Keto–enol/enolate equilibria in the 2-acetylcyclopentanone system. An unusual reaction mechanism in enol nitrosation

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The keto–enol equilibrium of 2-acetylcyclopentanone (ACPE) was studied in water by analysing the effect that aqueous micellar solutions produce in the UV absorption spectrum of this compound. Aqueous solutions of anionic, cationic, or nonionic surfactants forming micelles have been used. The quantitative treatment of absorbance changes measured at the maximum absorption wavelength as a function of surfactant concentration gave the keto–enol equilibrium constant, K_E. In the same sense, the analysis of spectral changes measured as a function of pH in aqueous basic media allowed us to determine the acidity equilibrium constant, K_a. The combination of both equilibrium constants gives the acidity constant of the enol ionizing as an oxygen acid, $pK_a^E = 7.72$ and the acidity constant of the ketone ionizing as a carbon acid, $pK_a^K = 8.12$. The kinetic study of the nitrosation reaction of ACPE has been realized in aqueous strong acid media under several experimental conditions. As expected, the reaction is first-order with respect to ACPE concentration, but in sharp contrast to other β-dicarbonyl compounds, the dependence of both $[H^+]$ or $[X^-]$ ($X^- = Cl^-$, Br^-, or SCN^-) is not simple first-order; instead a fractional order which varied from 1 to 0 was observed. The kinetic interpretation of these experimental facts has been done on the basis of a reaction mechanism that considers the formation of an intermediate in steady-state, which has been postulated as a chelate-nitrosyl complex. The quantitative treatment of the experimental data gave the values of every rate constant appearing in the proposed reaction mechanism.

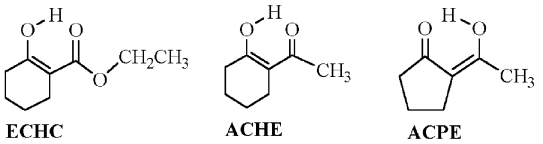
Introduction

Despite the interest in determining the rate of the water enol-reactions, the keto–enol interconversion has played a major role in the development of correlations between rates and the mechanisms of enol-reactions in solution.[1] Information on rates of enolization is often obtained from the study of bromination reaction of the enol,[2,3] or of flash-photolysis in the case of monoketones.[4]

Frequently, the keto and enol forms of many 1,3-dicarbonyl compounds are both present in aqueous solutions in measurable proportions. Nevertheless, the enol tautomer is the predominant form in apolar or non-hydrogen bond donor or acceptor solvents. In the last few years, we have used aqueous micellar solutions of various surfactants to determine the enol content in water of several 1,3-dicarbonyl compounds, including acyclic β-diketones or β-keto-esters.[5–7]

We now have extended these investigations to the cyclic-1,3-dicarbonyl compounds shown in Scheme 1. Ethyl cyclohexanone-2-carboxylate, ECHC, is stable in dry dioxane, but the hydrolysis of the ester occurs at measurable rates in aqueous solution.[8–10] In aqueous alkaline medium the enolate is rapidly generated, but the ester also hydrolyses in this medium. It could be possible that the conversion of the enol to the keto form was slower than the ester hydrolysis; which is a kinetically indistinguishable situation. 2-Acetylcyclohexanone, ACHE, is quite stable in either water or organic solvents. Nevertheless, whereas *e.g.* ACHE exists entirely in the enol form in dioxane solvent, a mixture of both the keto and the enol tautomers is present in aqueous medium. Nevertheless, a very surprising observation is the fact that the keto–enol interconversion is slow in either direction. In alkaline medium, the enolate is rapidly generated and quite stable, but the subsequent acidification of the solution gives the enol in quantitative proportions, which subsequently transforms into the keto tautomer until the equilibrium proportions are reached.[11] Finally, 2-acetylcyclopentanone, ACPE, shows a similar behaviour to that observed with acyclic-1,3-diketones: in aprotic solvents such as dioxane the enol tautomer is the majority form; in aqueous acid medium, both tautomers exist in equilibrium and their interconversion is fast.

In this work, we report the results obtained in the study of the keto–enol/enolate equilibrium of ACPE under several experimental conditions. Moreover, as nitrosation is an appropriate reaction to detect enols and enolates, kinetic studies of the nitrosation of ACPE in aqueous acid medium have also been performed. The kinetic results were interpreted on the basis of an 'unexpected' reaction mechanism in enol-nitrosation.



Scheme 1 The structures of some cyclic-1,3-dicarbonyl compounds.

Experimental

Materials

2-Acetylcyclopentanone (ACPE) an Aldrich product of the maximum purity was used as supplied. Surfactants, sodium

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dodecyl sulfate (SDS), tetradecyltrimethylammonium chloride (TTACl), tetradecyltrimethylammonium bromide (TTABr) and polyoxyethylene-9-dodecyl ether ($C_{12}E_9$), all from Sigma or Aldrich of the highest purity, were used without further purification. All other reagents were supplied by Merck and used as received. Solutions were prepared with doubly distilled water obtained from a permanganate solution.

Methods

UV-vis absorption spectra and kinetic measurements were recorded with a Kontron-Uvikon (model 942) double-beam spectrophotometer provided with a thermostated cell holder. The pH was measured with a Crison pH-meter equipped with a GK2401B combined glass electrode and calibrated using commercial buffers at pH 4.01, 7.01 and 9.26. All measurements were performed at 25 °C. Stock solutions of ACPE (~0.017 M) were prepared in dioxane (spectrophotometric grade). Aqueous solutions of ACPE ($\sim 4 \times 10^{-3}$ M) were obtained by diluting the appropriate volume of the dioxane solution into the required volume of water.

Equilibrium constants were determined from spectroscopic measurements. Scans of the spectra were monitored by working with a matched pair of quartz cells (sample + reference). The latter contained all the reagents except for ACPE. Each scan was registered after 15 min of thermostating.

Kinetic measurements were carried out under pseudo-first order conditions, with a nitrite concentration at least 15-times greater than that of ACPE. The nitrosation reaction was observed by recording the decrease in absorbance at 285 nm due to ACPE-enol consumption. The reaction was initiated by injecting 30 μL of a stock solution of ACPE in dioxane (0.017 M) into a 1.0 cm quartz cuvette containing 3.0 mL of acid solution of appropriate concentration, nitrite, and ionic strength, which had been previously equilibrated in the instrument cell holder for 15 min. In every case the integrated method was followed, and the rate constants are derived from the fits of the experimental data (absorbance–time, A–t) to the standard exponential model given by eqn. (1), where A, A_∞, and A_0 are mean absorbance readings at times t, infinite, and 0, respectively, and k_0 represents the pseudo-first order rate constant.

$$A = A_\infty + (A_0 - A_\infty)e^{-k_0 t} \quad (1)$$

Satisfactory correlation coefficients ($r > 0.999$) and residuals were obtained in every case.

