Fluorescence Spectra of 2-Pyridylbenzimidazoles. A Specific Interation of 2-(2-Pyridyl)benzimidazole with Ethanol

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The fluorescence spectra of 2-(2-pyridyl)- (**1a**), 2-(3-hydroxy-2-pyridyl)- (**1b**), 1-methyl-2-(2-pyridyl)-, 2-(3-pyridyl)-, and 2-(4-pyridyl)-benzimidazole have been studied, and it has been found that their intensities are very strong, except for an ethanolic solution of **1a**. It is likely, therefore, that a specific interaction, probably a bridge-type complexation of **1a** with an ethanol molecule where imidazolic proton is explicitly involved, is responsible for the observed reduction in the fluorescence intensity for ethanol solutions. The fluorescence emission with a large Stokes' shift of **1b** is very strong, in ethanol as well as in other organic solvents tested, indicating a faster intramolecular proton transfer in the excited singlet state than intermolecular deactivation relaxation with ethanol molecules.

The fluorescence and phosphorescence intensities of an aromatic molecule are dependent on the relative alignment of the energy levels of its singlet and triplet states. Therefore, the fluorescence intensity of an aromatic molecule may differ much from those of the isomers. The emission nature of pyrazine, for example, is quite different from those of pyridazine and pyrimidine.[1]

It has been proved in some cases that intramolecular interactions, especially intermolecular hydrogen bonding, between a solvent and a solute molecule in the ground or excited state play an important role in fluorescence emission.[2] This type of interaction seems to be very important in the cases of heteroaromatic compounds, such as acridine, which have been proved to show a remarkable solvent dependence on the emission nature.[3,4]

Recently, it has been reported that pyrrolo[2,3-*b*]-pyridine shows two emission bands in a rather concentrated solution in non-polar solvents as well as in a dilute ethanol solution, and that the emission band at longer wavelengths can be attributed to the isomeric species produced *via* intermolecular proton transposition.[5]

This paper will be concerned with the fluorescence spectra of several 2-pyridylbenzimidazoles in various solvents.

Experimental

Materials. Four compounds, 2-(2-pyridyl)- (**1a**), 2-(3-hydroxy-2-pyridyl)- (**1b**), 2-(3-pyridyl)- (**2**), and 2-(4-pyridyl)-benzimidazole (**3**), were prepared by the condensation of *o*-phenylenediamine with an appropriate pyridinecarboxylic acid at elevated temperatures, according to the literature method.[6]

1-Methyl-2-(2-pyridyl)benzimidazole (1c). To a dried dimethyl sulfoxide solution (20 ml) containing sodium hydride (1/50 mol) was added **1a** (1/200 mol) under nitrogen purging. The solution was slowly heated up to 85 °C and, then kept for 30 min to yield a dark brown solution. To this solution, cooled in an ice-water bath, methyl iodide (1/50 mol) was added in portions, with care taken not to raise the solution temperature above 30 °C. The reaction mixture was then poured into water (500 ml), resulting in an oil-suspended aqueous solution. The oil was extracted with ethyl acetate. The subsequent evaporation of the solvent yielded a pale yellow oil which crystallized with treated with a glass rod. The pale yellow fine solids were charged on an alumina column and eluted with benzene. The evaporation of the solvent gave fine colorless crystals (**1c**): mp 64—65 °C; Found; C, 68.75; H, 5.30; N, 18.39%. Calcd for $C_{13}H_{11}N_3 \cdot H_2O$: C, 68.72; H, 5.72; N, 18.50%.

Spectral Measurements. The absorption and fluorescence spectra were recorded on a Hitachi spectrophotometer, Model 356, and a Hitachi fluorescence spectrophotometer, Model MPF-2, respectively, both at room temperature. Cyclohexane and 1,2-dichloroethane of a spectral grade and diethyl ether, benzene, and ethanol of a guaranteed grade were used without further purification.

