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EXCITED STATE PROTOTROPIC EQUILIBRIA OF SOME QUINOLINOLS

S. SCHULMAN and Q. FERNANDO
Department of Chemistry, University of Arizona, Tucson, Arizona 85721

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Abstract—The prototropic equilibrium constants for the first excited singlet states of the cation-zwitterion equilibria of a series of quinolinols and 5-isoquinolinol have been determined by fluorescence as well as absorption measurements. The results obtained by the two methods are not in good agreement and the reasons for this are discussed. Hückel MO calculations have been carried out on the molecules studied. The protonation energies and the one electron charge densities on the oxygen atoms can be qualitatively correlated with the excited state equilibrium constants.

EXCITED state protropic equilibrium constants have been determined by three different methods. The first method is based on the Förster cycle.[1] In this method the equivalence in energy of two different paths to the excited state of a base from the ground state of its conjugate acid, together with several simplifying assumptions, yields a relationship from which pK^* can be evaluated. For this purpose, the ground state pK, for the corresponding equilibrium, and the positions of the absorption maxima of both species of the conjugate acid-base pair must be known.

$$pK^* = pK - \frac{Nhc}{2{\cdot}303\,RT}\left(\frac{1}{\lambda_A} - \frac{1}{\lambda_B}\right) \qquad (1)$$

λ_A and λ_B are the absorption maxima of conjugate acid and base, respectively. $N = 6{\cdot}023 \times 10^{23}$ molecules/mole, $h = 6{\cdot}625 \times 10^{-27}$ erg sec, $c = 3 \times 10^{10}$ cm/sec. If both members of the conjugate pair fluoresce, the emission maxima of the conjugate pair may be used in place of the absorption maxima in equation (1). The assumptions involved in the derivation of Eq. (1) are:

(a) The actual work of optical excitation at λ_{max} exceeds the reversible work of electronic excitation by equal amounts for acid and conjugate base.

(b) The electronic transitions are chosen such that the conversion of the electronically excited acid to the electronically excited base is an adiabatic process.

These assumptions have been discussed extensively by Jaffe and Jones.[2]

A second method of determining pK^* values also makes use of the Förster cycle, but errors caused by assumption (b) are minimized by making use of the mirror-image relationship which exists between the absorption and emission bands of the same species. If an average of the absorption and emission maxima of one species is taken, it should give a good approximation of the position of the 0–0 band for that species. This will be true if the spacings between the vibronic states are the same in both the ground and excited states. If the positions of the 0–0 bands for both members of the conjugate pair can be located, assumption (b) can be effectively eliminated.

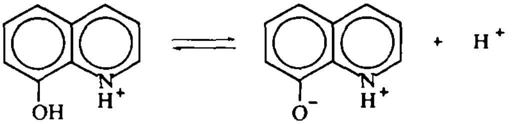
This method is, of course, limited to those compounds in which both members of the conjugate acid-base pair are fluorescent.

The third method of determining pK^* values is essentially a titration of one member of the conjugate acid-base pair which fluoresces. A plot of the fluorescence intensity as a function of the solution acidity gives a sigmoid shaped curve and its inflection point corresponds to the pK^*, provided that prototropic equilibrium is established within the lifetime of the excited state. For this method to be successful, at least one member of the conjugate acid-base pair must be fluorescent.

If the excited state equilibria measured by any of the above techniques all correspond to the same electronic state and the assumptions in the Förster cycle calculation are valid, it is to be expected that pK^* values, obtained by the different methods for a given equilibrium in a given compound, will be approximately equal. Mason *et al.* have determined the pK^* of the cation–zwitterion equilibrium of 3-quinolinol by a fluorescence titration and from the Förster cycle, using absorption as well as fluorescence spectra independently.[3] The values of pK^* obtained by the three methods were $-0{\cdot}5$, $-0{\cdot}3$ and $-0{\cdot}2$, respectively. Despite the many assumptions that are involved in the use of each of the three methods, the agreement in the pK^* values is very good. In the present work, pK^* values have been determined for a series of aromatic hydroxy compounds by the methods described above, in an attempt to correlate the observed acidities in the ground and excited states with the acidity order predicted from Hückel MO calculations.

