1** (50 mM). Trace C, the difference between smoothed traces A and B, represents the absorption spectrum of the short-lived ylide species.

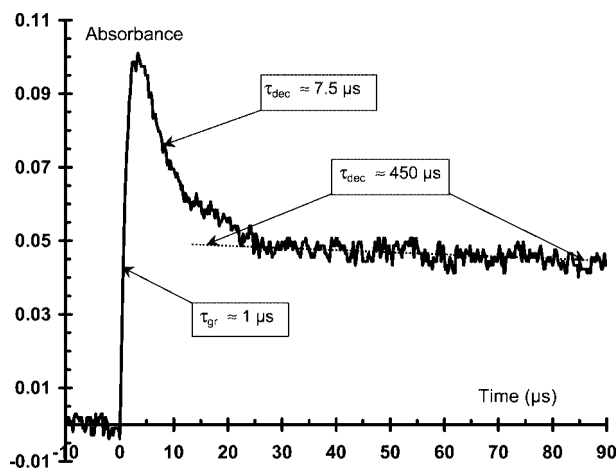


Figure 6. Kinetic behavior of the transient absorption produced by excitation of an isooctane solution of chlorophenyldiazirine in the presence of **1** (50 mM; monitored at 650 nm).

The lifetime of the second component, monitored at 500 nm, depends strongly on temperature, and an Arrhenius plot, $\ln(1/\tau_{\text{decay}}) = f(1/T)$, shown in Figure 7, yields an activation energy, ΔE_a , of 12.94 kcal mol⁻¹ and a frequency factor, A , of $6.8 \times 10^{12} \text{ s}^{-1}$. As the ylide lifetime is most probably limited by its rate of cyclization, these kinetic parameters would be those of the cyclization reaction. However, as stated by one of the referees, the value of the frequency factor seems awfully large for a cyclization reaction. As an alternative, the lifetime of the long-lived ylide might be limited by its conversion into the short-lived ylide, which then undergoes a rapid cyclization.

In CH₂Cl₂, the absorption spectrum of the ylide(s) (PCC←**1**) shows only one component that resembles the spectrum of the long-lived component observed in isooctane and also more or less resembles the absorption spectrum of the iminium ylide observed when PCC is produced in the presence of PhCH=NMe, as shown in Figure 8.

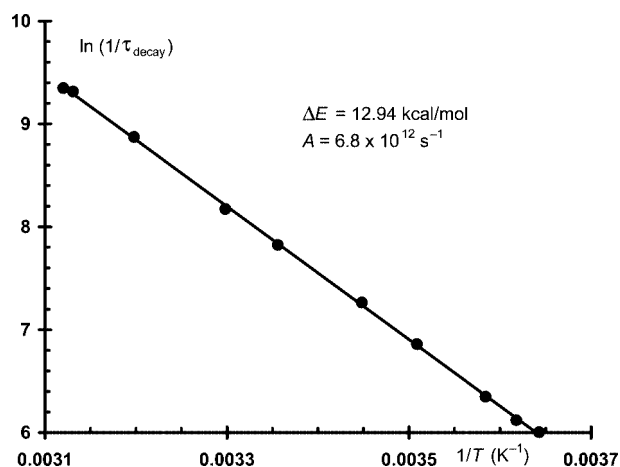


Figure 7. Arrhenius plot for the decay of the long-lived ylide 2-Pyr-CH=Nc-hexyl→PCC (monitored at 500 nm in isooctane).

However, the lifetime of this iminium ylide depends little on the temperature, changing from 290 μs at 13 °C to 200 μs at 47 °C. Its decay is sensitive to oxygen even though the rate constant for reaction with O₂, around $2 \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$, is small,^[9] and it is not strictly first order: the fit between the experimental and calculated decay curves is improved when a second-order process with $k_2 \approx (1.5 \times 10^4 \times \epsilon) \text{ M}^{-1} \text{ s}^{-1}$ at 500 nm^[10] is added to the analysis.