TABLE 1. ABSORPTION AND FLUORESCENCE SPECTRAL DATA OF THREE 2-PYRIDYLBENZIMIDAZOLES (**1a**, **2**, AND **3**) IN VARIOUS SOLVENTS

Compd	Solvent[a]	Absorption		Fluorescence[b]	
		λ_{max}(nm)[c]	ε	λ_F (max)	I_{rel}[d]
1a	CH	311.5	25400	349.0	15
	Benzene	312.0	23100	357.0	11
	DCE	310.5	22600	359.0	10
	EE	310.0	23300	352.0	19
	Ethanol	309.0	20500	358.0	1
2	CH	314.5	20500	355.0	22
	Benzene	311.0	19700	352.5	15
	DCE	310.0	20000	354.5	17
	EE	309.0	21500	347.5	26
	Ethanol	312.0	20100	360.0	16
3	CH	310.0	20900	358.0	11
	Benzene	309.0	20900	357.0	9
	DCE	306.5	20900	363.0	13
	EE	306.0	23200	352.0	12
	Ethanol	306.5	20700	372.5	14

a) CH, DCE, and EE stand for cyclohexane, 1,2-dichloroethane, and ethyl ether respectively. b) The concentrations were 4.23×10^{-6}, 4.20×10^{-6}, and 4.22×10^{-6} M for **1a**, **2**, and **3** respectively. The excitation wavelength of 310 nm was selected. c) The vibrational structures in the absorption and emission spectra were observed for cyclohexane solutions, but not for most of the other solutions. Therefore, the $0 \rightarrow 1'$ and $0' \rightarrow 1$ transition components are recorded here as the band peak for the sake of easy comparison. d) The relative intensity was given as the ratio of the peak height to that for an ethanol solution of **1a**.

Results and Discussion

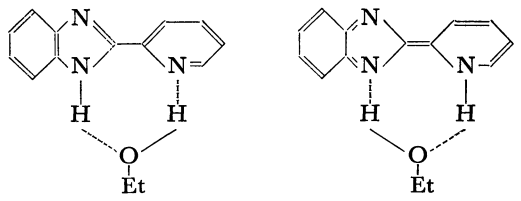
*Fluorescence Spectra of Three 2-Pyridylbenzimidazoles, **1a**, **2**, and **3**.* Table 1 summarizes the results of the absorption and emission spectral measurements of **1a**, **2**, and **3** in various organic solvents.

The observed red shifts and the enhancement of the molar extinction coefficients for the first absorption bands of these compounds, as compared with those for benzimidazole,[7] indicate the complete conjugation of the pyridyl substituent with the benzimidazole moiety.

It is possible to say that the fluorescence bands of these compounds are not separated much from, and take mirror images with, the absorption band, indicating that the molecular conjugations in the excited singlet states differ little from those in the ground states. The fluorescence spectra were found to be independent of the excitation wavelengths and of the concentration.

The fluorescence intensities of these compounds are very strong and of the same order of magnitude, except for the case of **1a** in ethanol. It is noteworthy that benzene did not quench the fluorescence emission of these compounds, taking into account the quenching interactions between benzene and indole,[8] where the NH group has been suggested as being essential. The absence of any quenching effect of benzene in the present case is probably to be ascribed to: (i) the presence of a rather bulky pyridyl group, which is believed to prohibit the benzene molecule from interacting with the NH group and (ii) a stronger interaction of the NH group with the pyridine-N atom internally (**1a**) or intermolecularly (**2** and **3**) than with the benzene solvent molecules.

It is of interest that the fluorescence intensity of **1a** in an ethanol solution is much weaker than in cyclohexane. Figure 1 shows the quenching effect of ethanol on the fluorescence spectrum of **1a** in the binary solvent system of cyclohexane and ethanol. From the figure it is clear that ethanol molecules effectively quench the fluorescence emission of **1a**. By plotting the fluorescence intensities *versus* the quencher concentration, a value of 0.05 mol/l was obtained for the quencher efficiency of ethanol. This value is comparable with that reported for the chloroform–indole in cyclohexane.[8] On the other hand, ethanol molecules did not quench the emission of **2** and **3**. From these observations it is possible to assume that the fluorescence quenching by ethanol does not originate from a simple intermolecular hydrogen bonding, but from a specific bridge-type intermolecular hydrogen bonding, which is possible only for a combination of ethanol and **1a** which has two nitrogen atoms in a proper proximity. The specific bridge-type intermolecular hydrogen bonding is shown schematically in **A**. As can readily be expected from the figure, this type of intermolecular hydrogen bonding is impossible between an ethanol molecule and **2** or **3**.



