Spectral properties and structures of supramolecular complexes of naphthylpyridine with β-cyclodextrin

V. B. Nazarov,[a]★ V. G. Avakyan,[b] S. P. Gromov,[b] M. V. Fomina,[b] T. G. Vershinnikova,[a] and M. V. Alfimov[b]

[a]Institute of Problems of Chemical Physics, Russian Academy of Sciences, 1 prosp. Akad. Semenova, 142432 Chernogolovka, Moscow Region, Russian Federation. Fax: +7 (096) 515 3588. E-mail: vnazarov@icp.ac.ru
[b]Photochemistry Center, Russian Academy of Sciences, 7A ul. Novatorov, 119421 Moscow, Russian Federation. Fax: +7 (095) 936 1255. E-mail: avak@photonics.ru

The electronic absorption and fluorescence spectra of 4-(2-naphthyl)pyridine (**1**) and *N*-methyl-4-(2-naphthyl)pyridinium perchlorate ($\mathbf{2}^+ \cdot ClO_4^-$) were studied in aqueous solutions in the absence and presence of β-cyclodextrin (β-CD). In aqueous solutions and organic solvents in the presence of water or H^+ ions, compound **1** exhibits intense fluorescence with a maximum at 21 270 cm^{-1}, and its quantum yield in an aqueous solution is 0.9±0.09. The same fluorescence spectrum was detected for an aqueous solution of $\mathbf{2}^+ \cdot ClO_4^-$. In an aqueous solution, compound **1** and β-CD form stable fluorescing supramolecular 2 : 2 complexes, whose structure was calculated by the quantum-chemical MNDO/PM3 method. The formation of these complexes induces a hypsochromic shift of the fluorescence maximum of **1** by 5000 cm^{-1}. The stability constant of the complex is $\sim 2 \cdot 10^3$ L mol^{-1}. A decrease in the pH results in the formation of a protonated form of **1** ($\mathbf{1} \cdot H^+$) and destruction of the complex, thus favoring the escape of the substrate from the β-CD cavity. The quantum-chemical calculations showed that the insertion of **1** into the β-CD cavity is thermodynamically more favorable than hydration; on the contrary, the formation of $\mathbf{1} \cdot H^+$ increases dramatically the hydration energy, which promotes the escape of $\mathbf{1} \cdot H^+$ from the β-CD cavity; cation $\mathbf{2}^+$ does not form a complex with β-CD; in the thermodynamically most favorable 2 : 2 complex, the naphthalene fragments of two molecules **1** are parallel to each other in a broad section of the β-CD dimer constructed according to the head-to-head type.

Key words: naphthylpyridines, β-cyclodextrin, complex, structure, quantum-chemical calculations, electronic absorption spectra, fluorescence spectra.

Arylpyridines represent an important class of heterocyclic compounds used for the production of liquid-crystalline materials as ligands, organic luminophores, and biologically active compounds.[1,2] The naphthylpyridine framework integrated into more complicated structures of biologically active compounds is met rather often (see, *e.g.*, the patent[3]), because it resembles both endogenous bioactive amines and exogenous neurotoxin *N*-methyl-4-phenyltetrahydropyridine. Therefore, the photochemistry of naphthylpyridines is of great interest. Special attention has recently been given to the photochemistry of arene complexes with cyclodextrins (CD). This interest is caused because, first, the inclusion of arenes into a CD cavity favors an increase in the lifetime of their fluorescence and phosphorescence and, second, these complexes simulate the properties of arenes included in cavities of biological objects. In addition, organic compounds containing a pyridine fragment possess unusual spectral properties. Unsubstituted pyridine does not luminesce[4] but arenes with a pyridine fragment can luminesce in solutions under certain conditions.[5—7] The spectral properties of these compounds can change upon the protonation of a nitrogen atom of the pyridine fragment.

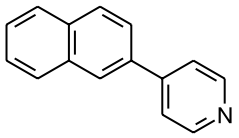
The purpose of this work is to study the luminescence properties of 4-(2-naphthyl)pyridine (**1**) and its *N*-methyl derivative ($\mathbf{2}^+ \cdot ClO_4^-$) in aqueous solutions at different pH in the absence and presence of β-cyclodextrin (β-CD, **3**).

Experimental

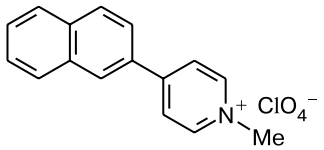
4-(2-Naphtyl)pyridine was synthesized by an original procedure to be published later. Perchlorate of its *N*-methyl derivative was synthesized by the treatment of compound **1** with methyl iodide followed by the addition of a concentrated solution of perchloric acid to an ethanolic solution of 1-methyl-4-(2-naphthyl)pyridinium iodide.

