Solvent Effects on the Fluorescence Properties of Methyldihydroquinolinones

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The absorption and fluorescence spectra and the fluorescence quantum yields of two methyl-2,3-dihydro-4(1H)-quinolinones in various solvents are reported. In some solvents deuteration-induced fluorescence enhancement has been observed. The solvent effects in aprotic solvents are consistent with the general type of solvent interaction. For protic solvents, solute-solvent complexation in the excited state is suggested.

Key words: Fluorescence, Dihydroquinolinones, Hydrogen bond.

1. Introduction

In many molecules large changes in charge distribution can be induced in the excited state upon absorption of a photon. The final relaxed state often involves a certain degree of complexation between the solvent and the solute. Fluorescence quenching by proton transfer or hydrogen-bonding interactions has received special attention as one of the fundamental processes of radiationless deactivation. Such phenomena would be fairly general with molecules enabeling intramolecular charge-transfer transitions, and the study of their excited-state relaxation processes is a subject of considerable current interest.

Dihydroquinolinone derivatives are of pharmaceutical interest, some of them being employed as central nervous system depressants, antipyretics, and anti-inflammatory drugs [1]. They are also of interest owing to the possibility of their transformation into 4(1H)-quinolinones, a newly developed group of antibiotics [2]. In this paper, fluorescence spectra and fluorescence quantum yields in a large number of solvents, as well as deuteration-induced fluorescence enhancement phenomena are reported for the 2,3-dihydro-4(1H)-quinolinones shown in Figure 1.

2. Experimental

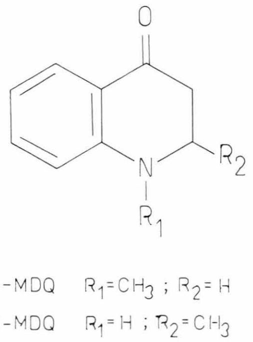
The investigated compounds were synthesized by standard procedures [3, 4] and purified by recrystallization or preparative thin-layer chromatography.

The UV-VIS absorption spectra were taken on a spectrophotometer Specord M-40 (Carl Zeiss, Jena, BRD). The fluorescence spectra were recorded on a Perkin-Elmer MPF-44 spectrofluorimeter. The fluorescence quantum yields Q_F were determined relative to quinine bisulphate ($Q_F = 0.54$ in 1N sulfuric acid [5]). All solvents used were of spectroscopic grade.

3. Results and Discussion

Table 1 shows the spectral characteristics of 2-MDQ in different solvents.

The emitting state of dihydroquinolinones results from an intramolecular charge transfer (ICT) [6]. For the fluorescence charge transfer states which have been observed previously, the effects of the solvent interactions on the energy and hence the wavelength of emission have been classified into general solvent effects (i.e. the way in which the solvent reorganizes to stabilize the charge separated state electrostatically) and specific solvent interactions (e.g. hydrogen bond-



1-MDQ $R_1 = CH_3$; $R_2 = H$

2-MDQ $R_1 = H$; $R_2 = CH_3$

Fig. 1. Structure of the investigated compounds.

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Table 1. Experimental Spectral Characteristics of 2-MDQ in various solvents. ν_{abs}, ν_{em} position of the lowest-energy absorption and the fluorescence maximum; n refractive index [15]; ε static dielectric constant [15]; Δf orientational polarisability of the solvent (see text); $E_T(30)$ empirical polarity parameter [16]; Q_F relative fluorescence quantum yield; ν in cm^{-1}; E in $kcal \cdot mol^{-1}$.

Solvent	ε	n	$E_T(30)$	ν_{abs}	ν_{fl}	Q_F
1. Acetone	20.70	1.3587	42.2	27 300	22 700	0.21
2. Acetonitrile	37.50	1.3416	46.0	27 300	22 300	0.28
3. 1-Butanol	17.51	1.3985	50.2	26 500	20 500	0.27
4. Chloroform	4.81	1.4429	39.1	27 400	21 900	0.29
5. Cyclohexane	2.02	1.4235	31.2	28 300	25 200	0.002
6. Cyclohexanol	15.00	1.4641	46.9	26 400	20 600	0.29
7. Diethylether	4.34	1.3526	34.6	27 900	24 000	0.12
8. Dioxane	2.21	1.4203	36.0	27 600	22 300	0.29
9. Ethanediol	37.70	1.4318	56.3	26 300	19 900	0.16
10. Ethanol	24.55	1.3594	51.9	26 500	20 200	0.19
Ethanol-d_1				26 500	20 200	0.25
11. Ethylacetate	6.02	1.3698	39.1	27 500	23 300	0.17
12. Glycerol	42.50	1.4716	–	26 100	19 600	0.04
13. Heptane	1.92	1.3870	–	28 500	25 300	0.002
14. Hexane	1.88	1.3800	30.9	28 500	25 300	0.002
15. Methanol	32.70	1.3265	55.5	26 600	20 000	0.15
16. 1-Propanol	20.33	1.3856	50.7	26 200	20 300	0.20
17. THF	7.58	1.4050	37.1	27 500	23 400	0.16
18. Toluene	2.38	1.4969	33.9	27 900	23 800	0.11
19. Water	78.39	1.3329	63.1	27 000	19 700	0.05