A **A′**

A similar quenching effect, of course, is commonly observed for some alcoholic solutions of **1a**. The fluorescence intensity of **1a** in some alcoholic solutions is in this order: MeOH<EtOH<*n*-PrOH<*n*-BuOH (Table 2). This order is inversely proportional to the proton exchange activity of the hydroxyl group.

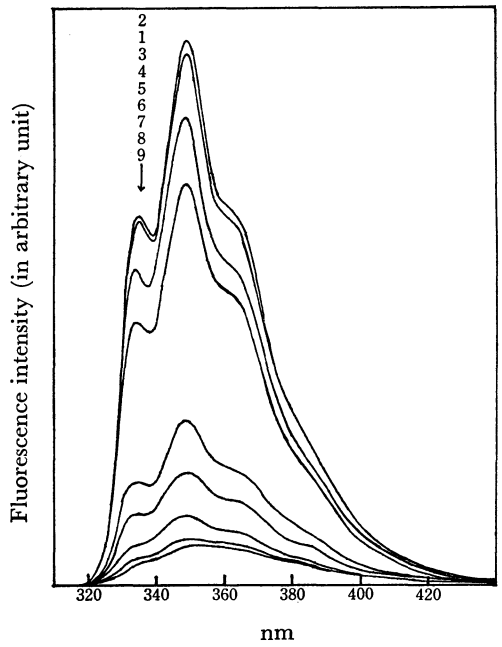


Fig. 1. Fluorescence spectrum of 2-(2-pyridyl)benzimidazole in cyclohexane–ethanol binary solvents (1.6×10^{-5} M, excitation at 310 nm). Ethanol contents are: 1, 0; 2, 0.01; 3, 0.05; 4, 0.1; 5, 0.5; 6, 1.0; 7, 2.0; 8, 5.0; and 9, 10.0.

TABLE 2. SPECTRAL PARAMETERS OF **1a** IN VARIOUS ALCOHOLS AT ROOM TEMPERATURE (21 ± 1 °C)[a]

Solvent	Absorption		Emission		
	λ_{max}	ε	λ_{ex}	λ_F(max)	I[b]
Methanol	308	21100	300	362	1.0
Ethanol	309	20500	300	358	1.4
Propanol	310	21100	300	356	1.7
Butanol	311	20800	300	354	2.1

a) Solutions were prepared by diluting a cyclohexane solution of **1a** with an appropriate alcohol, the resultant concentration being 1.48×10^{-5} M. b) The relative intensities of the emission bands were estimated from the ratio of the peak height to that of the methanol solution. The small difference in the molar extinction coefficients was neglected.

Molecular Mechanism of Fluorescence Quenching by Ethanol. Compound **1c** is similar to **1a** except for the replacement of the imidazolic proton by the methyl group. Consequently, it is unable to form a hydrogen-bonded complex like **A** with an ethanol molecule; thus it can serve as a convenient control for the experiments with **1a**. As would be expected, the absorption and fluorescence spectra of **1c** are very similar to those of **1a** (an ethanol solution; λ_{max}=304 nm, ε=20300, λ_F(max)=361 nm).

This means that the molecular configuration of **1c** is very similar to that of **1a** in both the ground and the excited singlet states, except for the inability to form a specific bridge-type complex with an ethanol molecule. As expected, therefore, no serious fluorescence quenching by ethanol molecules was observed for **1c**, when solvents were changed from cyclohexane to ethanol.

It is clear, therefore, that the NH group in the imidazole moiety is explicitly involved in quenching the fluorescence of **1a** by ethanol.