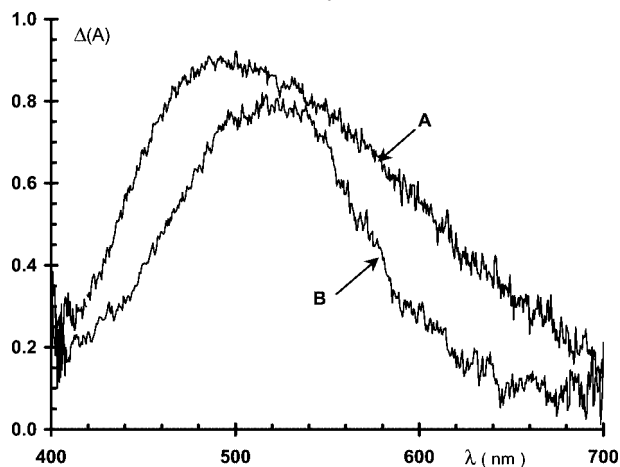


Figure 8. Absorption spectra of the ylides 2-Pyr-CH=Nc-hexyl→PCC in CH₂Cl₂ (trace A) and PhCH=NMe→PCC in isooctane (trace B). Both spectra were recorded 1 μs after excitation, in a single-shot experiment for trace B and an averaged four-shot experiment for trace A.

Discussion

The nature of the main product **III** has been well defined, as has the mechanism for its formation, which is the same as the mechanism described for the system PCC + BiPy. However, from the reported flash photolysis measurements, it is not clear whether the formation of **III** results from the cyclization of either an iminium ylide or a pyridinium ylide, or both. The very broad transient absorption spectrum observed in isooctane is clearly due to two ylide species, which

may be either the iminium and pyridinium ylides, or two rotamers of the pyridinium ylide.

Absorption Spectra

The absorption spectra of the iminium ylide $\text{PCC} \leftarrow \text{PhCH}=\text{NMe}$ and of the long-lived transient are similar. This suggests that the latter could be an iminium ylide whereas the short-lived transient could be a pyridinium ylide. Alternatively, the two transient species could be rotamers of the pyridinium ylide resulting from rotation around the $>\text{C}^--\text{N}^+<$ ylide bond (rotamers **PyY-1** and **PyY-2** in Scheme 1) similar to the two rotamers of the $\text{PCC} \leftarrow \text{VP}$ ylide, characterized by λ_{max} at 500 and 620 nm and lifetimes equal to 20 and 0.5 μs , respectively. The interconversion between rotamers of this type is slow (or non-existent) because the $>\text{C}^--\text{N}^+<$ ylide bond has some double bond character. Its calculated length, in the range 1.36–1.38 Å, is closer to that of a C=N double bond (1.29 Å) than to that of a C–N single bond (1.49 Å). As shown in Figure 9, the λ_{max} of the calculated absorption spectrum of a pyridinium ylide depends greatly on the tilt angle between the carbenic phenyl group and the pyridyl moiety, whereas the enthalpy of formation is nearly unaffected by such a change. In contrast, the calculated absorption spectrum of the iminium ylide is less sensitive to the planarity of the system. The most stable conformations, with a tilt angle of the phenyl of around 60°, have a maximum absorption in the 430–440 nm range and, even with a tilt angle equal to 5°, the calculated value of λ_{max} does not exceed 490 nm.