Results and discussion

1. Keto–enol/enolate equilibria

2-Acetylcyclopentanone is a β-diketone that shows physicochemical characteristics similar to those observed for benzoylacetone.[5] ACPE is relatively soluble and very stable in water. The UV absorption spectrum of ACPE in aqueous acid solution shows strong absorption centered at 285 nm and a less intense band at $\lambda < 200$ nm (scan [3] in Fig. 1). In aqueous acid micellar solutions of SDS (0.26 M) the intensity of the absorption band at 285 nm increases strongly with respect to that recorded in water, whereas the intensity of the band observed at $\lambda < 200$ nm decreases a little; and a 1–2 nm displacement of the maximum absorption to higher wavelengths can also be noted (scan [2] in Fig. 1). In dioxane solution, the absorption maximum appears at 284 nm, showing higher absorbance values than even in aqueous micellar solutions. For example, at [ACPE] $= 2.8 \times 10^{-4}$ M the absorbance readings at $\lambda = 285$ nm were 0.472, 1.150, and 1.727, respectively, for the aqueous, micellar (0.26 M of SDS), and dioxane solution.

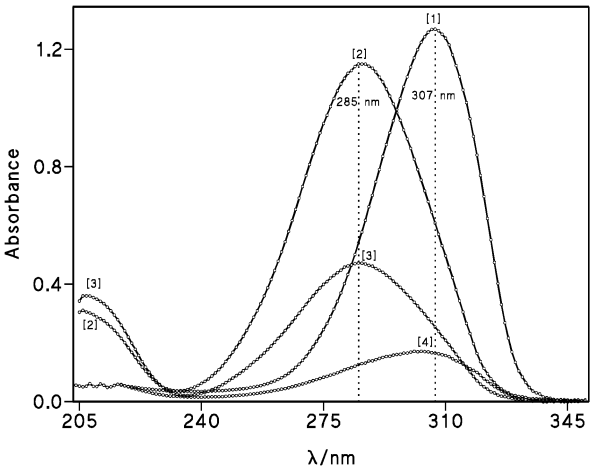
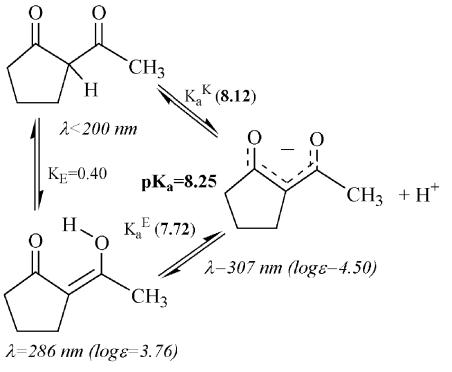


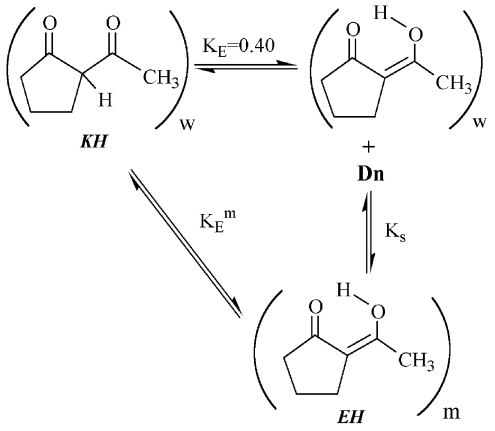
Fig. 1 Electronic absorption spectrum of ACPE in aqueous solutions at 25 °C under several experimental conditions: [1] alkaline medium ([OH^-] = 0.16 M; [ACPE] = 4.0×10^{-5} M); [2] acid medium of micellar solutions ([H^+] = 0.050 M; [SDS] = 0.26 M; [ACPE] = 2.8×10^{-4} M); [3] acid medium ([H^+] = 0.050 M; [ACPE] = 2.8×10^{-4} M), and [4] basic medium of pH 6.78 (phosphate buffer 0.15 M; [ACPE] = 4.0×10^{-5} M).

In aqueous basic media only a very strong absorption band centered at 307 nm is observed (scans [1] and [4] in Fig. 1). These experimental facts indicate that ACPE exists in aqueous acid medium as a mixture of both the keto ($\lambda_{max} < 200$ nm) and enol ($\lambda_{max} = 285$ nm) tautomers, whereas the enolate ion ($\lambda_{max} = 307$ nm) is the predominat species in basic medium. The keto–enol/enolate transformations are rapid, in the time-scale of these measurements. Scheme 2 reports the involved equilibria.

Keto–enol equilibrium. The enol tautomer of a β-dicarbonyl compound is stabilized by intramolecular hydrogen bonds; therefore the enol concentration increases in aprotic solvents, *i.e.* when intermolecular H-bonding with the solvent does not compete. This means that the keto–enol equilibrium is very sensitive to solvent nature. Aqueous micellar solutions are microheterogeneous media, in which micellar aggregates provide a more aprotic solvent than does the bulk water phase. An increase of the enol concentration is observed with the increase of surfactant concentration, *i.e.* with the micellar pseudophase, which is due to the stabilization of the enol form in the micelles and to the fact that more hydrophobic substrates, such as the enol, are well accepted by hydrophobic solvents. The only tautomeric form uptaken by the micelle is the enol form, since a clear isosbestic point (~232 nm) is observed on varying the [surfactant]. We also assume that the enol is



Scheme 2 Keto–enol/enolate equilibria of 2-acetylcyclopentanone in water.



Scheme 3 The involved keto–enol equilibria of ACPE in aqueous micellar medium.

located at the micellar interface since no detectable shift (< 2 nm) in λ_{max} is caused by the presence of micelles.