A molecular complex like **A** has been proposed for pyrrolo[2,3-*b*]pyridine in ethanol. In that system, the second fluorescence band was observed at a longer wavelength and was ascribed to the isomeric species which was produced by proton transposition *via* the ethanol molecule being intermolecularly hydrogen bonded.[5] In the present case, however, it is not clear whether or not a similar isomerization occurs through intramolecular proton transposition like that, because no second fluorescence band was observed at any longer wavelength.

As a tentative explanation of the molecular mechanism in the fluorescence quenching of **1a** by ethanol, the present author proposes a proton exchange in the excited singlet state between the solute and solvent molecules in the bridge-type complex, **A**. In the case of ethanol solutions of **2** and **3**, an ethanol molecule can not form a bridge-type complex like **A**. Therefore, it is reasonable that no fluorescence quenching was observed for ethanol solutions of **2** and **3**.

Table 3. Relative fluorescence intensities (R) of **1a**, **2**, and **3** in phosphate buffers at pH 6.8

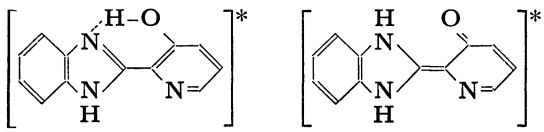
Compound	Concentration	Excitation	R[a]
1a	2.82×10^{-5} M	320 nm	0.73
2	2.05	300	0.44
3	2.21	320	0.90

a) The R value for an ethanol solution of **1a** at the same concentration was assumed to be 1. The difference in light intensities at 300 and 320 nm was taken into consideration in calculating R.

In the case of aqueous solutions of **1a**, **2**, and **3**, the fluorescence intensities are as weak as that of **1a** in ethanol (Table 3). This implies that a proton transposition-isomerization like that proposed for pyrrolo[2,3-*b*]-pyridine is not responsible for the fluorescence quenching in question, because such a proton-transposed isomer (like **A'**) can not be written for **2**. In aqueous solutions of **2** and **3**, the concerted operation of water molecules makes it possible to exchange protons through polymeric aggregates of water molecules.

Recently Kikuchi *et al.*[9] proposed a transient proton transfer as an internal conversion mechanism for the system of naphthol and pyridine.

Rapid Proton Transfer in the Excited Singlet State of ***1b***. The first absorption band and the fluorescence band of **1b** in various solvents are listed in Table **4**. The absorption band of **1b** is located at a longer wavelength than that of **1a** in any solvent, primarily because of the effect of the OH-group introduction, but also partly because of its intramolecular hydrogen bond between the phenolic hydroxyl and the N-3 atom. The observed large Stokes' shift (*ca.* 9000 cm^{-1}) of the emission band can be attributed to an isomeric species, **K**, which is formed by the intramolecular proton transfer shown schematically below:



E **K**

From the table it is clear that the fluorescence intensity of **1b** in ethanol is as strong as in the other solvents examined. This indicates that no serious quenching by ethanol operates and that the intramolecular proton transfer in the excited singlet state occurs in a very short period, within which hardly no quenching by ethanol occurs. In this connection, the rate of the intramolecular proton transfer has been reported to be 1.1×10^{10} s^{-1} for 2,4-bis(dimethylamino)-6-(2-hydroxy-5-methylphenyl)-1,3,5-triazine.[10] If the same proton-transfer rate is assumed in the present case, the ethanol-quenching rate can be roughly estimated as 1×10^{9} s^{-1} or less, because no quenching effect of ethanol was observed.

Table 4. Absorption and fluorescence spectral data of **1b** in various solvents

Solvent	Absorption[a]		Fluorescence[b]	
	$\lambda(0\rightarrow0')$	ε	λ_F(max)	I_{rel}
CH	344.5	30000	457	1.0
Benzene	342.5	28300	452	1.0
DCE	343.0	25300	448	1.3
EE	345.9	26700	450	1.4
Ethanol	342.0	25500	442	1.4

a) The concentration was 2.26×10^{-5} M. b) The concentration was 4.53×10^{-6} M.

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