Published in Russian in *Izvestiya Akademii Nauk. Seriya Khimicheskaya,* No. 11, pp. 2420—2425, November, 2004.

1066-5285/04/5311-2525



1



$\mathbf{2}^+ \cdot ClO_4^-$

Compounds were characterized by ^{1}H NMR spectra recorded on a Bruker DRX-500 spectrometer using Me_4Si as an internal standard.

4-(2-Naphthyl)pyridine (1). M.p. 104—105 °C (from hexane). ^{1}H NMR ($CDCl_3$), δ: 7.55 (m, 2 H, H(6), H(7)); 7.63 (m, 2 H, H(3′), H(5′)); 7.75 (dd, 1 H, H(3), J = 8.5 Hz, J = 1.7 Hz); 7.89 and 7.93 (both m, 1 H each, H(5), H(8)); 7.96 (d, 1 H, H(4), J = 8.5 Hz); 8.12 (s, 1 H, H(1)); 8.71 (m, 2 H, H(2′), H(6′)).

1-Methyl-4-(2-naphthyl)pyridinium iodide was synthesized by the reaction of 4-(2-naphthyl)pyridinium (**1**) with methyl iodide. M.p. 215—216 °C. ^{1}H NMR ($CDCl_3$), δ: 4.66 (s, 3 H, NMe); 7.61 (m, 2 H, H(6), H(7)); 7.79 (d, 1 H, H(3), J = 7.4 Hz); 7.88 (d, 1 H, H(4), J = 7.4 Hz); 7.99 (m, 2 H, H(5), H(8)); 8.35 (m, 3 H, H(5′), H(3′), H(1)); 9.25 (m, 2 H, H(2′), H(6′)).

1-Methyl-4-(2-naphthyl)pyridinium ($\mathbf{2}^+ \cdot ClO_4^-$) was synthesized by the addition of a concentrated solution of perchloric acid to an ethanolic solution of 1-methyl-4-(2-naphthyl)pyridinium.

To prepare complexes, we used β-cyclodextrin (Cyclolab, Hungary) without additional purification. Inclusion complexes were obtained by the addition of **1** to aqueous solutions of β-CD heated to 50 °C, and they were studied at room temperature (~20 °C). Spectra of the resulting samples were measured after 1 day and more. The concentration of **1** in solutions was 10^{-4}—10^{-6} mol L^{-1}. Bidistilled water, hexane purified by filtration through a column packed with silica gel followed by distillation, and acetonitrile (Grade-F, Reakhim) with the water content not higher than 0.01% were used as solvents.

Electronic absorption spectra were recorded on a Specord-M40 spectrophotometer. Luminescence spectra were measured on Elyumin-2M and Perkin Elmer LS55 spectrofluorimeters. A previously used[8] technique for measuring lifetimes was modified. The number of discrete signal levels was brought to 1024, and a signal of phosphorescence decay consisting of 350 experimental points was delivered to an IBM PC computer and processed using a program developed by one of the authors of the present study. All indicated instruments were coupled with computers for measurement data transfer and primary processing of information. The quantum yield of fluorescence φ_f was measured by a standard procedure using anthracene as an external standard for which φ_f = 0.3 in ethanol.[9]

Semiempirical quantum-chemical calculations of **1**, protonated **1**, and their 1 : 1, 1 : 2, and 2 : 2 inclusion complexes with β-CD were performed by the MNDO/PM3 method (further designated as PM3) with a standard set of parameters[10] and using the PC GAMESS 99 program package.[11] As the starting β-CD molecule, we used the previously optimized structure close to a global minimum. Its heat of formation ΔH_f is −1468.4 kcal mol^{-1},[12] and the molecule has the symmetry C_7 and is stabilized by intramolecular hydrogen bonds O(2)—H...O(3′) between secondary OH groups in an broad rim of the cavity. Proton donors are OH groups in position 2 of one unit of glucose, and proton acceptors are oxygen atoms in position 3′ of the adjacent glucose unit. The "head-to-head" β-CD dimer has also been calculated previously, its ΔH_f being −2950.3 kcal mol^{-1}.[12] The energy of complex formation (E_{bind}) was calculated as the difference between the heat of complex formation ΔH_f(complex) and the sum of heats of formation of components ΔH_f(**1**) and ΔH_f(β-CD). In all cases, the insertion of **1** into the cavity of one or two β-CD molecules and the dimerization of binary complexes β-CD·**1** are energetically favorable, which corresponds to negative values of E_{bind}. The results obtained are presented in Table 1.