ing, etc. [7]. For non-hydrogen bonding solvents the stabilization of the CT state arising from the general type of solvent interaction can be related to the polarisability of the solvent expressed in terms of a function of the solvent dielectric and refractive index [7]:

$$\tilde{\nu}_{em} - \tilde{\nu}_{abs} = 2(\Delta\mu^2 \Delta f)/h c a^3,$$

where h is the Planck's constant, c is the speed of light, a is the Onsager radius, $\Delta\mu = \mu_e - \mu_g$ is the change of the dipole moment upon excitation and $\Delta f = f - f'$ is the solvent polarisability function, where

$$f = \frac{\varepsilon - 1}{2\varepsilon + 1}, \quad f' = \frac{n^2 - 1}{2n^2 + 1}.$$

ε is the solvent static dielectric constant and n is the refractive index of the solvent.

Figure 2 shows the dependence of the Stokes shift in aprotic solvents on the solvent polarity parameter Δf.

It can be seen that the data point corresponding to dioxane is off the line; this has been observed in other systems [8] and may arise because the conformation of the dioxane molecule may be altered when it is solvating a charge transfer excited state. From other solvent polarisability-fluorescence wavelength correlations [8] it has been found that the effective dielectric constant of dioxane is 6 or 7. Using a value of this order brings the dioxane point onto the line in Figure 2.

By adding the Van der Waals volume increments [9] the Onsager radius a (i.e. the radius of the sphere occupied by the molecule in the solvent) of 2-MDQ has been estimated to be 3.67 Å. This value is close to the Onsager radius of 7-chloro-2,3-dihydro-4(1H)-quinolinone (3.6 Å) [10].

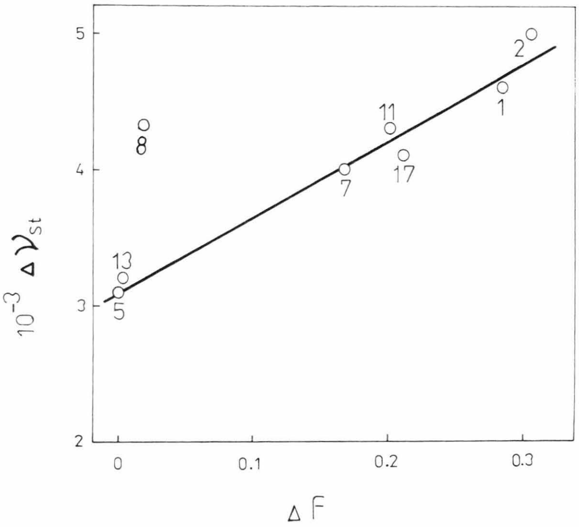

Fig. 2. Dependence of the Stokes shift $\Delta\nu_{St}$ of 2-MDQ on the solvent polarity parameter Δf (see text). Slope 5605 cm^{-1}, intercept 3085 cm^{-1}, $r = 0.985$.

From the slope in Fig. 2 the change of the dipole moment $\Delta\mu$ is determined to be 5.25 D.