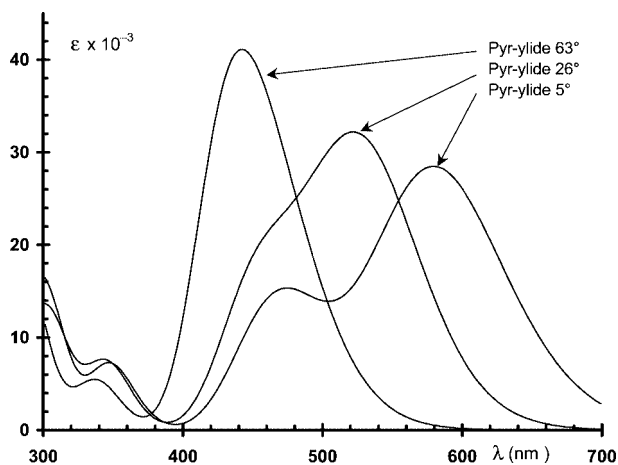


Figure 9. Calculated absorption spectrum for the pyridinium ylide *anti-a* for several values of θ , which is the tilt angle between the phenyl and pyridyl groups. As θ decreases from 63° to 26° and then to 5°, λ_{max} increases from 440 to 520 and then to 580 nm but the calculated enthalpy of formation, ΔH_f , remains nearly constant (70, 71, and 73 kcal mol⁻¹).

A third possibility — rotamerism around the C–C pyridyl–imine bond (rotamerism *anti* $\leftrightarrow$ *syn*) similar to that observed in the case of the $\text{PCC} \leftarrow \text{BiPy}$ ylide — may be discarded because rotamers of this type are in fast equilibrium so their lifetimes should be the same. The energy barriers for the rotation of the imine group with respect to the pyr-

idinium ylide moiety are calculated to be around 2 or 3 kcal mol⁻¹ higher, with the more stable geometries being those with the imine in an *anti* position (out of plane by $\pm 60^\circ$). A complete description of the energetics of this rotation is given as Supporting Information.

Thus, from the study of the spectroscopic properties, the species absorbing in the red must be a pyridinium ylide, although the species with a maximum absorption at 500 nm could be either an iminium ylide or a pyridinium ylide. The question therefore remains as to whether it is possible to determine the nature of this second ylide from the study of its kinetic properties, rates of formation, and cyclization?

Rate of Formation

The value of the rate constant for the formation of the ($\text{PCC} \leftarrow \text{I}$) ylides ($3.2 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$) is similar to those previously measured for the formation of the pyridinium ylides $\text{PCC} \leftarrow \text{pyridine}$ ($3.3 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$) and $\text{PCC} \leftarrow \text{VP}$ ($7 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$), but it is also similar to that measured in this work for the formation of the iminium ylide $\text{PCC} \leftarrow \text{PhCH}=\text{NMe}$ ($k_r = 1.06 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$). The reaction pathways leading to the formation of the pyridinium and iminium ylides were therefore calculated by semi-empirical methods. As shown in Figure 10, the formation of both ylides is exothermic by 50 kcal mol⁻¹ and is hindered by a small activation energy of around 4 kcal mol⁻¹ in both cases, in agreement with rate constants that are two or three orders of magnitude lower than the rate of diffusion-controlled reactions.

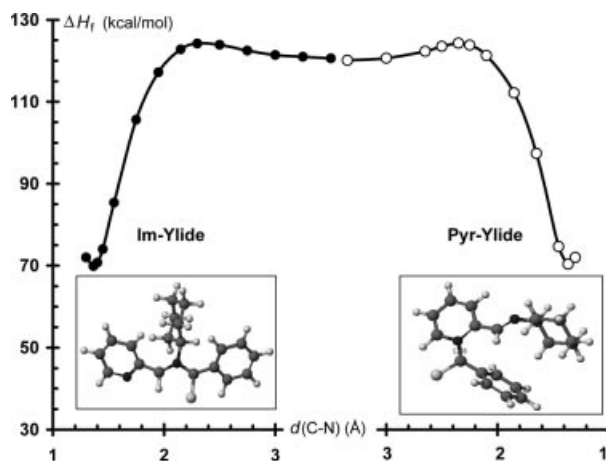


Figure 10. Calculated reaction paths for the formation of a pyridinium ylide (open circles) or an iminium ylide (closed circles). Starting from the optimized geometries of these ylides, the enthalpy of formation of the system is calculated as a function of the distance between the carbene center and the related N atom. For each point, this distance is imposed and locked but all the other geometrical parameters of the structure are recalculated to minimize the value of ΔH_f .