From the previous considerations, Scheme 3 might be proposed, in which KH and EH represent, respectively, the keto and enol tautomeric forms of ACPE, and D_n refers to the micellized surfactant, *i.e.* $[D_n] = [\text{surfactant}]_t - \text{c.m.c.}$ The increase in absorbance at 285 nm of the aqueous micellar solutions of ACPE with the increase in [surfactant] can be described by eqn. (2), where l ($= 1$ cm) is the optical pathlength and ε_{EH} is the molar absorption coefficient of the enol.

$$A_{285} = \varepsilon_{EH} l([EH]_w) + [EH]_m) \quad (2)$$

Taking into account that $[ACPE]_t = [KH]_w + [EH]_w + [EH]_m$, and the expressions of both K_E and K_s resulting from Scheme 3, eqn. (3) can be easily obtained to relate the absorbance readings as a function of micellized surfactant concentration, $[D_n]$. The solid lines in Fig. 2 correspond to the theoretical fit of eqn. (3) to the experimental points of A_{285} *vs.* $[D_n]$. The optimized parameters K_s and $K_E/(1 + K_E)$ were determined from this method by using A^0_{285} (the absorbance of the solution in the absence of surfactant) and c.m.c. as known parameters.

$$A_{285} = \frac{A^0_{285}(1 + K_s[D_n])}{1 + \left(\frac{K_E K_s}{1 + K_E}\right)[D_n]} \quad (3)$$

The results obtained, presented in Table 1, indicate that ACPE is near 30% enolized in water and the association constant of the enol to micelles achieves low values; in other words, it is a moderately hydrophobic species. Even though the hydrophobicity of TTAX (X = Cl or Br) micelles (14 C-atoms in the hydrocarbon chain) is higher than that of SDS or $C_{12}E_9$ micelles, the enol of ACPE binds stronger to anionic micelles of SDS than cationic or nonionic ones. A possible contribution of the sulfate head groups (H-bond acceptors only) in H-bonding interactions with the enol could explain the results.

Beer–Lambert law behaviour. At ACPE concentrations in the range (0.5 to 5) $\times 10^{-4}$ M, the absorbance of the aqueous, aqueous micellar solutions of SDS 0.26 M, and dioxane solutions, was measured at 285 nm using a bandpass of 2 nm.The measurements were taken in the presence of 0.050 M hydrochloric acid, except in the case of dioxane. The experimental results are shown in Fig. 3. In every case, a perfectly linear correlation between A_{285} and [ACPE] is observed, thereby indicating negligible association of the substrate molecules, *i.e.* the absorption band at 285 nm obeys the Beer–Lambert law in water, aqueous micellar solutions, or in dioxane solvent. It is also noticeable that there is a higher enol content in dioxane or in the presence of micelles than in water.

By remembering that $A_{285} = \varepsilon_{EH} l[EH]_w$ (experiments in water) or $A_{285} = \varepsilon_{EH} l([EH]_w + [EH]_m)$ (experiments in micelles), and that $[ACPE]_t = [KH] + [EH]$, eqns. (4) and (5) may be deduced to express the absorbance variation as a function of ketone concentration in both aqueous or aqueous micellar solutions, respectively.

$$A_{285} = \frac{\varepsilon_{EH} \ell K_E}{1 + K_E}[ACPE]_t \quad (4)$$

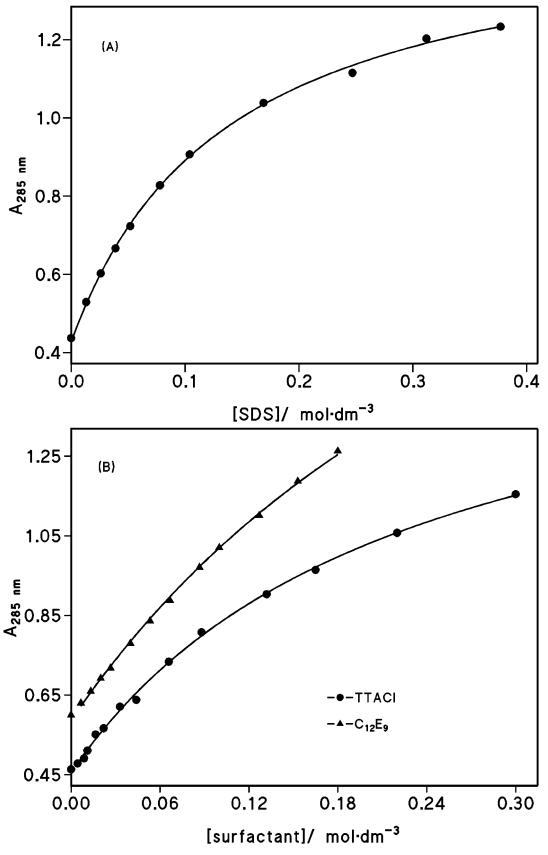


Fig. 2 Absorbance readings of aqueous acid ($[H^+] = 0.017$ M, HCl) micellar solutions of ACPE (2.8×10^{-4} M) as a function of surfactant concentration: (A) anionic surfactant of sodium dodecyl sulfate, SDS; (B) cationic surfactant of tetradecyltrimethylammonium chloride, TTACl, and nonionic surfactant of polyoxyethylene-9-dodecylether, $C_{12}E_9$. The curves fit eqn. (3); for parameters, see Table 1.

Table 1 Experimental conditions and optimized parameters obtained in the study of the influence of surfactant concentration on the UV-spectrum of ACPE dissolved in aqueous HCl 0.050 M micellar solutions. Eqn. (3) fits the experimental data; Fig. 2 displays some of the results

Surfactant	$[ACPE]_t$/M	A^0_{285}	c.m.c./M	K_s/mol^{-1}dm^3	$K_E/(1 + K_E)$	r	K_E
SDS	2.8×10^{-4}	0.548	4.0×10^{-3}	23.7 ± 0.7	0.299	0.999_5	0.43
$C_{12}E_9$	3.1×10^{-4}	0.600	3.7×10^{-3}	12.8 ± 0.2	0.252	0.999_7	0.34
TTACl	2.8×10^{-4}	0.463	3.0×10^{-3}	15.6 ± 0.5	0.283	0.999_4	0.39
TTABr	2.8×10^{-4}	0.473	3.5×10^{-3}	13.0 ± 0.9	0.260	0.999_5	0.35
Average $K_E = 0.38$							