Table 1. Heats of formation (ΔH_f) and the energies of complex formation (E_{bind}/kcal mol^{-1}) for inclusion compounds of naphthylpyridine and β-CD

Compound, complex	ΔH_f	E_{bind}	ΔE_{bind}
β-CD	−1468.4	0	
2 β-CD[a]	−2950.3	−13.5	
1	71.36		
$\mathbf{2}^+$	221.5		
β-CD·**1**[b]	−1408.0	−11.0	0
β-CD·**1**[c]	−1404.9	−7.8	3.2
β-CD·**1**·H^+[b]	−1265.8	−18.9	10.6 (7.9)[d]
β-CD·**1**·H^+[c]	−1276.4	−29.5	0 (21.7)[d]
β-CD·$\mathbf{2}^+$[b]	−1264.3	−14.5	
β-CD·$\mathbf{2}^+$[c]	−1274.9	−25.1	
2 β-CD **1**[e]	−2891.4	−12.5	7.1
2 β-CD·2 **1**[f]	−2827.2	−19.6 (−17.4)	0
2 β-CD·2 **1**[g]	−2826.3	−18.7 (−13.4)	0.9 (4.0)

[a] "Head-to-head" β-CD dimer.
[b] Naphthalene fragment in a cavity of β-CD.
[c] Pyridine fragment in a cavity of β-CD.
[d] Difference in energies of complex formation of charged and uncharged forms of **1** with β-CD.
[e] Naphthylpyridine in a cavity of the "head-to-head" β-CD dimer.
[f] Complex 2 β-CD·2 **1** with parallel naphthalene fragments in the broad section of the β-CD dimer.
[g] Complex 2 β-CD·2 **1** with a naphthalene fragment parallel to a pyridine fragment in the broad section of the β-CD dimer.

The theoretical proof of a possibility of escaping the protonated form of naphthylpyridine from the β-CD cavity in an aqueous solution is based on a comparison of the free energy of complex formation of **1**·H^+ with β-CD (ΔG_{cavity}) and the free energy of hydration of **1**·H^+ (ΔG_{H_2O}). The calculation of ΔG_{cavity} was performed by a correlation dependence[13]

$$\Delta G_{cavity} = -2.1 + 0.066\ E_{bind}$$

between E_{bind} and experimental values of ΔG_{H_2O} found in the literature for 25 complexes of naphthalene derivatives and other compounds with cyclodextrins. The calculation of ΔG_{H_2O} for naphthalene (**4**), **1**, and **1**·H^+ was performed by the Tomasi polarized continuum method (PCM) using the PCM procedure in the Gaussian 98 program package. The obtained values of free energies are presented in Table 2.

Table 2. Energies of complex formation (E_{bind}), total energies (E_{total}) in the B3LYP/6-31+G** basis set, and free Gibbs energies of inclusion in the β-CD cavity (ΔG_{cavity}) and hydration (ΔG_{H_2O}) for compounds **1** and **4**, complex **1**·H^+, and cation $\mathbf{2}^+$

System	E_{bind} /kcal mol^{-1}	ΔG_{cavity} /kcal mol^{-1}	System	E_{total}/au	ΔG_{H_2O} /kcal mol^{-1}
β-CD·**4**	−12.4	−2.9	**4**	−383.77692	−1.3
β-CD·**1**	−11.0	−2.8	**1**	−633.48223	−7.3
β-CD·**1**·H^+	−29.5	−4.1	**1**·H^+	−629.97233	−47.2
β-CD·$\mathbf{2}^+$	−25.1	−3.8	$\mathbf{2}^+$	−672.78968	−42.4

Note. The energy E_{bind} was calculated by the PM3 method; the free energies ΔG_{cavity} were calculated by the formula $\Delta G_{cavity} = -2.1 + 0.066\ E_{bind}$; ΔG_{H2O} was calculated by the quantum-chemical Tomasi polarized continuum method (PCM) at a level of the B3LYP/6-31+G** theory using the Gaussian-98 program.[14]

Results and Discussion

Electronic absorption spectra. The normalized electronic absorption spectra of **1** and $\mathbf{2}^+ \cdot ClO_4^-$ in different solvents are presented in Fig. 1. In nonpolar hexane, the long-wave absorption maxima of **1** are most shifted to a short-wave region. In a neutral aqueous solution of **1**, a small bathochromic shift (~400 cm^{-1}) is observed in the spectrum (relatively to the spectrum in hexane), and an additional weak absorbance appears at 30 000 cm^{-1}, which can belong (by analogy to an assumption concerning the spectrum of 2,2′-bipyridine in an aqueous solution[5]) to a covalent hydrated form of **1**. The spectrum of $\mathbf{2}^+ \cdot ClO_4^-$ in an aqueous solution has a large bathochromic shift relatively to the spectrum of **1** and a more resolved vibrational structure of bands. The same spectrum is characteristic of an acidic aqueous solution of **1**. This spectral effect is explained by the protonation of **1** and formation of an ion **1**·H^+, whose spectral properties resemble those of cation $\mathbf{2}^+$.