The dipole moment of the electronically excited state can be evaluated also from the solvent field effects on the absorption spectra only. The correlation method of Varma and Groenen [11] has been used for

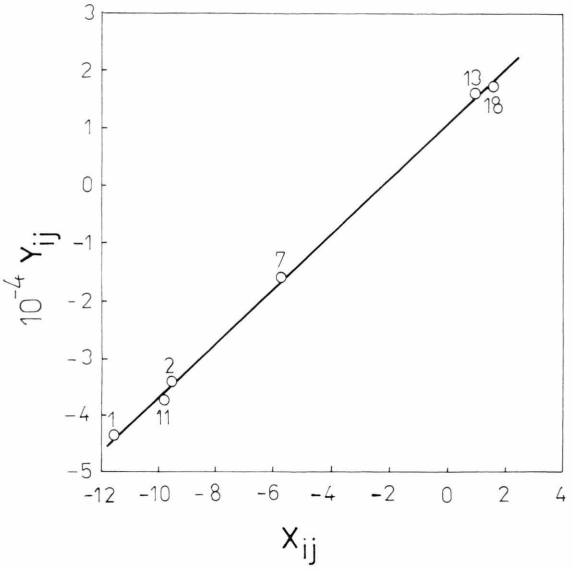

Fig. 3. Dependence of 2-MDQ absorption maximum as a function of solvent dielectric properties. Y_{ij} and X_{ij} are explained in the text. Slope 4765 cm^{-1}, intercept 10 530 cm^{-1}, $r = 0.999$.

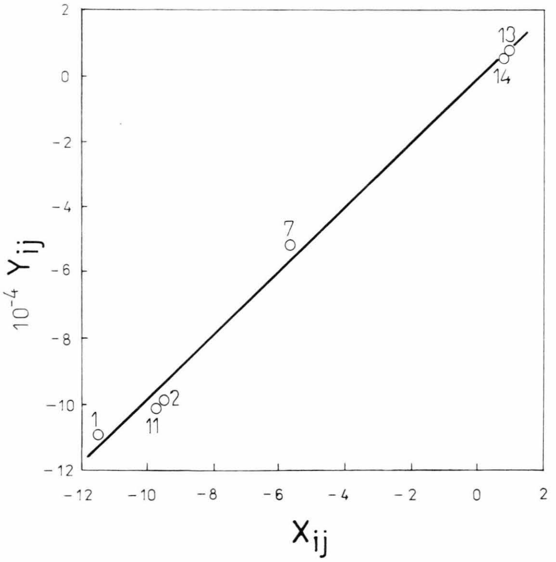

Fig. 4. Dependence of 2-MDQ fluorescence maximum as a function of solvent dielectric properties. Y_{ij} and X_{ij} are explained in the text. Slope 11 272 cm^{-1}, intercept 12 638 cm^{-1}, $r = 0.983$.

the data analysis. The plot of Y_{ij}^{abs} vs. X_{ij} for 2-MDQ is shown in Fig. 3, where

$$Y_{ij} = \frac{\nu_j^{\text{abs}} - \nu_i^{\text{abs}}}{f_i' - f_j'}, \qquad X_{ij} = \frac{f_i - f_j}{f_i' - f_j'}.$$

Only absorption data in aprotic solvents were used. Values of $\nu_j^{\text{abs}} - \nu_i^{\text{abs}}$ smaller than 50 cm^{-1} and $f_i' - f_j' < 0.01$ have not been considered. From the slope we obtain $\Delta\mu\,\mu_g = 23.41$ D. Using the value obtained on the basis of the Lippert model $\Delta\mu = 5.25$ D we calculate $\mu_g = 4.46$ D. This value is in excellent agreement with that calculated by the PPP method ($\mu_g = 4.09$ D) and the CNDO method ($\mu_g = 4.30$ D).

The angle between the directions of μ_e and μ_g has been calculated to be 2.94° (PPP) and 6.39° (CNDO). Consequently, to a good approximation they can be considered parallel. Using the obtained values for μ_g and $\Delta\mu$ we calculate $\mu_e = 9.71$ D.

It has been shown that in the case of 7-chloro-2,3-dihydro-4(1H)-quinolinone the Onsager radius in the first excited state (4.54 Å) differs substantially from that in the ground state (3.6 Å) [10]. In order to check whether we have the same situation in our case we applied the method of Varma and Groenen [11] to the fluorescence spectra as well. In Fig. 4 a plot of Y_{ij}^{fl} vs. X_{ij} is shown.

From the slope of the obtained straight line, using the values obtained for $\mu_e = 9.71$ D and $\Delta\mu = 5.25$ D, we estimate that the Onsager radius of 2-MDQ in the first excited singlet $\pi\pi^*$ state is 3.74 Å, i.e. it practically does not change upon excitation.

An interesting correlation is observed between the energy of the fluorescence maximum and the electrophilicity of the solvent (Figure 5).