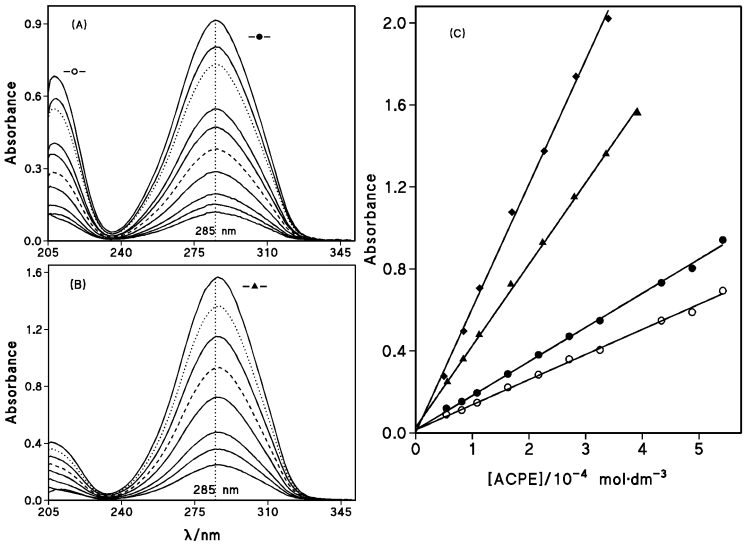


Fig. 3 Concentration dependence of the electronic absorption spectrum of ACPE (A) in aqueous acid solutions and (B) in aqueous micellar solutions of SDS 0.26M; (C) Beer–Lambert plots at $\lambda = 285$ nm of ACPE dissolved in (◆) dioxane; (▲) aqueous micellar solutions of SDS 0.26 M, and in water (●) $\lambda = 285$ nm, (○) $\lambda = 208$ nm. See Table 2 for parameters.

$$A_{285} = \frac{\varepsilon_{EH}\ell K_E}{1+K_E}\,\frac{1+K_s[SDS]_m}{1+\dfrac{K_sK_E}{1+K_E}[SDS]_m}\,[ACPE]_t \qquad (5)$$

Least-squares fitting of the A_{285} *vs.* $[ACPE]_t$ yielded the results of Table 2. The gradient of the straight line drawn with the date measured in water has a value of $S_1 = 1641 \pm 17$ mol^{-1} dm^3; if the value of $K_E(=0.38)$ determined previously is introduced in the expression of the gradient of A_{285} *vs.* $[ACPE]_t$ given by eqn (4), one determines $\varepsilon_{EH} = 5956$ mol^{-1} dm^3 cm^{-1}. On the other hand, if we assume that ACPE exists in dioxane entirely in the enol form, then the slope of the corresponding straight line equals the molar absorption coefficient of the enol, *i.e.* $\varepsilon_{EH} = 6015 \pm 106$ mol^{-1} dm^3 cm^{-1}. By introducing this value in the expression of S_1 one gets $K_E = 0.375$, which agrees with the same value determined in this study from the effect of surfactant concentration on keto–enol equilibrium and listed in Table 1. These values (5956 or 6015 mol^{-1} dm^3 cm^{-1}) determined for the molar absorption coefficient of the enolic form are lower than that often assumed[12] $(16-12)\times 10^3$ mol^{-1} dm^3 cm^{-1}, but agrees with previous work by us that shows that the extinction coefficient of the enol varies from one dicarbonyl compound to another.[6]

In the same way, least-squares fitting of the A_{285}–$[ACPE]_t$ measured in aqueous SDS micellar solutions of [SDS] = 0.26 M (c.m.c. $= 4\times 10^{-3}$ M) to eqn. (5) gives a slope value of $S_2 = 3976 \pm 50$ $mol^{-1}dm^3$. From the ratio S_2/S_1 one gets $K_s = 20.3$ mol^{-1} dm^3 if the K_E value is assumed to be that determined previously. This result compares quite well with that determined at fixed [ACPE] and variable [SDS], a fact that rules out the possibility of keto-tautomer association and disapproves the old assumption of a unique value for the molar absorption coefficient of the enol of any dicarbonyl compound at the maximum wavelength absorption.

Table 2 The slope values (S) of the plots of the absorbance readings at 285 nm against [ACPE] obtained in different media

Medium	[HCl]/mol dm^{-3}	S/mol^{-1} dm^3	r	K_E
Dioxane	No acid	6015 ± 106	0.999_6	—
Micellar (SDS 0.26 M)	0.050	3980 ± 50	0.999_7	0.38
Water	0.050	1641 ± 17	0.999_8	0.375

Determination of the pK_a of ACPE. The absorption spectrum of ACPE was analyzed as a function of pH. Phosphoric acid (1)–hydrogen phosphate or hydrogen carbonate–carbonate buffers of total buffer concentration 0.15 M were used to obtain pH values in the range 6 to 11. The concentration of ACPE was kept constant and equal to 4.0×10^{-5} M. Typical results, depicted in Fig. 4, show that the intensity of the absorption band due to enolate, centered at 307 nm, increases with pH. The dependence of absorbance measurements on pH describes a sigmoid curve, typical of an acid–base titration (see Scheme 2).

Enolate anions are ambident species, *i.e.* there are two sites of protonation and the equilibrium enolization constant, K_E, linking the two tautomeric protonated forms, is a function of the acidity constants of these two species. Thus, titration of an equilibrium mixture of keto and enol tautomers yields a mixed acid ionization constant, K_a, whose value corresponds to the pH of the inflection point. This acid ionization constant measured in water can be defined as in eqn. (6).

$$K_a = \frac{[E^-]_t[H^+]}{[KH]+[EH]} = \frac{K_a^K K_a^E}{K_a^K + K_a^E} = \frac{K_a^K}{1+K_E} = \frac{K_a^E K_E}{1+K_E} \qquad (6)$$

The absorbance at 307 nm is given by: $A_{307} = \varepsilon_{EH}\ell[EH] + \varepsilon_E\ell[E^-]$. Hence, the mass balance equation: $[ACPE]_t = [KH] + [EH] + [E^-]$, along with the expressions of eqn. (6) allow us to obtain eqn. (7) which relates the absorbance measurements as a function of pH. In this equation A_a and A_b refer to the absorbance readings at very low and very high pH, respectively.

$$A_{307} = \frac{A_a 10^{pK_a} + A_b 10^{pH}}{10^{pK_a} + 10^{pH}} \qquad (7)$$

The solid sigmoid curve in Fig. 4(A) was constructed from eqn. (7) with the experimental values of $A_a = 0.035$ and $A_b = 1.275$ (which gives $\varepsilon_E = 31900$ mol^{-1} dm^3 cm^{-1}) and the adjusted value of $pK_a = 8.25 \pm 0.02$ ($r = 0.99_7$). >From the latter value and by making used of K_E determined previously, the relationships of eqn. (6) give $pK_a^K = 8.12$ and $pK_a^E = 7.72$, that is, the stronger acid (enol) of a pair of compounds in equilibrium with a common anion (enolate) is the minor component of the mixture.