Rate of Decay

The lifetime of the ($\text{PCC} \leftarrow \text{I}$) ylide that absorbs in the blue–green part of the spectrum is strongly temperature-dependent, with kinetic parameters $A \approx 6.8 \times 10^{12} \text{ s}^{-1}$ and

$E_a = 12.9 \text{ kcal mol}^{-1}$, very similar to those measured for the (PCC $\leftarrow$ VP) ylide (around 10^{13} s^{-1} and 12 kcal mol^{-1}).^[11] In contrast, the lifetime of the iminium ylide (PCC $\leftarrow$ PhCH=NMe) depends very little on the temperature. However, this does not prove that the long-lived (PCC $\leftarrow$ 1) ylide is a pyridinium ylide. The ylide (PCC $\leftarrow$ PhCH=NMe) does not decay by cyclization as this would require the attack of a phenyl ring, whereas the cyclization of a (PCC $\leftarrow$ 1) iminium ylide, involving the attack of a pyridyl ring on its N atom, may be much easier.

According to calculations (see Figure 11), the enthalpy barrier, ΔH_a , for the cyclization of the pyridinium and iminium ylides to give CP1 is around 20 kcal mol^{-1} in both cases, i.e., similar to that calculated for the cyclization of the PCC $\leftarrow$ VP ylide (25 kcal mol^{-1}).^[12] The calculated value of ΔH_a is substantially larger than the experimental value of E_a but this is a well-known characteristic of semi-empirical methods due to the fact they use parameters (PM3 or AM1) designed for stable species and not for transition states. More important than the absolute values of ΔH_a is the significant result that the cyclization of the pyridinium and iminium ylides may occur at nearly the same rate, assuming that the entropy and frequency factors are similar for both systems. With ΔH_a values of around 20 kcal mol^{-1} for the cyclization of the pyridinium ylide and 30 kcal mol^{-1} for the cyclization of the iminium ylide we could discard the latter, but this is not the case. Therefore, neither the shape of the absorption spectra of the ylide species nor the values of the rate constants for their formation and cyclization allow us to distinguish unambiguously between the two types of ylide. Therefore, we used a different approach to tackle the problem.

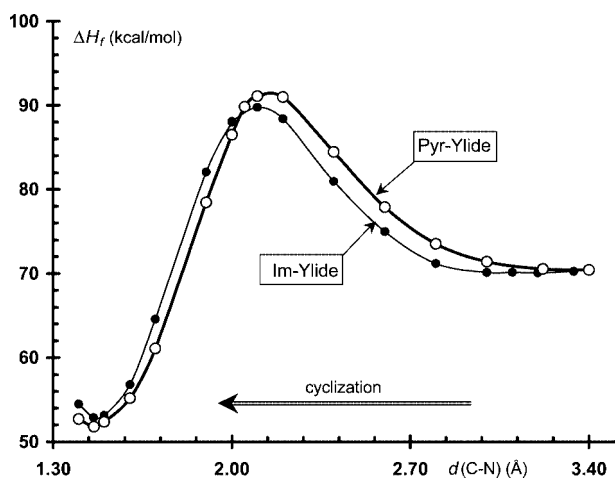


Figure 11. Calculated reaction paths for the cyclization of a pyridinium ylide (open circles) or an iminium ylide (closed circles).