Because of the partially ionic character of the excited state we have considered the $E_T(30)$ value [12] as an appropriate indicator of the electrophilicity of the solvent. A separate correlation line is found for 2-MDQ in strongly interacting solvents containing acidic hydrogen (i.e. alcoholic solvents and water, Fig. 5), suggesting a different nature of the excited state in these solvents. The variation of the fluorescence quantum yield can also be divided into two groups according to the nature of the solvent (Figure 6).

In all solvents studied except alcohols and water the quantum yield increases as the emission energy decreases. In alcoholic solvents, although they have the lowest emission energies, the quantum yield is smaller than in acetone and acetonitrile and decreases with the emission energy. This behaviour is consistent with the conclusion drawn from the fluorescence spectral

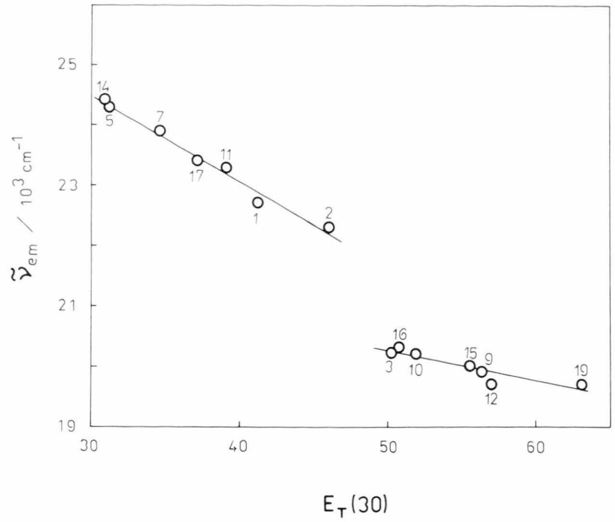

Fig. 5. Dependence of the energy of the fluorescence maximum $\tilde{\nu}_{em}$ of 2-MDQ on the empirical solvent polarity parameter $E_T(30)$.

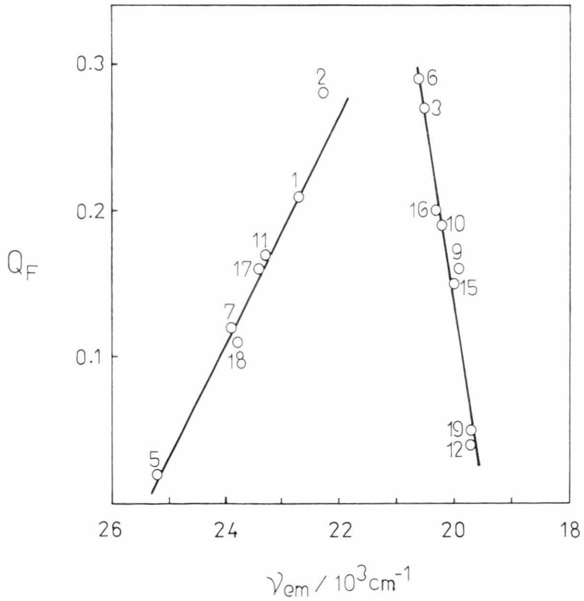

Fig. 6. Relative fluorescence quantum yield of 2-MDQ plotted as a function of the energy of the fluorescence maxima.

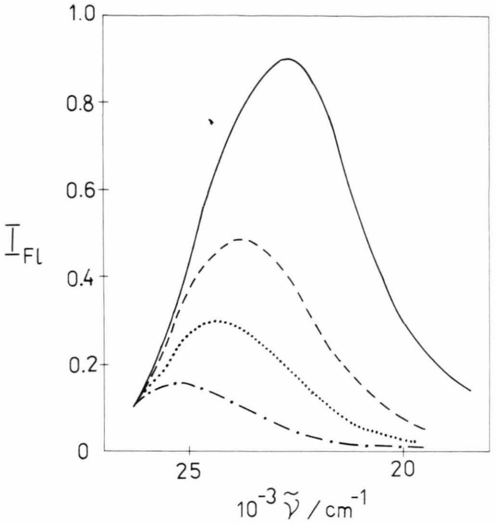

Fig. 7. Fluorescence spectra of 2-MDQ in cyclohexane/ethanol mixtures: (-·-) 4.3×10^{-3} M l^{-1} ethanol; (····) 8.7×10^{-3} M l^{-1} ethanol; (----) 1.3×10^{-2} M l^{-1} ethanol; (—) 1.74×10^{-2} M l^{-1} ethanol.

data of the different nature of the emitting state in aprotic and protic solvents.