On the other hand, the experimental data of A_{307}–$[H^+]$ may be related through eqn. (8), where A_{EH}^{∞} and A_E^{∞} correspond to the absorbance readings when all the [ACPE] is in the enol or enolate forms, respectively. The solid line in Fig. 4(B) fits

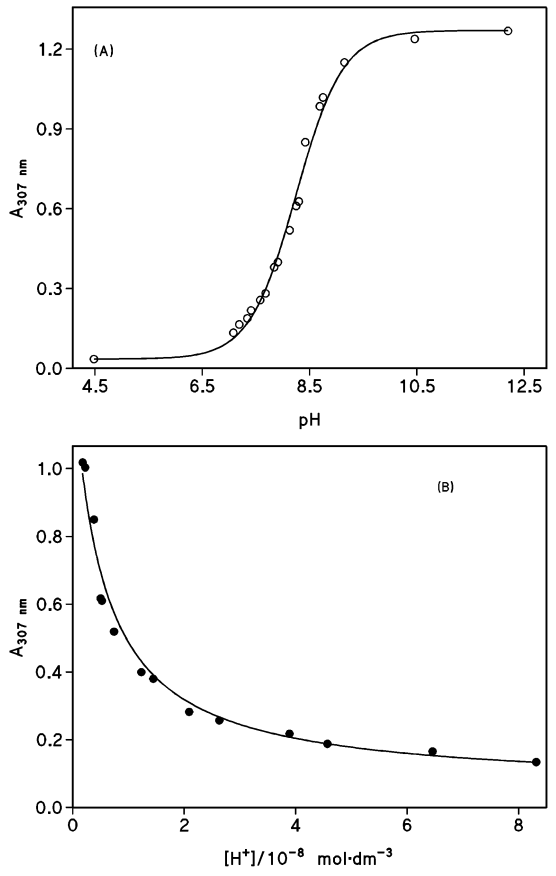


Fig. 4 (A) Spectrophotometric titration curve for the acid ionization of ACPE (4.0×10^{-5} M) in aqueous solutions of the buffers acetic acid–acetate, HPO_4^{-2}–$H_2PO_4^-$, and carbonate–bicarbonate; $[buffer]_t = 0.15$ M. Solid line fit eqn. (7). (B) Plot of absorbance reading against $[H^+]$ according to eqn. (8).

eqn. (8) to the experimental points when $K_a^E = (1.8 \pm 0.1)10^{-8}$ mol dm^{-3}; $(1 + K_E)/K_E = 3.4 \pm 0.2$; $A_{EH}^{\infty} = 0.202 \pm 0.05$, and $A_E^{\infty} = 1.30 \pm 0.03$. All these results are in good agreement with those previously reported.

$$A_{307} = \frac{A_{EH}^{\infty}[H^+] + A_E^{\infty} K_a^E}{K_a^E + \frac{1 + K_E}{K_E}[H^+]} \quad (8)$$

2 Nitrosation of the enol

The kinetic features of the nitrosation reaction of ACPE in aqueous acid medium were investigated by monitoring the decreasing absorbance at $\lambda = 285$ nm due to enol consumption. The method of flooding was applied in obtaining the experimental data of absorbance–time (A–t), which fit eqn. (1) perfectly. Thus, first-order reactions with respect to ACPE concentration, the limiting reagent, were observed under all experimental conditions used.

Influence of [nitrite]. The influence of nitrite concentration was analysed in aqueous $HClO_4$ solutions 0.020 M, and $[ACPE] = 1.7 \times 10^{-4}$ M at ionic strength, $I = 0.20$ M, controlled with $NaClO_4$. The pseudo-first order rate constant, k_0, increases proportional to [nitrite]. The results listed in Table 3 are consistent with eqn. (9) with $\alpha = (1.20 \pm 0.02)$ mol^{-1} dm^3 s^{-1} ($r = 0.999_8$).

$$k_0 = \alpha[\text{nitrite}] \quad (9)$$

Influence of ionic strength. The influence of ionic strength (controlled with $NaClO_4$) was analyzed at $[nitrite] = 1.6 \times 10^{-3}$ M and $[H^+] = 0.033$ M (by using $HClO_4$). The results are listed in Table 4. It can be seen that k_0 increases smoothly with the ionic strength, *i.e.* an effect which cannot be interpreted as a primary kinetic salt effect.

Table 3 Variation of the pseudo-first order rate constant, k_0, as a function of [nitrite] obtained in the kinetic study of the nitrosation of 2-acetylcyclopentanone in aqueous $HClO_4$ solutions 0.020 M at ionic strength 0.20 M, controlled with $NaClO_4$, and 25 °C

$k_0/10^{-3}$ s^{-1}	[nitrite]/10^{-3} M
1.13	0.86
2.22	1.73
3.34	2.59
4.50	3.45
4.95	4.32
6.15	5.18
8.05	6.91
10.5	8.60
13.0	10.4
14.3	12.1

Influence of acidity. The influence of $[H^+]$ (controlled either with $HClO_4$ or HCl) was investigated at constant nitrite concentration and $I = 0.20$ M. Fig. 5 shows the variation of the overall rate constant as a function of $[H^+]$. These 'unusual' k_0 *versus* $[H^+]$ profiles in ketone nitrosation reactions were adapted to eqn. (10) with the values of β and δ depicted in Table 5.

$$k_0 = \frac{\beta[H^+]}{1 + \delta[H^+]} \quad (10)$$

One may note the higher δ-value obtained from the experiments performed in the presence of Cl^- than that determined in the presence of ClO_4^-.

Influence of halide ion concentration. The influence of Cl^-, Br^-, and SCN^- (in general X^-) concentration on the nitrosation reaction of ACPE was investigated under several experimental conditions of [nitrite], $[H^+]$, and ionic strength. Representative results are plotted in Fig. 6. As can be seen, the variation of the observed rate constant as a function of $[X^-]$ can be summarized by eqn. (11) in every case, where k_0^w represents the observed rate constant measured in the absence of X^-.

$$k_0 = \frac{k_0^w + \gamma[X^-]}{1 + \eta[X^-]} \quad (11)$$

The corresponding values of the unknown parameters γ and η are collected in Table 6 along with the experimental condi-

Table 4 Variation of the pseudo-first order rate constant, k_0, as a function of ionic strength (I), controlled with $NaClO_4$, obtained in the kinetic study of the nitrosation of 2-acetylcyclopentanone in aqueous $HClO_4$ solutions 0.033 M at $[nitrite] = 1.6 \times 10^{-3}$ M and 25 °C

I/M	$k_0/10^{-3}$ s^{-1}
0.033	2.62
0.066	2.65
0.099	2.84
0.17	2.87
0.23	2.94
0.30	3.13
0.37	3.19
0.47	3.53
0.57	3.70
0.67	3.90