RESULTS AND DISCUSSION

All the compounds studied were found to fluoresce in concentrated perchloric acid. In dilute perchloric acid ($\sim 10^{-1}$ M) acid, and in neutral aqueous solutions containing 5-quinolinol, 8-quinolinol and 5-isoquinolinol, the fluorescence was quenched, whereas it was shifted to longer wavelengths in the case of 6-quinolinol and 7-quinolinol. Ballard and Edwards have attributed the quenching in 8-quinolinol to a prototropic equilibrium that exists between the first excited singlet states of the cationic and zwitterionic forms of 8-quinolinol,[4] as shown in Eq. (2). That the equilibria studied here are also first excited singlet cation–zwitterion equilibria, was demonstrated by an examination of the fluorescence properties of the N-Me derivatives of the quinolinols. The N-methylmethosulfates of all the quinolinols fluoresced in concentrated perchloric acid and had emission maxima close to those of the non-methylated quinolinols. In the aqueous solution, the N-methylated 5-quinolinol and 5-isoquinolinol did not fluoresce while the 6- and 7-quinolinols fluoresced with emission maxima close to those of the 6- and 7-quinolinols in aqueous solution. Moreover, the variations of the fluorescence intensities of the N-methylated quinolinols with perchloric acid concentration were similar to those of the unmethylated quinolinols. Since the N-methylated derivatives in aqueous solution are structurally similar to the zwitterionic forms of the unmethylated compounds, it is reasonable to infer that the equilibria observed in the fluorescence titrations of these



(2)

compounds are between the cationic and zwitterionic species. The positions of the emission band maxima for the quinolinols and their N-Me derivatives are summarized in Table 1.

TABLE 1. EMISSION MAXIMA OF THE QUINOLINOLS AND THEIR N-METHYLATED DERIVATIVES IN CONCENTRATED PERCHLORIC ACID AND IN AQUEOUS SOLUTION

Compound	λ_{max} (conc $HClO_4$); mμ	λ_{max} (H_2O); mμ
5-Quinolinol	505	—
N-Methyl-5-quinolinol methosulfate	508	—
6-Quinolinol	441	536
N-Methyl-6-quinolinol methosulfate	446	538
7-Quinolinol	428	505
N-Methyl-7-quinolinol methosulfate	432	505
8-Quinolinol	487	—
N-Methyl-8-quinolinol methosulfate	489	—
5-Isoquinolinol	446	—
N-Methyl-5-isoquinolinol methosulfate	446	—

The pK^* values for 6-quinolinol, 7-quinolinol and 5-isoquinolinol were determined from the inflection points of the sigmoid curves obtained by plotting the fluorescence intensity as a function of the acidity (H_0) for a series of solutions of perchloric acid containing 5×10^{-5} M quinolinol. The maximum acidity of the perchloric acid used, $H_0 = -6{\cdot}9$, did not permit the completion of the titration curves of 5 and 8-quinolinols. When measurements were attempted in sulfuric acid solutions of higher acidity, sulfonation of the quinolinols occurred and the fluorescence intensity was affected. The pK^* values of 5-quinolinol and 8-quinolinol were estimated from the few data available for each compound in the following manner.

The relation between the excited state dissociation constant, K^*, and the excited state concentrations of the zwitterion and cation, $[Z^*]$ and $[C^*]$, respectively, is

$$H_0 = pK^* + \log\frac{[Z^*]}{[C^*]}$$

If h_0 is defined by the equation $H_0 = -\log h_0$

$$K^* = h_0\frac{[Z^*]}{[C^*]}$$

At a constant intensity of exciting radiation,

$$[C^*] + [Z^*] = A \text{ (a constant)}$$

and

$$K^* = h_0\left(\frac{A}{[C^*]} - 1\right)$$

If C^* is the fluorescent species, the fluorescence intensity, I_f is proportional to the concentration of the cation in the excited singlet state.

$$\text{i.e., } [C^*] = kI_f$$

so that

$$K^* = m\frac{h_0}{I_f} - h_0 \text{ where } m = \frac{A}{k}$$

Hence, a plot of h_0 vs h_0/I_f should be linear and the intercept on the h_0 axis should give $-K^*$. The uncertainty in K^* is large when the number of data points necessary to establish a straight line becomes small.

The pK^* values for the cation–zwitterion equilibria of the five compounds studied are listed in Table 2. The emission band maxima listed in Table 1 can be used to calculate pK^* values from the Förster cycle, provided that the pK values for the corresponding ground state cation–zwitterion equilibria are known. The ground state pK values determined by Mason, in aqueous solution, are 7·03 for 6-quinolinol and 6·01 for 7-quinolinol.[5] Using these data in the Förster cycle, the pK^* for 6-quinolinol was found to be −1·57 while that for 7-quinolinol was 1·55. Obviously, these results do not agree with the values obtained by the fluorescence titration technique (Table 2). This is to be expected since the ground state pK values were obtained in aqueous solution while the emission spectra were obtained in fairly concentrated solutions of perchloric acid. It would be more profitable, therefore, to use the emission band maxima and the pK^* values obtained from the fluorescence titrations to evaluate the experimentally inaccessible ground state pK values in a concentrated perchloric acid medium. Such a calculation gives a pK of 5·40 for 6-quinolinol and 5·65 for 7-quinolinol. Therefore, as expected, these compounds are stronger acids in a concentrated perchloric acid medium than in an essentially aqueous medium.

