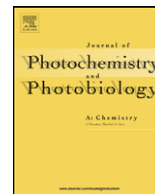




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## New 1,3,5-triphenyl-2-pyrazoline-containing 3-hydroxychromones as highly solvatofluorochromic ratiometric polarity probes

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### ABSTRACT

Two novel 1,3,5-triphenyl-2-pyrazoline moiety containing derivatives of 3-hydroxychromone were synthesized and studied by  $^1\text{H}$  NMR, absorption and fluorescence spectroscopy. The prospects of practical application of these compounds exhibiting high solvatofluorochromism into analytical chemistry and biophysics as effective ratiometric polarity probes were discussed proceeding from the data on their fluorescent properties.

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### 1. Introduction

In the past decades, 3-hydroxychromones have been objects of an extensive research interest due to their extraordinary photochemical behavior in the excited state. This class of fluorescent dyes undergoes an excited state intramolecular proton transfer (ESIPT) process which produces an alternative light-emitting form called phototautomer, thus forming a fluorescent spectrum with two highly intense and well separated bands sensitive to a number of parameters of the dye molecule's microenvironment [1]. These properties resulted in a variety of applications for modified 3-hydroxychromones as laser dyes [2,3], photochromic materials [4,5], optical data storage devices [6]. 3-Hydroxychromone derivatives are also widely used to develop new approaches in fluorescent cellular spectroscopy [7], metal ions complexation analysis [8,9], probing nanocavities [10,11], design of sensors immobilized on various polymer substrates [12], etc.

Diversification of spectral properties by further modification of parent 3-hydroxychromone is ongoing in two synthetic ways. Obtaining derivatives with different substituents in the position 2 of the chromone bicycle led to polyhydroxyflavones [13], dialkylaminoflavones [14], as well as a number of their heterocyclic

substitutes [15,16]. From the other side, much attention was aimed on the functionalization of the benzene ring of the chromone bicycle [17–20].

In this work, the synthesis and fluorescent properties of two novel heterocyclic derivatives of 3-hydroxychromone are discussed, as well as possibility for their use as prospective solvatofluorochromic and ratiometric fluorescent probes of solvent polarity and polar admixtures.

### 2. Experimental

2-(4-(3-Phenyl-5-(4-methoxyphenyl)-4,5-dihydro-1H-pyrazol-1-yl)phenyl)-3-hydroxy-4H-chromen-4-one (**2a**) and 2-(4-(3-phenyl-5-(4-methoxyphenyl)-4,5-dihydro-1H-pyrazol-1-yl)phenyl)-3-hydroxy-4H-benzo[h]chromen-4-one (**2b**) were synthesized in two steps: the modified method of aldol condensation with donor aldehydes [17] was used to obtain chalcones, then Algar–Flynn–Oyamada oxidation [21,22] led to chromones (see Fig. 1). The traditional scheme of aldol condensation in ethanol–water sodium hydroxide solution failed because of remarkable electron-donor effect of 1,3,5-triphenyl-2-pyrazoline fragment which deactivates the corresponding aldehyde.

On the first step, corresponding chalcones were obtained by condensation of 2 g (5.6 mmol) of commercially available 1-(4'-formyl-phenyl)-3-phenyl-5-(4'-methoxy-phenyl)-2-pyrazoline with 5.6 mmol of *o*-hydroxy acetophenone in 10 ml of dried DMSO in the presence of 2 molar excess of sodium methoxide. After

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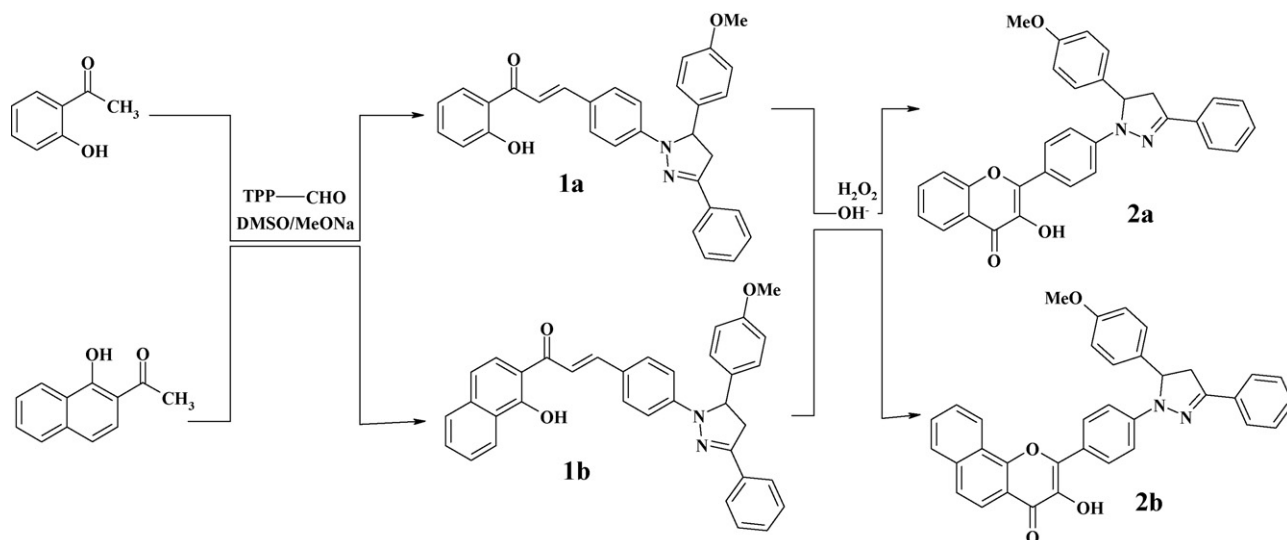