The cyclohexyl group of **1** was changed to a *tert*-butyl group to give 2-Pyr-CH=N*t*Bu (**3**). In the most stable geometries calculated for the iminium ylide, the cyclohexyl group is nearly orthogonal to the two aromatic rings such that the C-H α to the imino N atom is pointing towards one of these rings (see inset in Figure 10). With a *tert*-butyl

group this C-H is changed to a C-CH₃, which, due to steric hindrance, should destabilize the iminium ylide and increase the activation energy barrier for its formation, $E_{a(f)}$. This is confirmed by the results of calculations, as shown in Figure 12. With the Schiff base **3**, the calculated value of the enthalpy barrier for the formation of the iminium ylide is 4 kcal mol^{-1} larger than for the formation of the pyridinium ylide, whereas these values are the same for the cyclohexyl-substituted Schiff base **1**. Consequently, if the two transient species observed with the system (PCC + **1**) were a pyridinium ylide, with a short lifetime and absorbing in the red, and an iminium ylide absorbing in the blue, then the relative importance of the second one should be largely decreased or even completely suppressed^[13] for the system (PCC + **3**). In fact, the characteristics of the transient species observed for the systems (PCC + **3**) and (PCC + **1**) are the same, as can be seen when comparing Figures 13 and 5.

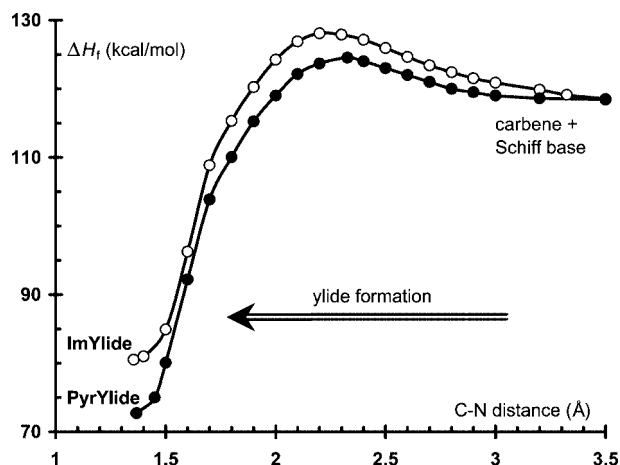


Figure 12. Calculated reaction pathways for the formation of the pyridinium and iminium ylides (PCC $\leftarrow$ 3).

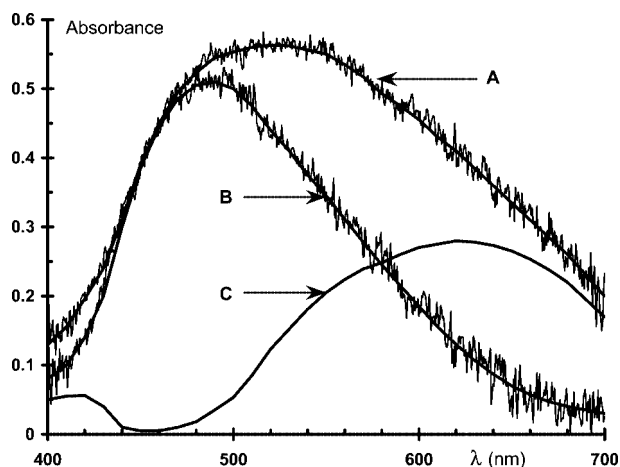


Figure 13. Absorption spectra of the transient species formed by photolysis of an isoctane solution of chlorophenyldiazirine + 2-Py-CH=N*t*Bu. The spectra were recorded 1 μ s (trace A) and 25 μ s (trace B) after excitation by a 20-ns laser pulse at 355 nm. The latter is the spectrum of the long-lived ylide. Trace C, which is the difference between the two former, corresponds to a short-lived ylide.

In both cases, there are two ylide species. One absorbs in the red ($\lambda_{\text{max}} = 650$ nm for **1** and 620 nm for **3**) and has a short lifetime; the second absorbs in the blue-green region ($\lambda_{\text{max}} = 500$ nm for **1** and 490 nm with **3**) and has a much longer lifetime. The small blue shift from 650 to 620 nm observed when going from **1** to **3** can be explained by a decrease of the planarity of the pyridinium ylide that absorbs in the red due to the steric effect of the additional CH_3 .