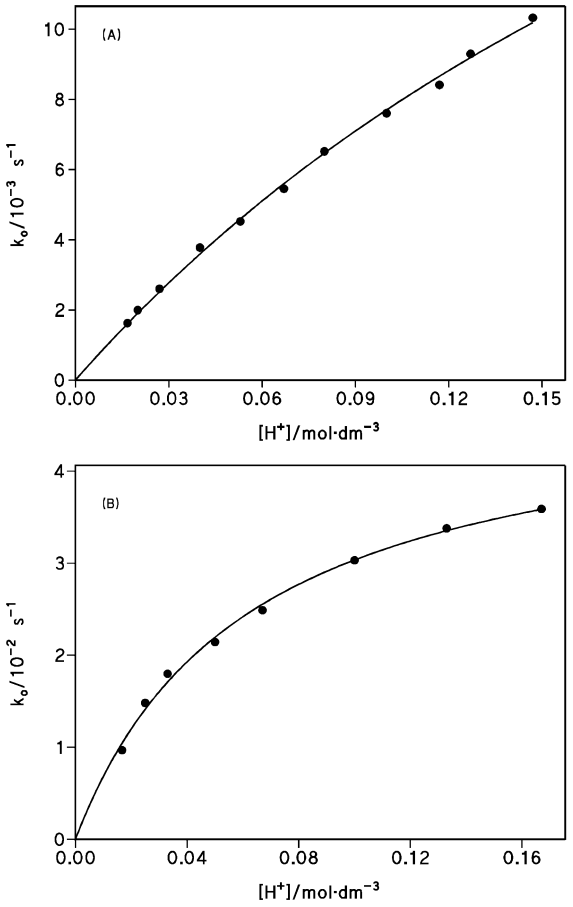


Fig. 5 Influence of $[H^+]$ on the pseudo-first order rate constant, k_0, for the nitrosation of ACPE at ionic strength 0.20 M, 25 °C and (A) [nitrite] = 1.6×10^{-3} M, $[H^+]$ controlled with $HClO_4$ and I controlled with $NaClO_4$; (B) [nitrite] = 2.5×10^{-3} M, $[H^+]$ controlled with HCl and I controlled with NaCl; the curves fit eqn. (10); for parameters, see Table 5.

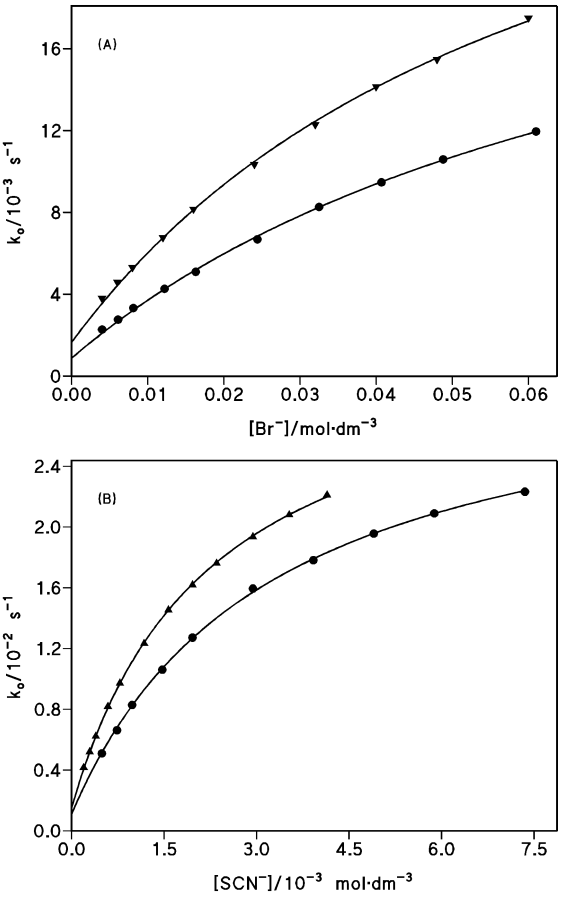


Fig. 6 Influence of $[X^-]$ on the pseudo-first order rate constant, k_0, for the nitrosation of ACPE performed in aqueous perchloric acid at ionic strength 0.20 M (controlled with $NaClO_4$), 25 °C and (A) X = Br; $[H^+] = 0.10$ M, at (●) [nitrite] = 1.6×10^{-3} M, (▼) [nitrite] = 2.5×10^{-3} M; and (B) $X^- = SCN^-$ at [nitrite] = 1.6×10^{-3} M and (●) $[H^+] = 0.010$ M, (▲) $[H^+] = 0.015$ M. The curves fit eqn. (11), for parameters, see Table 6.

tions. By observing the results obtained *e.g.* in the presence of Br^-, one may note that the η-parameter depends on $[H^+]$, but is not dependent on [nitrite], whereas the other two parameters vary with both [nitrite] and $[H^+]$. On the other hand, it is also remarkable that the η-values vary with the nature of X^-: values increase on going from Cl^-, Br^-, to SCN^-, *i.e.* η-values increase with the nucleophilic character of X^-.

Reaction mechanism of nitrosation. In aqueous strong mineral acid solutions, the effective nitrosating agents are those derived from protonation of nitrous acid: $HNO_2 + H^+ \equiv NO^+ + H_2O$, with $K_{NO} = 3 \times 10^{-7}$ mol^{-1} dm^3 being the corresponding equilibrium constant.[13] In the presence of non-basic nucleophiles (X^-), such as Cl^-, Br^-, or SCN^-, equilibrium formation of nitrosyl compounds, namely XNO, also occurs: $X^- + HNO_2 + H^+ \equiv XNO + H_2O$, with K_{XNO} being the corresponding equilibrium constant, which at 25 °C takes on values of 1.14×10^{-3} when $X^- = Cl^-$; 5.1×10^{-2} when $X^- = Br^-$, or 30 mol^{-2} dm^6 when X^- represents SCN^-.[14] Nitrosyl compounds act as nitrosating species and, despite their lower reactivity with regard to that of NO^+, catalysis by X^- is generally observed, due to the greater concentration of the nitrosyl compounds resulting from the high value of K_{XNO} in comparison to K_{NO}.