TABLE 2. EXCITED STATE ACID DISSOCIATION CONSTANTS DETERMINED BY FLUORESCENCE TITRATION

Compound	pK^*
5-Quinolinol	−6·0
6-Quinolinol	−3·2
7-Quinolinol	−2·1
8-Quinolinol	−6·5
5-Isoquinolinol	−4·7

The absorption spectra of the quinolinols and their N-methylated derivatives were measured in order to determine the pK^* values of the quinolinols by the Förster cycle. The band maxima for the lowest energy transitions along with the ground state pK values determined by Mason[5] are summarized in Table 3. These data were used to calculate the pK^* values for the cation–zwitterion equilibria in aqueous media and the results obtained are tabulated in Table 4.

TABLE 3. LOWEST ENERGY BAND MAXIMA AND GROUND STATE ACID DISSOCIATION CONSTANTS FOR THE CATION–ZWITTERION EQUILIBRIA OF THE QUINOLINOLS

Compound	pK (5)	λ_{max} (mμ) in 0·1 M $HClO_4$	λ_{max} (mμ) in Buffer at pH 7·0
5-Quinolinol	6·49	370	450
N-Methyl-5-quinolinol methosulfate	6·10	—	462
6-Quinolinol	7·03	343	400
N-Methyl-6-quinolinol methosulfate	7·15	—	408
7-Quinolinol	6·01	348	402
N-Methyl-7-quinolinol methosulfate	5·56	—	406
8-Quinolinol	6·00	358	430
N-Methyl-8-quinolinol methosulfate	6·80	—	444
5-Isoquinolinol	6·84	359	400
N-Methyl-5-isoquinolinol methosulfate	6·90	—	408

TABLE 4. EXCITED STATE ACID DISSOCIATION CONSTANTS CALCULATED BY THE FÖRSTER CYCLE FROM ABSORPTION MAXIMA OF CATION AND ZWITTERION

Compound	pK	pK^*
5-Quinolinol	6·49	−3·6
6-Quinolinol	7·03	−1·8
7-Quinolinol	6·01	−1·5
8-Quinolinol	6·60	−3·3
5-Isoquinolinol	6·84	+1

It is evident from the data in Tables 2 and 4 that the pK^* values determined by the fluorescence titration technique do not agree with those determined from absorption spectra. The most striking difference is that in all cases the absorption measurements indicate that the quinolinols are much weaker acids in their excited states. Several explanations for these discrepancies can be advanced, any or all of which might account for this trend in the pK^* values obtained by the two methods.

Fluorescence measurements are made in concentrated perchloric acid and absorption measurements in solutions that are essentially aqueous. Solvent effects could therefore account for the increased acidity of the compounds in perchloric acid media. Moreover, the averaging of the fluorescence spectra and absorption spectra may not yield the 0–0 band since the mirror image relationship between the two types of spectra may be vitiated if the media in which fluorescence and absorption measurements are made are quite different.

In this work, the equilibria that have been studied involve the zwitterion and cation forms, but the H_0 scale is defined for equilibria between the neutral and cation forms. If the H_0 scale was adequate to describe zwitterion–cation equilibria, the straight line obtained, when values of H_0 are plotted against corresponding values of log $[Z^*]/[C^*]$, should have a slope of unity. In this work, the straight lines had slopes of about 0·7; correction of the pK^* values obtained by the fluorescence titration by this factor would tend to give better agreement between the two sets of pK^* values in all but one instance, namely the 5-isoquinolinol. It might be argued that the anomaly arises because equilibrium was not obtained in the excited state in the case of 5-isoquinolinol. Hence, the pK^* value obtained by the fluorescence titration technique would be in error; however, in all cases, including the 5-isoquinolinol, sigmoid curves were obtained when the fluoroescence intensities were plotted against H_0 values; in the case of the 5-isoquinolinol, an excellent straight line was obtained when values of H_0 vs log $[Z^*]/[C^*]$ were plotted. These observations confirm that equilibrium was attained between the cation and zwitterion in their excited states. In order to resolve the anomalous pK^* values of the 5-isoquinolinol, it would be necessary to carry out an investigation of the excited state acidities of a series of isoquinolinols.