The ratio of the absorbance values measured at λ_{max} ($A_{490}/A_{620} = 1.8$ for **3** and $A_{500}/A_{650} = 1.2$ for **1**) indicate a relative population of the ylide absorbing in the blue larger with **3** than with **1** if one assumes that the absorption coefficients are unaffected (or only slightly affected) by the change of the Schiff base.^[14] If the ylide absorbing in the blue were an iminium ylide, one would get the opposite, i.e., a strong decrease of the relative population of this ylide, the formation of which is impeded by the steric effect of the CH_3 . We therefore conclude that the two ylide species are rotamers of a pyridinium ylide.

With this assignment, the hypothesis according to which the lifetime of the long-lived ylide is determined by its rate of conversion into the short-lived ylide, and not by its rate of cyclization, as already stated above, becomes quite plausible. The calculated value of the energy barrier for rotation around the ylide bond is about 14 kcal mol^{-1} (see Supporting Information), which is close to the experimental value of 13 kcal mol^{-1} , a very large frequency factor is expected for an intramolecular rotation, and the geometry factors determining the rate of cyclization (distance $\text{C}^7 \cdots \text{N}^1$ and orbital orientations) may be such that the cyclization reaction is fast for one rotamer and very slow for the other one.

Conclusions

Thermolysis of chlorophenyldiazirine in the presence of a large excess of the 2-pyridyl Schiff bases (2-Pyr-CH=NR , R is an aromatic or alkyl) gives (almost) quantitatively the corresponding 2-substituted-3-phenylimidazo[1,5-*a*]pyridinium salt. When the reaction is conducted in an alkane solvent, this salt precipitates and is easily obtained with a high level of purity after filtration and repeated washing of the precipitate with a non-polar solvent.

A laser flash photolysis study of the reaction mechanism reveals that the chlorophenylcarbene produced by decomposition of the diazine reacts with the Schiff base to give two different ylides. These two ylides give, upon intramolecular cyclization, the same intermediate product, which rapidly eliminates a chloride anion. Neither a comparison of the calculated and experimental absorption spectra nor the semi-empirical calculations of the activation energies for the formation and cyclization of the various possible ylides allows us to determine the nature of the two ylides — either rotamers of a pyridinium ylide or a pyridinium ylide and an iminium ylide. However, a comparison of systems where R is a cyclohexyl or a *tert*-butyl group indicates that the two ylide species involved in the mechanism are rotamers of a pyridinium ylide.

Experimental Section

General: Isooctane and dichloromethane (SDS or Aldrich) were “UV spectroscopy” or “HPLC” grades. Isooctane was kept over molecular sieves in order to minimize its water content. A medium pressure Hg lamp (Philips HPK 125) and a set of filters (UG, 5 and WG 360 Schott glasses) to isolate the 366-nm line were used for continuous irradiations. The evolution of the UV/Vis spectrum of the solutions after these irradiations was recorded with a diode-array spectrophotometer (HP, 8452A).

The flash photolysis system used for kinetics measurements in the 10 ns–1 ms range uses a frequency-tripled mode-locked Nd-YAG laser (Quantel), providing 200-ps single pulses with 30 mJ energy at 355 nm for the excitation and the analytical light beam is provided by a pulsed 75-W Xe arc. The excitation and analytical light beams cross at right angles in a $10 \times 10 \text{ mm}^2$ spectroscopic cell held between diaphragms that restrict the analysis to a small volume ($2 \times 3 \times 10 \text{ mm}^3$) of the solution located close to the cell window receiving the excitation. The optical paths are thus equal to 10 mm for the analysis and 2 mm for the excitation, which allows a homogeneous excitation of the analyzed volume. The detection system has a 3-ns response time. We collected the data on a digital oscilloscope (Tektronix TDS 620B, 500 MHz, 2.5 GS/s) operating in oversampling mode to improve the signal/noise ratio.