For ketones with high enol content, like ACPE, the rate determining step is, in general, the reaction between the enol and the nitrosating agent.[6,10,15–17] In such cases, the reaction is first-order in [ketone], $[H^+]$, and [nitrite], as we have found in the nitrosation of *e.g.* benzoylacetone[6] or ethyl cyclohexanone-2-carboxylate.[10] Thereupon, eqn. (12) can be written to account for the experimental facts, where k_1 and k_2 refer to the nitrosation reaction paths by NO^+ and XNO, respectively.

$$\text{rate} = (k_1 + k_2[X^-])[\text{ketone}][H^+][\text{nitrite}] \qquad (12)$$

The results exposed in the current work for the case of 2-acetylcyclopentanone are not in agreement with eqn (12).

Table 5 Experimental conditions and parameters obtained in the variation of the observed rate constant, k_0, for nitrosation of ACPE as a function of [nitrite], eqn. (9), or $[H^+]$, eqn. (10)

[nitrite]/M	$[H^+]$/M	I/M	α/mol^{-1} dm^3 s^{-1}	β/mol^{-1} dm^3 s^{-1}	δ/mol^{-1} dm^3
Variable	0.020 *(HClO$_4$)*	0.20 *(NaClO$_4$)*	1.20 ± 0.02	—	—
1.6×10^{-3}	variable *(HClO$_4$)*	0.20 *(NaClO$_4$)*	—	0.101 ± 0.003	3.1 ± 0.3
2.5×10^{-3}	variable *(HCl)*	0.20 *(NaCl)*	—	0.79 ± 0.03	16 ± 1

Table 6 Conditions and parameters obtained in the study of the influence of [X^-] in the nitrosation of ACPE. Eqn. (11) fits the experimental data of k_0 *versus* [X^-]; typical results are shown in Fig. 6

X^-	[nitrite]/M	$[H^+]$/M	I/M [a]	k_0^w/s^{-1}	$\gamma/mol^{-1}dm^3s^{-1}$	$\eta/mol^{-1}dm^3$	r	k_4/k_5 [b]
Cl^-	1.6×10^{-3}	0.015	0.45	1.63×10^{-3}	0.037 ± 0.002	1.3 ± 0.2	0.999	87.1
Cl^-	1.6×10^{-3}	0.030	0.53	3.91×10^{-3}	0.062 ± 0.002	1.75 ± 0.10	0.999_7	58.3
Br^-	1.6×10^{-3}	0.010	0.20	0.95×10^{-3}	0.244 ± 0.003	7.1 ± 0.3	0.999_8	855
Br^-	1.6×10^{-3}	0.015	0.20	1.65×10^{-3}	0.454 ± 0.015	16 ± 1	0.999_2	1053
Br^-	2.5×10^{-3}	0.010	0.20	1.42×10^{-3}	0.568 ± 0.006	7.75 ± 0.6	0.999_7	705
Br^-	1.6×10^{-3}	0.017	0.20	1.85×10^{-3}	0.53 ± 0.01	14.8 ± 0.9	0.999_6	987
SCN^-	1.6×10^{-3}	0.010	0.20	1.1×10^{-3}	9.98 ± 0.10	316 ± 5	0.9999	31600
SCN^-	1.6×10^{-3}	0.015	0.20	1.5×10^{-3}	14.8 ± 0.1	450 ± 5	0.9999_5	30000

[a] Controlled with $NaClO_4$. [b] In mol^{-1} dm^3.

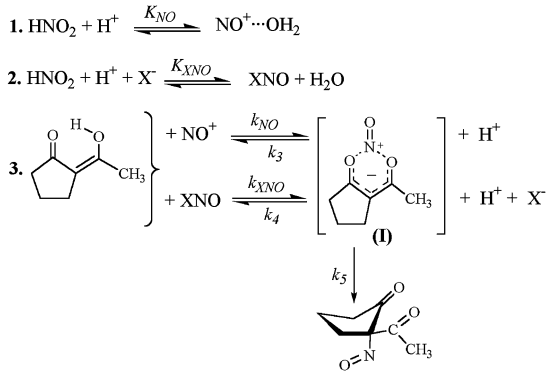
Recently, we have studied the nitrosation of 1,1,1-trifluoro-3-(2-thenoyl)acetone in aqueous acid medium.[18] Contrary to the expected behaviour for a 'usual' nitrosation process involving enols, the rate equation determined for this trifluoroketone was independent of $[H^+]$ and showed a dependence on $[Br^-]$ similar to that summarized by eqn (11) with the sole exception that $k_0^w \sim 0$. These experimental facts have been interpreted by means of a reaction mechanism in which the enolate is the species that undergoes nitrosation to give a *chelate-nitrosyl complex* as an intermediate in steady-state, that is formed in a reversible step from the attack of BrNO through the enolate anion, and subsequently rearranges to give the stable C-nitroso compound in the rate limiting step.

A rate equation of type (10) would also be derived if the nitrosation occurs via the enolate anion. However, as the overall acidity constant of the keto–enol/enolate equilibrium is $K_a = 5.6\times10^{-9}$ M (Scheme 2), the resulting expression of k_0 should be independent of acidity under the experimental conditions of $[H^+]$ for data in Fig. 5.

An alternative explanation emerges if we consider that nitrosation occurs initially and reversibly at the oxygen atom of the –OH enol (concurrently with the proton-loss) to form a chelate-nitrosyl complex intermediate, which then rearranges to the stable C-nitroso compound. The corresponding reaction mechanism is shown in Scheme 4.

A quite similar reaction scheme has been assumed to explain the kinetic features observed in the nitrosation of aliphatic nitro-compounds in aqueous acid medium,[19] and several other cases of NO rearrangements have been reported.[20,21]

From Scheme 4, in which the enol form of ACPE is the nitrosatable species either by NO^+ or by XNO (in the presence of X^-), by taking into account the mass balance equation, $[ACPE]_t = [KH] + [EH]$ which implies $[EH] = [ACPE]_t K_E/(1+K_E)$, that $[NO^+] = K_{NO}[nitrite][H^+]$; $[XNO] = K_{XNO}[nitrite][H^+][X^-]$, and by assuming a steady-state for the intermediate, eqn (13) can be easily derived.



Scheme 4 Postulated reaction mechanism of the nitrosation of ACPE in aqueous acid media.

$$k_0 = \left[\frac{k_{NO}K_{NO} + k_{XNO}K_{XNO}[X^-]}{1 + \frac{k_3}{k_5}[H^+] + \frac{k_4}{k_5}[H^+][X^-]}\right]\frac{K_E}{1+K_E}[H^+][\text{nitrite}] \quad (13)$$

The comparison between eqn. (10) and (13) indicates that, in the absence of X^-, the δ-parameter equals the ratio of the rate constants k_3/k_5, *i.e.* $\delta = 3.1\pm0.3$ mol^{-1} $dm^3 = k_3/k_5$ (see Table 5). Nevertheless, in the presence of $[Cl^-] = 0.20$ M, $\delta = k_3/k_5 + [Cl^-]k_4/k_5$; then, from the observed value of $\delta = 16\pm1$ mol^{-1} dm^3 along with the value of $k_3/k_5 (= 3.1\pm0.3$ mol^{-1} $dm^3)$ determined in the study of the influence of $[H^+]$ in the absence of X^-, one gets $k_4/k_5 = 64.5$ mol^{-2} dm^6.