For the purpose of getting further experimental evidence about the nature of the excited state we have recorded the fluorescence spectra of 2-MDQ in solvent mixtures of non-polar and polar solvents. Upon addition of minor amounts of polar aprotic solvents (dioxane, acetonitrile or dimethylsulfoxide) to heptane solutions of 2-MDQ the fluorescence maxima quickly more to lower frequencies and the fluorescence intensity rapidly increases, while the half-width of the emission band remains unchanged. As there is no change in the shape of the emission band we ascribe the observed non-linearity of the solvatochromic shift to the general process of "dielectric enrichment" of the solvent shell of the dipole molecule [13].

Very dilute concentrations of ethanol (10^{-2}–10^{-3} M l^{-1}) have a different effect on the fluorescence spectrum of 2-MDQ dissolved in heptane: it not only shifts to the red but also broadens considerably (Figure 7).

The observed broadening of the emission band upon adding of traces of ethanol to 2-MDQ in heptane (Fig. 7) suggests the appearance of a new emission band presumably due to the hydrogen-bonded species. Upon further increase of the alcohol concentration (i.e. of the solvent polarity) the fluorescence maximum moves continuously to the red, the bandwidth remaining almost constant. This shift may be attributed to the general dipolar solvent-solute interactions. Thus the protic perturbation is due to a combination of specific and non-specific interactions.

To probe the effects of hydrogen bonding on the excited state, radiationless decay processes and the nature of the emitting state, we studied the effects of

Table 2. Experimental Spectral Characteristics of 1-MDQ. ν_{abs}, ν_{fl} Energy of the Longest Wavelength Absorption and Fluorescence Maximum; Q_{F} Fluorescence Quantum Yield; ν in cm^{-1}.

Solvent	ν_{abs}	ν_{fl}	Q_{F}
Cyclohexane	27 600	24 600	0.03
Ethylacetate	26 800	22 400	0.18
Acetone	26 600	21 800	0.22
Acetonitrile	26 400	21.600	0.28
Chloroform	26 200	21 700	0.37
Chloroform-d	26 200	21 800	0.33
Ethanol	26 100	19 700	0.23
Ethanol-d_1	26 100	19 700	0.31
Water	25 400	18 800	0.06
Deuteriumoxide	25 400	18 800	0.14

deuterium substitution in the solvent for 2-MDQ and 1-MDQ (which possesses no NH group capable of deuterium exchange). Measurements have been performed for 1-MDQ in $CHCl_3$, $CDCl_3$, C_2H_5OH, C_2H_5OD, H_2O and D_2O. Table 2 shows the position of the longest-wavelength absorption and the fluorescence maximum of 1-MDQ together with the fluorescence quantum yields.

It can be seen that upon deuteration of the solvent the absorption and fluorescence spectra of 1-MDQ remain practically unchanged and only the fluorescence intensity varies: while the deuteration of the C–H bond of chloroform does not affect Q_{F}, the deuteration of the O–H bonds of ethanol and water leads to an enhancement of the fluorescence intensity. By far the larger non-radiative deactivation of the studied compounds in protic solvents than in aprotic ones and the deuterium isotope effects indicate that the O–H bond of the solvent plays a specific role in the radiationless deactivation.

For a hydrogen-bonded complex possessing an ICT transition the hydrogen bond is stronger in the relaxed fluorescent state than in the ground one. The internal conversion (IC) to the ground state thus results in vibrational excitation of the high-frequency modes involved in hydrogen bonding, i.e. $\mathrm{O{-}H \cdots O{=}C}<$ for water due to the sudden change in bond lengths. The vibrational modes of the intermolecular hydrogen bonds are therefore considered to act as accepting modes in the internal conversion between the ICT and the ground state [14, 15]. Deuteration of the solvent O–H bonds lowers the vibrational frequency and the Franck-Condon overlap factor for the transition. Therefore a slower IC rate and a higher fluorescence quantum yield is anticipated.

The fluorescence spectral data, quantum yield measurements and isotope effects presented lead to a self-consistent picture involving hydrogen-bond formation between the substrate and the protic solvent. The excess of stabilization energy is of the order of 2300 cm^{-1}, as estimated from the difference of the emission maxima of 2-MDQ in acetonitrile and methanol, which are of the same polarity.

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