We measured the transient absorption spectra by using a CCD camera coupled to a gated MCP image intensifier (Andor Instaspec V) attached to a spectrograph (Oriol Multispec). Some time (adjustable from -10 ns to several milliseconds) after the excitation of the sample by an 8-ns pulse of 355-nm light provided by a frequency-tripled Q-switched Nd-YAG laser (BMI), a delay/pulse generator (Stanford Research Systems, DG535) activated the MCP during a given time window (adjustable from 5 ns to several microseconds). The absorption spectrum of the ylide species was obtained with a 100- or 200-ns time window, much shorter than their lifetime.

We used a package of molecular mechanics and semi-empirical methods (CACH 3.2 for Windows) to calculate the geometries, the enthalpies of formation (MOPAC with PM3 parameters), and the UV/Vis absorption spectra (ZINDO) of various species involved in this study.

Phenylchlorocarbene was generated by photolysis of chlorophenyldiazirine in isooctane by laser pulses at 355 nm. We prepared chlorophenyldiazirine from benzamidine by oxidation with NaOCl, according to the procedure by Graham,^[15] and purified it by chromatography on a silica column with hexane as eluent.

The 2-pyridyl Schiff bases 2-Pyr-CH=NR [R = cyclohexyl (**1**) or phenyl (**2**)] were obtained by mixing equimolar amounts of 2-pyridinecarboxaldehyde and cyclohexylamine or aniline in the presence of catalytic amounts of *p*-toluenesulfonic acid. The water released by the reaction was removed from the organic mixture by CaCl_2 . The products were purified by recrystallization from a solution in hexane. Their purity was checked by IR spectroscopy, where the CO stretching band of the aldehyde and some bands of the amine were easily detected.

2-Pyr-CH=NC₆H₁₁ (1**):** UV (in isooctane): $\lambda_{\text{max}} (\epsilon \times 10^{-4}) = 236$ nm (1.16), 266 (0.446, sh), 272 (0.454), 280 (0.31, sh). IR: $\tilde{\nu} = 1437$, 1450, 1469, 1568, 1588, 1648, 2855, 2929 cm^{-1}

2-Pyr-CH=NC₆H₅ (2**):** UV (in isooctane): $\lambda_{\text{max}} (\epsilon \times 10^{-4}) = 228$ nm (1.12), 234 (1.12), 260 (1.12, sh), 278 (1.17), 326 (0.6, sh)

Synthesis of III-1: 10 mL of an isooctane solution of chlorophenyldiazirine (0.1 M) was added portionwise (2 mL portions added every 30 min) to 15 mL of boiling isooctane containing 1.05 g of **1**.

The mixture was then refluxed for 2 h. The yellow precipitate formed during the reaction was filtered, washed with hexane, and dissolved in EtOH. The UV absorption spectra of the filtered iso-octane and of the hexane used to wash the precipitate showed only the presence of **1** in excess and did not indicate the formation of the non-ionic product **V**. Evaporation of the EtOH solution gave 230 mg (isolated yield: 75%) of a product which shows the following characteristics: UV (in water): $\lambda_{\text{max}} = 292$ nm (see Figure 1). IR (KBr): $\tilde{\nu} = 710$ cm⁻¹, 757, 781, 1167, 1343, 1448, 1470, 1526, 1654, 2856, 2940, 3010, 3042, 3073, 3433 (very broad).

Synthesis of III-2: This compound was synthesized analogously to **III-1** but with **2** instead of **1**. ¹H NMR (250 MHz, CDCl₃): $\delta = 7.08$ (t, $J_{\text{H,H}} = 7$ Hz, 1 H, H³ or H⁴), 7.23 (t, $J_{\text{H,H}} = 8$ Hz, 1 H, H³ or H⁴); this triplet is mixed with the CHCl₃ signal but is clearly resolved in deuterated acetone), 7.44–7.60 (m, 10 H, phenyls), 7.86 and 7.89 (d, $J_{\text{H,H}} = 9$ Hz, 1 H, H²), 8.04 and 8.07 (d, $J_{\text{H,H}} = 6$ Hz, 1 H, H⁷), 8.13 (s, 1 H, H¹) ppm.