By assuming $K_E = 0.38$ determined in the first section of this work, the β-values allow us to determine the reactivity of ACPE enol toward the nitrosating agents NO^+ or ClNO. In the absence of Cl^-, $\beta = k_{NO}K_{NO}K_E[\text{nitrite}]/(1+K_E)$, then the experimental conditions and β-values reported in Table 5 give $k_{NO}K_{NO} = 230$ mol^{-2} dm^6 s^{-1}. In the same way, the influence of [nitrite] at constant $[H^+]$ ($= 0.020$ M) gave $\alpha = 1.20\pm0.02$ mol^{-1} dm^3 s^{-1}. The comparison between eqn. (9) and (13) shows that in the absence of X^-, $\alpha = k_{NO}K_{NO}K_E[H^+]/(1+K_E)$, which results in $k_{NO}K_{NO} = 218$ mol^{-2} dm^6 s^{-1}, in good agreement with the value obtained in studying the influence of acidity. By assuming a mean value for $k_{NO}K_{NO} = 224$ mol^{-2} dm^6 s^{-1}, the value of β ($= 0.79\pm0.03$ mol^{-1} dm^3 s^{-1}) reported in Table 5 along with the experimental conditions, gives $k_{ClNO}K_{ClNO} = 4.6\times10^3$ mol^{-3} dm^9 s^{-1} (or $k_{ClNO} = 4.05\times10^6$ mol^{-1} dm^3 s^{-1} for the reactivity of nitrosyl chloride with the enol of ACPE).

The influence of $[X^-]$ was studied at low $[H^+]$, see Table 6; thus the term $(k_3/k_5)[H^+]$ is negligible with respect to 1 (unity), in other words, the denominator of eqn (13) simplifies to $(1 + [H^+][X^-]k_4/k_5)$, which by comparison with eqn (10) gives $\eta = [H^+]k_4/k_5$. At this point one may understand the variation of η with acidity reported in Table 6. For example, from the two sets of experiments performed in the presence of Cl^-, it is possible to obtain $k_4/k_5 = 86.7$ or 58.3 mol^{-2} dm^6, in good agreement with the same value of $k_4/k_5 = 64.5$ $mol^{-2}dm^6$ determined in the study of the influence of acidity at constant $[Cl^-] = 0.20$ M. The average value of the three preceding data is reported in Table 7. The same procedure has been applied to determine the average values of k_4/k_5 for the case of Br^- and SCN^- which are also listed in Table 7. These values increase with the nucleophilic character of X^-, in agreement with the nature of the k_4-process, in the relative proportion of 1:13:440. In this sense, the values of $\log(k_4/k_5)$ are satisfactorily correlated with the Swain and Scott nucleophilicity parameter, n:[22] $\log(k_4/k_5) = -(2.9\pm0.5) + (1.5\pm0.1)n$,

Table 7 Kinetic rate constants obtained in the nitrosation of ACPE in aqueous acid medium at 25 °C. See Scheme 4 for their meaning.

X-NO	K_{XNO}/ mol^{-2} dm^6	k_{XNO}/ mol^{-1} dm^3 s^{-1}	k_4/k_5 mol^{-2} dm^6
NO^+ (X≡H_2O)	3.0×10^{-7} [a]	7.3×10^8	3.1[b]
ClNO	1.14×10^{-3}	4.2×10^6	70
BrNO	0.051	1.2×10^6	900
SCNNO	30	6.5×10^4	31 000

[a] In mol^{-1} dm^3. [b] For the case of H_2O as nucleophile, *i.e.* k_3/k_5 in mol^{-1} dm^3.

($r = 0.99_7$). The positive and high gradient of the correlation indicates that Cl^-, Br^-, or SCN^- are better nucleophiles than water, and the nucleophilic character increases in the expected order: $Cl^- < Br^- < SCN^-$. This finding supports the proposed reaction mechanism, even though unexpected in enol nitrosation reactions.

On the other hand, the values of γ reported in Table 6 allow us to determine the reactivities of the nitrosating agents nitrosyl chloride, nitrosyl bromide and nitrosyl thiocyanate. By comparing eqn. (11) and (13) one gets that $\gamma = k_{XNO}K_{XNO}[H^+][\text{nitrite}]K_E/(1 + K_E)$. From this expression, taking into account the $[H^+]$ and [nitrite] used in each case (Table 6), it is possible to calculate the second order rate constants (k_{XNO}) for the attack by ClNO, BrNO and SCNNO reported in Table 7. The reactivity order found as $NO^+ > NOCl > NOBr > NOSCN$ is that expected, but the values of k_{XNO} are below those for the corresponding reactions of aromatic amines (such as 1-naphthylamine)[23] or the carbanion of malononitrile,[24] where both NOCl and NOBr react at the diffusion limit. However, the enol of 2-acetylcyclopentanone proves to be the most reactive 1,3-dicarbonyl compound in nitrosation among those studied.[6,18]

Conclusions

In sharp contrast with the homologous substrate: 2-acetylcyclohexanone, the keto–enol interconversion in ACPE system is a rapid reaction in both directions. The keto–enol equilibrium constant determined in water as $K_E = 0.38$, indicates that the amount of the enol tautomer present at equilibrium is higher than 25%. Nevertheless, the presence of micelles enhances the total enol content by taking up this tautomer. In aqueous basic media, the enolate is generated and the measured acid ionization constant was $pK_a = 8.25$.

The nitrosation of ACPE in aqueous strong acid media goes through the enol tautomer to give an intermediate, that is postulated as the chelate-nitrosyl complex, which is in steady-state whatever the nature of the nitrosating agent: NO^+, NOCl, NOBr, or NOSCN. The reactivities in water of these reactants with the enol of ACPE increase according to the expected trend: $NO^+ > NOCl > NOBr > NOSCN$. In the same sense, the observed trend of the nucleophilic character, evaluated from the ratio of the rate constants k_4/k_5, increases as $Cl^- < Br^- < SCN^-$, *i.e.* in accordance with the Swain-Scott nucleophilicity parameter.

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