In an attempt to correlate the observed acidity orders in both the ground state and excited states, Hückel MO calculations were carried out on all of the compounds studied here, as well as for 3-hydroxyquinoline. The bond integral and coulomb integral parameters used to correct the carbon–carbon bond-integral (β) and the carbon coulomb integral (α) for negatively charged oxygen and positively charged nitrogen in the zwitterion, and for neutral oxygen and positively charged nitrogen in the cation, were those suggested by Burton and Davis.[6] The energy levels and orbital coefficients for the zwitterion and cation forms were calculated by means of a digital computer. It was assumed that the heterocyclic nitrogen atom contributed one electron to the π-system while the exocyclic oxygen atom contributed two electrons to the π-system. The difference in π-energy (ΔE_π) between the zwitterion and cation should be a measure of the energy of protonation and the one electron charge densities on the oxygen atom (q_0) should give qualitative information about the relative acidities of the ground and excited states of these compounds. These quantities were calculated from the squares of the orbital coefficients of the highest occupied orbitals in the case of ground state species, and from the squares of the lowest unoccupied orbital coefficients in the case of the excited state species. The calculated values of ΔE_π, ΔE_π^*, q_0 and q_0^* are given in Table 5.

TABLE 5. DIFFERENCES IN π-ELECTRON ENERGIES AND ONE ELECTRON CHARGE DENSITIES UPON OXYGEN IN GROUND (ΔE_π AND q_0) AND EXCITED (ΔE_π^* AND q_0^*) STATES

Compound	ΔE_π	q_0		ΔE_π^*	q_0	
		Cation	Zwitterion		Cation	Zwitterion
3-Quinolinol	0·605β	0·191	0·520	0·365β	0·034	0·022
5-Quinolinol	0·532β	0·164	0·402	0·321β	0·000	0·000
6-Quinolinol	0·574β	0·184	0·490	0·348β	0·025	0·025
7-Quinolinol	0·589β	0·161	0·500	0·370β	0·038	0·021
8-Quinolinol	0·551β	0·184	0·453	0·320β	0·000	0·000
5-Isoquinolinol	0·436β	0·122	0·370	0·399β	0·100	0·222

In view of the approximations that are made in these calculations, no quantitative correlations can be made. Certain qualitative trends can, however, be seen. In all cases, the one electron charge densities on the phenolic oxygen are lower in the excited states of both zwitterion and cation than they are in the corresponding the ground states. This confirms the experimental observation that the phenolic groups of all the compounds should be more acidic in the excited state than in the ground state. This further substantiated by the lower values of $\Delta E_{\pi}{}^{*}$ when compared with the ΔE_{π} values in Table 5.

In the excited state, 5-quinolinol and 8-quinolinol are the most acidic molecules; 6-quinolinol and 7-quinolinol are molecules of intermediate acidity and 3-quinolinol is the least acidic. The position of 5-isoquinolinol is anomalous; the fluorescence titration technique indicates that its acidity is between the most acidic and intermediate groups, whereas the Förster cycle calculation indicates that it is in the least acidic group. An examination of the $\Delta E_{\pi}{}^{*}$ and q^{*} values in Table 5 confirms the observed relative excited state acidities of all the quinolinols and indicates that 5-isoquinolinol is the least acidic molecule, as predicted by the Förster cycle calculation. From the experimental data available at present, it is not possible to resolve the anomaly that has been observed with 5-isoquinolinol.

EXPERIMENTAL

Materials. 5-Quinolinol, 6-quinolinol, 7-quinolinol, 8-quinolinol and 5-isoquinolinol were obtained from K and K Laboratories, Plainview, New York. The compounds were recrystallized several times from EtOH. A fluorescent impurity in the 5-quinolinol was removed by repeated recrystallization. The N-Me derivatives of the quinolinols were prepared by dissolving them in excess Me_2SO_4 and allowing the excess to evaporate slowly. Crystals of the N-methylated compounds were collected and recrystallized from EtOH. Mallinckrodt Analytical Grade perchloric acid was used in this work.

Fluorescence spectra were obtained with an Aminco–Bowman Spectrophotofluorimeter and a Sargent X-Y recorder. The emission monochromator of the spectrophotofluorimeter was calibrated against the emission spectrum of a quinine bisulfate soln; the 365 mμ line of mercury was used as the excitation source.

Absorption spectra were measured with a Cary Model 14 recording spectrophotometer with 1 cm quartz cells.

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