Crystallographic Data for III-1: Prismatic, transparent, light-brown single crystals of approximate dimensions 1.20 × 0.08 × 0.08 mm were selected under a polarizing microscope and mounted on a Bruker-Nonius κ -CCD diffractometer (Mo- K_{α} radiation, $\lambda = 0.71073$ Å). Data collection was performed at 150 K using mixed ϕ and ω scans, 45 s per frame and a crystal–detector distance of 45 mm. Structural determination was performed by direct methods and the atomic parameters refined by full-matrix least-squares on F^2 using the SHELX-97^[7a] programs within the WINGX package.^[7b] C₁₉H₂₃ClN₂O, [C₁₉H₂₁N₂] $\cdot$ Cl $\cdot$ H₂O, orthorhombic, space group *Pbca*, $a = 10.997(5)$, $b = 11.396(5)$, $c = 27.830(5)$ Å, $V = 3488(2)$ Å³, $\rho_{\text{calcd.}} = 1.260$ g cm⁻³, 97.9% completeness to theta 26.37°, 24143 collected data, 3486 independent reflections ($R_{\text{int}} = 0.023$) for 216 refined parameters, $R_{\text{obs}} = 0.033$, $wR_{2\text{obs}} = 0.086$, $(\Delta/\sigma)_{\text{max}} = 0.001$, largest difference peak and hole 0.25/–0.26 e Å⁻³. The crystal packing is based on an asymmetric unit that contains one formula unit. Chloride and water entities are linked through hydrogen bonds.

The perchlorate of **III-2** crystallizes as large, well-shaped, transparent, light-brown single crystals of approximate dimensions 0.5 × 0.25 × 0.25 mm. Despite many attempts, the crystal structure could not be solved in a reliable way. The presence of a strong statistic disorder affecting both the **III-2** entity and the perchlorate prevents any accurate description of the molecular structures. This compound crystallizes in the triclinic system with unit cell dimensions $a = 9.398(5)$, $b = 12.799(5)$, $c = 14.636(5)$ Å, $\alpha = 89.15(2)^\circ$, $\beta = 88.17(2)^\circ$, $\gamma = 77.30(2)^\circ$, $V = 1716(2)$ Å³. The final classical quality criterion are acceptable ($R_{\text{obs}} = 0.074$, $wR_{2\text{obs}} = 0.080$) but as almost all the atoms occupy two statistical positions no reliable quantitative detailed analysis could be performed with this data set. However, the nature of the sample is clear.

CCDC-603236 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Center via www.ccdc.cam.ac.uk/data_request/cif.

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- [10] The order of magnitude of ϵ at 500 nm is 10⁴ M⁻¹ cm⁻¹. This value is deduced from the absorption spectrum of the iminium ylide calculated with ZINDO and from the amplitude of the transient absorptions obtained under the same conditions for the ylide (PCC←PhCH=NMe) and for the triplet state of benzophenone in benzene (see: R. Bonneau, I. Carmichael, G. L. Hug, *Pure Appl. Chem.* **1991**, *63*, 2289). This gives a value for k_2 of around 10⁸ M⁻¹ s⁻¹, two orders of magnitude lower than the rate of diffusion-controlled reactions.
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- [12] See Figure 14 in ref.^[4].
- [13] At $T = 300$ K and with a 4 kcal mol⁻¹ difference between the energy barriers, the kinetic term $\exp(4000/RT) = 800$ so that the selectivity should be complete.
- [14] One may also assume that the absorption coefficients of the ylides absorbing in the red and in the blue are affected in the same manner when the Schiff base **1** is changed to **3**. If these two species are rotameric pyridinium ylides, the oscillator strength of their absorption bands should not depend on the nature of the Schiff base. Therefore, the values of ϵ_{500} and ϵ_{650} (in case of **1**) should be smaller than ϵ_{490} and ϵ_{620} (in case of **3**), respectively, because both the red and blue absorption bands are larger in the first case than in the second.
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