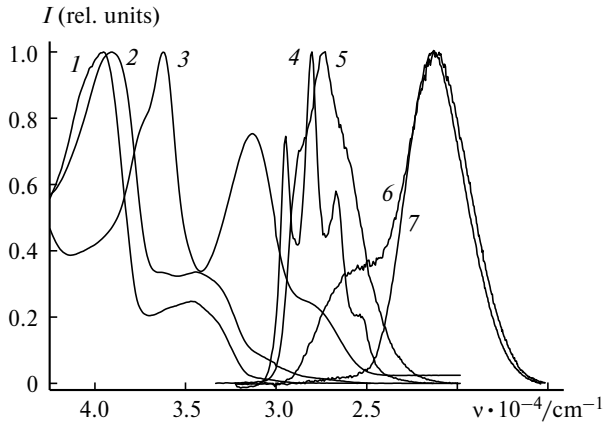


Fig. 1. Normalized electronic absorption (*1*—*3*) and fluorescence (*4*—*7*) spectra of solutions of **1** in hexane (*1*, *4*), water (*2*, *7*), and acetonitrile (*1*, *5*) and a complex with β-CD (*6*) and **1** in water with addition of an aqueous solution of acid $HClO_4$ (*3*) or $\mathbf{2}^+ \cdot ClO_4^-$ (*7*).

Luminescence spectra. The luminescence spectra of **1** and $\mathbf{2}^+ \cdot ClO_4^-$ differ substantially from both the spectra of unsubstituted naphthalene and the spectra of similar compounds containing a pyridine fragment. In particular, 4-phenylpyridine possesses no fluorescence in cyclohexane, diethyl ether, acetonitrile, and ethanol, whereas in the presence of water or in an acidic medium the protonated form of this compound fluoresces with $\varphi_f = 0.2$, and the fluorescence spectrum has a broad structureless band with a maximum at 26 300 cm^{-1}.[6] The absence of fluorescence is caused by the position of energy levels of this compound. According to the calculation,[6] 4-phenylpyridine excites to a triplet level, and no phosphorescence is observed in solution at room temperature.

A similar phenomenon is observed for 2,2′-bipyridine, which does not fluoresce in pure solvents: dimethylformamide, acetonitrile, benzene, cyclohexane, methanol, and ethanol.[5] However, an addition of water to any of these solvents or use of water as a solvent results in the appearance of a fluorescence band, whose maximum depends on the pH of the solution.[5]

In anhydrous hexane and acetonitrile, **1** possesses fluorescence, whose spectrum resembles in shape the fluorescence spectrum of naphthalene in these solvents but has a bathochromic shift due to the presence of a pyridine substituent (see Fig. 1, curves *4* and *5*). The well resolved vibrational structure of the fluorescence spectrum of **1** in hexane indicates a plane geometry of molecules **1** in the excited singlet state. The addition of an acid to these solutions changes sharply the fluorescence spectrum due to the formation of a cation **1**·H^+. Intense fluorescence with a maximum at 21 270 cm^{-1} appears (see Fig. 1, curve *7*). The formation of cation **1**·H^+ is also detected by a change in the absorption spectrum (see Fig. 1, curve *3*).

A similar process occurs in an aqueous solution of **1** in the presence of an acid (Scheme 1)

Scheme 1

$$(\mathbf{1}\cdot H_2O) + HX \longrightarrow (\mathbf{1}\cdot H^+) + X^- + H_2O \xrightarrow{h\nu}$$
$$\longrightarrow (\mathbf{1}\cdot H^+)^* + X^- + H_2O \longrightarrow$$
$$\longrightarrow (\mathbf{1}\cdot H^+) + X^- + H_2O + h\nu\ (21270\ cm^{-1})$$

This fluorescence, as that of 2,2′-bipyridine, is sensitive to a change in the pH. An increase in the pH results in a hypsochromic shift of the fluorescence maximum and a decrease in the band intensity.

A comparison of the absorption and fluorescence spectra of **1** in neutral and acidic aqueous solutions with the corresponding spectra of $\mathbf{2}^+\cdot ClO_4^-$ indicates that the protonation of **1** in a neutral aqueous solution occurs in the excited singlet state of **1**. In fact, the absorption spectrum of **1** in a neutral aqueous solution (see Fig. 1, curve *2*) differs from the absorption spectrum of $\mathbf{1}\cdot H^+$ identical to the spectrum of $\mathbf{2}^+$ (curve *3*), while the fluorescence spectra of **1** and $\mathbf{2}^+\cdot ClO_4^-$ coincide (curve *7*, ν_{max} = 21 270 cm^{-1}) (Scheme 2). The same effect was observed for 4-phenylpyridine.[6]

Scheme 2

$$\mathbf{1} + H_2O \longrightarrow (\mathbf{1}\cdot H_2O) \xrightarrow{h\nu} (\mathbf{1}^*\cdot H_2O) \longrightarrow$$
$$\longrightarrow (\mathbf{1}\cdot H^+)^* \parallel OH^- \longrightarrow$$
$$\longrightarrow (\mathbf{1}\cdot H_2O) + h\nu\ (21270\ cm^{-1})$$

For this reason, the presence of water traces in solutions of **1** in acetonitrile or hexane also induces fluorescence with a maximum at 21 270 cm^{-1}, while fluorescence is different in anhydrous solutions of **1** in these solvents (see Fig. 1, curves *4* and *5*). The measured φ_f value for fluorescence of **1** in an neutral aqueous solution is rather high: 0.9±0.09.

Inclusion complexes. The formation of an inclusion complex of **1** with β-CD (**3**) is established from a change in the fluorescence spectrum, whereas changes in the absorption spectrum are minimal. The fluorescence spectra of an aqueous solution of **1** at different concentrations of β-CD are presented in Fig. 2. An increase in the content of β-CD results in a decrease in the intensity of the fluorescence band with a maximum at 21 270 cm^{-1} and a simultaneous increase in the band with a maximum at 26 300 cm^{-1} (see Fig. 1, curve *6*). The processes related to complex formation are shown in Scheme 3.

Scheme 3

$$(\mathbf{1}\cdot H_2O) + \mathbf{3} \longrightarrow (\mathbf{1}\cdot\mathbf{3}) + H_2O \xrightarrow{h\nu}$$
$$\longrightarrow (\mathbf{1}^*\cdot\mathbf{3}) + H_2O \longrightarrow$$
$$\longrightarrow (\mathbf{1}\cdot\mathbf{3}) + H_2O + h\nu\ (26300\ cm^{-1})$$

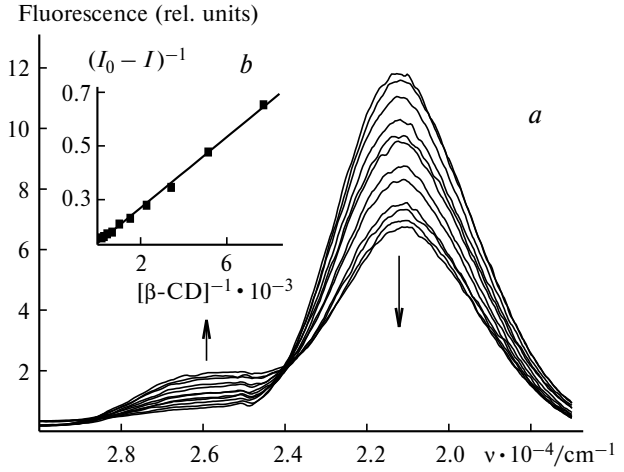


Fig. 2. *a*. Fluorescence spectra of an aqueous solution of **1** during changing the concentration of added β-CD from $5\cdot 10^{-3}$ to $1.3\cdot 10^{-4}$ mol L^{-1} (directions of arrows correspond to an increase in the concentration of β-CD). *b*. Results of spectra processing by the Benesi—Hildebrand method.

The 1 : 1 complexes also can produce a 2 : 2 complex.

Scheme 4

$$(\mathbf{1}\cdot\mathbf{3}) + (\mathbf{1}\cdot\mathbf{3}) \longrightarrow (\mathbf{3}\cdot\mathbf{1}\cdot\mathbf{1}\cdot\mathbf{3}) \xrightarrow{h\nu}$$
$$\longrightarrow (\mathbf{3}\cdot\mathbf{1}^*\cdot\mathbf{1}\cdot\mathbf{3}) \longrightarrow$$
$$\longrightarrow (\mathbf{3}\cdot\mathbf{1}\cdot\mathbf{1}\cdot\mathbf{3}) + h\nu\ (26300\ cm^{-1})$$

The fluorescence spectrum of an aqueous solution of **1** changes similarly when the pH increases, thus preventing the addition of a proton to **1** in the excited state. Since in an anhydrous solution the fluorescence spectrum of **1** is shifted to a short-wave region (see Fig. 1, curves *4* and *5*), the appearance of a new band in the same spectral region is explained by the incorporation of molecule **1** into the β-CD cavity. This restricts a contact of **1** with water molecules, whose interaction with **1** in the excited state leads to a protonated form. The addition of perchloric acid to an aqueous solution of complex $\mathbf{1}\cdot$β-CD returns the fluorescence spectrum to the shape observed in an aqueous solution of **1** in the absence of β-CD (see Fig. 1, curve *7*). This is likely caused by the decomposition of this complex and escape of the protonated form $\mathbf{1}\cdot H^+$ from the β-CD cavity due to the efficient hydration of this cation. Note that hydration can occur only beyond the cavity of β-CD (**3**) (Scheme 5).

Scheme 5

$$(\mathbf{3}\cdot\mathbf{1}\cdot\mathbf{1}\cdot\mathbf{3}) + 2\,H_3O^+ + 2\,X^- \longrightarrow$$

$$\longrightarrow 2\,(\mathbf{1}\cdot H^+) + 2\,X^- + 2\,\mathbf{3} + 2\,H_2O$$

This assumption is favored by the fact that the addition of β-CD to an aqueous solution of $\mathbf{2}^+\cdot ClO_4^-$ has no effect on the fluorescence and absorption spectra. It is most likely that ion $\mathbf{2}^+$ cannot form complexes with β-CD. Thus, varying the pH, one can efficiently control processes of formation of supramolecular complexes between **1** and β-CD (**3**).

The dependence of the fluorescence spectra on the β-CD concentration (see Fig. 2) made it possible to estimate a stability constant K_c for a complex of **1** with β-CD, which was ~2000 mol^{-1} L. The processing of the spectra by the Benesi—Hildebrand method (see Fig. 2, *b*) gave K_c. The linear dependence in a wide interval of concentrations indicates an equimolar ratio of the components. In other words, the composition of a fluorescing complex of **1** with β-CD is 1 : 1 or 2 : 2. A comparison of the obtained stability constant with K_c of the naphthalene complex (**4**) with β-CD (685 mol^{-1} L) and K_c of complex 2 **4**·2 β-CD ($4\cdot10^3$ mol^{-1} L)[15] shows that the equilibrium in our system is strongly shifted, most likely, toward the formation of the 2 : 2 complex 2 **1**·2 β-CD.

The fluorescence band at 26 300 cm^{-1} appeared upon complex formation could belong to excimers **1**, as it was observed for a naphthalene complex with β-CD.[16] To reveal the nature of this band, we measured the luminescence spectra at different concentrations of **1** (from 10^{-6} to $5\cdot10^{-4}$ mol L^{-1}) in the presence of β-CD. The shape of the luminescence spectrum is independent of the concentration of **1**, indicating the absence of excimeric fluorescence. An additional argument is the absence of excimeric fluorescence in the luminescence spectra of a 2 : 2 binary complex of 2-phenylnaphthalene (structural analog of naphthylpyridine) with β-CD. Thus, a bulky substituent in the second position of naphthalene prevents excimer formation.

The introduction of the third component (cyclohexane (**5**) or adamantane (**6**)) into an aqueous solution of binary complex **1**·β-CD results in the formation of a suspension containing, most likely, tertiary complexes **1**·β-CD·**5** or **1**·β-CD·**6**. Under these conditions, long-lived phosphorescence was observed previously[17] at room temperature for tertiary complexes **4**·β-CD·**5** or **4**·β-CD·**6**. In the case of the latter, this phosphorescence even did not require oxygen removal from the solution. However, the addition of the third component to complex **1**·β-CD induced no changes in the fluorescence spectrum, and only after elimination of dissolved oxygen by sodium sulfite, a weak phosphorescence with a maximum at 20 000 cm^{-1} and a lifetime of 0.5±0.15 s was observed.

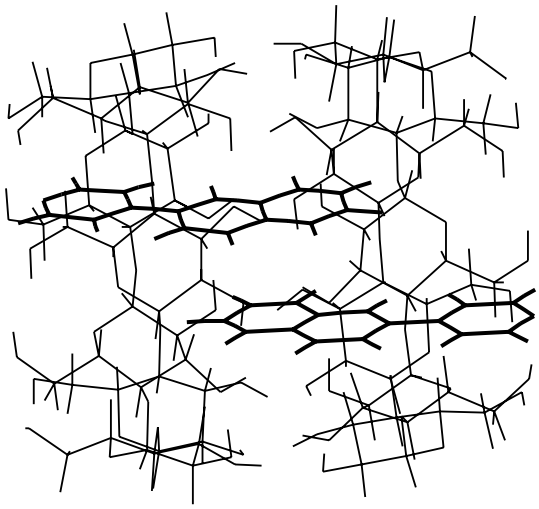


Fig. 3. Structure of complex 2 β-CD·2 **1** calculated by the quantum-chemical semiempirical PM3 method.

Energy of complex formation and the structure of the complexes. The calculated data (see Table 1) show that the insertion of a neutral molecule of **1** into the β-CD cavity is an energetically favorable process, and the presence of the naphthalene fragment in the cavity is by 3.2 kcal mol^{-1} more favorable than the pyridine fragment in the cavity. At the same time, this difference in energies does not exclude an equilibrium between complexes of both types. The energy preference of the first type complexes is likely explained by the fact that the naphthalene fragment occupies a larger part of the internal volume of β-CD. It can be explained similarly that the presence of two molecules of **1** in the cavity of the β-CD dimer is by 7.1 kcal mol^{-1} thermodynamically more favorable than one molecule of **1**. In other words, in addition to the formation of binary complexes, they can dimerize to form a 2 : 2 complex. This conclusion does not contradict the results of processing of the fluorescence spectra of **1** in an aqueous solution in the presence of β-CD by the Benesi—Hildebrand method. This method made it possible to establish experimentally the equimolar ratio of components and to exclude a possibility of formation of a 1 : 2 complex **1**·β-CD. The calculated structure of the 2 : 2 complex is shown in Fig. 3.

A comparison of the heats of formation of both 2 : 2 complexes shows that the configuration presented in Fig. 3 is by 0.9 kcal mol^{-1} thermodynamically more favorable than the 2 : 2 complex in which a naphthalene fragment of one molecule of the substrate is opposite to a pyridine fragment of another substrate.* In fact, such a low differ-

* The calculation also shows that a 2 : 2 complex, in which two pyridine fragments are opposite to each other, is not formed.

ence in binding energies could imply a thermodynamic equilibrium between complexes of both types at which the content of the first type complex would be 82%. The second method of estimating the preference of the first or second complex gives quantitatively different results. If both 2 : 2 complexes are considered to form due to the dimerization of the binary complexes, then it turns out that the dimerization leading to the formation of the both type complexes occurs with a thermal effect of 17.4 kcal mol^{-1} and the dimerization producing the second type complexes has a thermal effect of 13.4 kcal mol^{-1}. In this case, a 2 : 2 complex in which two naphthalene fragments are parallel to each other is energetically more favorable with an energy difference of 4 kcal mol^{-1}, providing its complete predomination in an equilibrium mixture. However, as follows from experiment, the parallel orientation of naphthalene fragments in the 2 : 2 complex is a necessary but insufficient condition for the manifestation of its excimeric fluorescence, which is observed for complex 2 **4**·2 β-CD.[16] The second condition for the appearance of excimeric fluorescence is the presence of aggregates[16] that were not observed for a system of **1** with β-CD.

According to the calculation, the influence of the protonation of **1** appears as a considerable increase in the binding energy, most likely, due to the ion-dipole interaction between components and in the fact that for $\mathbf{1}\cdot H^+$ the presence of the pyridinium fragment in the cavity is more preferential. For ion $\mathbf{2}^+$, it is also more energetically favorable to have the pyridinium fragment in the cavity (see Table 1).

A comparison of the free energies of complex formation with β-CD and hydration of **4**, **1**, and $\mathbf{1}\cdot H^+$ shows (see Table 2) that (1) the free energy of naphthalene (**4**) insertion into the β-CD cavity is higher than ΔG_{H_2O} of hydration; therefore, naphthalene prefers to be inside the hydrophobic cavity of β-CD; (2) ΔG_{cavity} of compounds **4** and **1** differ slightly; however, the solubility of the latter in water is higher than that of **4** due to the appearance of a more polar substituent; (3) the protonation of **1** increases ΔG_{cavity} due to the ion-dipole interaction; (4) after protonation, ΔG_{H_2O} increases dramatically and more than twofold exceeds ΔG_{cavity}. Due to this, as we believe, cation $\mathbf{1}\cdot H^+$ transits from the cavity to a solution. Cation $\mathbf{2}^+$ possesses similar properties (see Table 2) and, hence, is not prone to insert into the β-CD cavity in an aqueous solution.

* * *

The study of the electronic absorption and luminescence spectra of synthesized 4-(2-naphthyl)pyridine (**1**) and 1-methyl-4-(2-naphthyl)pyridinium perchlorate ($\mathbf{2}^+\cdot ClO_4^-$) shows that the protonation of **1** changes considerably the spectra. As a result of self-assembling, β-CD and **1** form stable supramolecular equimolecular complexes in an aqueous solution with a stability constant of $\sim 2\cdot 10^3$ mol^{-1} L, and their appearance induces a hypsochromic shift by 5000 cm^{-1} of the fluorescence maximum of **1** relatively to the spectrum in a neutral aqueous solution. A decrease in the pH resulting in the formation of the protonated form of **1** decomposes the complex and favors the escape of the substrate from the cavity of β-cyclodextrin to an aqueous solution. *N*-Methyl-4-(2-naphthyl)pyridinium perchlorate forms no complexes with β-CD in an aqueous solution. In the most thermodynamically favorable 2 : 2 complex, naphthalene fragments of two molecules **1** are parallel to each other in the broad rim of the β-CD dimer constructed according to the "head-to-head" type.

The authors thank A. A. Bagatur´yants for providing a possibility to use the Gaussian 98 program package.

This work was financially supported by the Russian Foundation for Basic Research (Project No. 03-03-32536) and the Foundation of the President of the Russian Federation (Program for Support of Leading Scientific Schools, Grant NSh-2028.2003.3).

References

1. S. P. Stanforth, *Tetrahedron*, 1998, **54**, 263.
2. S. G. Speciale, C. L. Liang, P. K. Sonsalla, R. H. Edwards, and D. C. German, *Neuroscience*, 1998, **84**, 1177.
3. J. Wu, E. D. Thorsett, J. S. Nissen, T. E. Mabry, L. H. Latimer, V. John, L. Y. Fang, and J. E. Audia, US Pat. 6,313,152h; *Chem. Abstrs*, 2000, **133**, 223044.
4. R. N. Nurmukhametov, *Pogloshchenie i lyuminestsentsiya aromaticheskikh soedinenii* [*Absorption and Luminescence of Aromatic Compounds*], Khimiya, Moscow, 1971, 120 9in Russian).
5. M. S. Henry and M. Z. Hoffman, *J. Am. Chem. Soc.*, 1977, **99**, 5201.
6. S. Hotchandani and A. C. Testa, *J. Photochem. Photobiol. A: Chem.*, 1991, **55**, 323.
7. P. R. Bangal and S. Chakravorti, *J. Photochem. Photobiol. A: Chem.*, 1998, **116**, 47.
8. V. B. Nazarov, V. I. Gerko, and M. V. Alfimov, *Izv. Akad. Nauk, Ser. Khim.*, 1996, 225 [*Russ. Chem. Bull.*, 1996, **45**, 2109 (Engl. Transl.)].
9. C. A. Parker, *Photoluminescence of Solutions, With Applications to Photochemistry and Analytical Chemistry*, Elsevier Publishing Company, Amsterdam—London—New York, 1968.
10. J. J. P. Stewart, *J. Comput. Chem.*, 1989, **10**, 209.
11. M. W. Schmidt, K. K. Baldridge, J. A. Boatz, S. T. Elbert, M. S. Gordon, J. H. Jensen, N. Matsunaga, K. A. Nguen, S. Su, T. L. Windus, M. Dupius, and J. A. Montgomery, *J. Comput. Chem.*, 1993, **14**, 347.
12. V. G. Avakyan, V. B. Nazarov, M. V. Alfimov, A. A. Bagatur´yants, and N. I. Voronezheva, *Izv. Akad. Nauk,*

Ser. Khim., 2001, 199 [*Russ. Chem. Bull., Int. Ed.*, 2001, **50**, 206].

13. V. G. Avakyan, V. B. Nazarov, V. Yu. Rudyak, M. V. Alfimov, and N. I. Voronezheva, *Tez. dokl. XV simpoziuma "Sovremennaya khimicheskaya fizika"* [*Proc. XV Symposium "Modern Chemical Physics*] *(September 18—29, 2003, Tuapse)*, p. 36 (in Russian).
14. M. J. Frisch, G. W. H. Trucks, B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, V. G. Zakrzewski, J. A., Jr., Montgomery, R. E. Stratmann, J. C. Burant, S. Dapprich, J. M. Millam, A. D. Daniels, K. N. Kudin, M. C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Mennucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G. A. Petersson, P. Y. Ayala, Q. Cui, K. Morokuma, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. Cioslowski, J. V. Ortiz, A. G. Baboul, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. Gomperts, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, J. L. Andres, C. Gonzalez, M. Head-Gordon, E. S. Replogle, and J. A. Pople, *Gaussian 98, Revision A.7*, Gaussian, Inc., Pittsburgh PA, 1998.
15. S. Hamai, *Bull. Chem. Soc. Jpn*, 1982, **55**, 2721.
16. V. B. Nazarov, V. G. Avakyan, T. G. Vershinnikova, and M. V. Alfimov, *Izv. Akad. Nauk, Ser. Khim.*, 2000, 1716 [*Russ. Chem. Bull., Int. Ed.*, 2000, **49**, 1699].
17. V. B. Nazarov, V. G. Avakyan, M. V. Alfimov, and T. G. Vershinnikova, *Izv. Akad. Nauk, Ser. Khim.*, 2003, 869 [*Russ. Chem. Bull., Int. Ed.*, 2003, **52**, 916].

Received April 9, 2003;
in revised form June 9, 2004