Fig. 1. Synthetic scheme for 1,3,5-triphenyl-2-pyrazoline-substituted 3-hydroxychromones.

heating the mixture at 100–120 °C during 2 h, the chalcone salt was neutralized to pH 6–7 with 5% HCl. The precipitate was filtered, washed with methanol and dried, giving 1.3 g of 3-(3,4,6-triphenylpyrazolin-2-yl)-1-(2-hydroxyphenyl)-2-propen-1-one (**1a**, 49% yield) and 1.65 g of 3-(3,4,6-triphenylpyrazolin-2-yl)-1-(1-hydroxynaphthalen-2-yl)-2-propen-1-one (**1b**, 56% yield).

The second step consisted of an oxidative cyclization of previously obtained chalcones into the corresponding chromones. Thus, 2.5 mmol of chalcone was dissolved in 5 ml of 96% ethanol with 2.5 ml of 50% aqueous NaOH solution. Then 2.5 ml of 35% H<sub>2</sub>O<sub>2</sub> solution was added dropwise. After this the reaction medium was heated to boiling during 3–5 min, then cooled, diluted with cold water and neutralized to pH 6–7 with 5% HCl. The precipitate was filtered, washed with methanol and dried. Both chromones were purified by column chromatography (Al<sub>2</sub>O<sub>3</sub>/CHCl<sub>3</sub>) giving 0.71 g of **2a** (58% yield) and 0.56 g of **2b** (42% yield).

**2a**: C<sub>31</sub>H<sub>24</sub>N<sub>2</sub>O<sub>4</sub>, MW 488.53, molecular ion in MS, *m/z*: 488, elemental analysis N (%): 5.73 (calc.), 5.9 (found), NMR <sup>1</sup>H data: 3.16 (dd, 1H, pyrazoline cycle methylenic), 3.68 (s, 3H, methoxy group), 3.95 (dd, 1H, pyrazoline cycle methylenic), 5.63 (dd, 1H, pyrazoline cycle methynic), 6.70–6.90 (m, 4H), 7.00–7.25 (m, 4H), 7.30–7.56 (m, 4H), 7.59–7.90 (m, 4H), 8.06 (dd, 1H, chromone bicycle), 9.66 (s, 1H, hydroxy group).

**2b**: C<sub>35</sub>H<sub>26</sub>N<sub>2</sub>O<sub>4</sub>, MW 538.59, molecular ion in MS, *m/z*: 538, elemental analysis N (%): 5.20 (calc.), 5.1 (found), NMR <sup>1</sup>H data: 3.15 (dd, 1H, pyrazoline cycle methylenic), 3.69 (s, 3H, methoxy group),

3.94 (dd, 1H, pyrazoline cycle methylenic), 5.61 (dd, 1H, pyrazoline cycle methynic), 6.79–6.97 (m, 3H), 6.98–7.21 (m, 5H), 7.35–7.45 (m, 4H), 7.60–7.88 (m, 5H), 7.90–8.34 (m, 2H), 9.66 (s, 1H, hydroxy group).

<sup>1</sup>H NMR spectra in DMSO-*d*<sub>6</sub> were taken on Varian 200 Mercury VX spectrometer. Mass-spectra were taken on Varian 1200L spectrometer (electron impact, 70 eV). Electronic absorption spectra were recorded on the HITACHI U3210 spectrophotometer, fluorescence spectra—on the HITACHI F4010 spectrofluorimeter. Fluorescence spectra deconvolution onto individual bands was realized using a computer program based on Siano and Metzler approximation of the emission band shape by the log–normal function [23].

Quantum chemical calculation of the molecular structure of **2a–b** was made with semiempirical method PM6 [24] using MOPAC2007 software [25]. Electronic spectra were calculated for the PM6 optimized geometry with the method ZINDO/S [26].

### 3. Results and discussion

Both title compounds **2a** and **2b** are well soluble in most of the organic solvents. As other representatives of their class, they exhibit intramolecular proton transfer reaction in the excited state. Absorbing light in the blue-wavelength region (430–480 nm) the investigated compounds emit intense orange fluorescence.

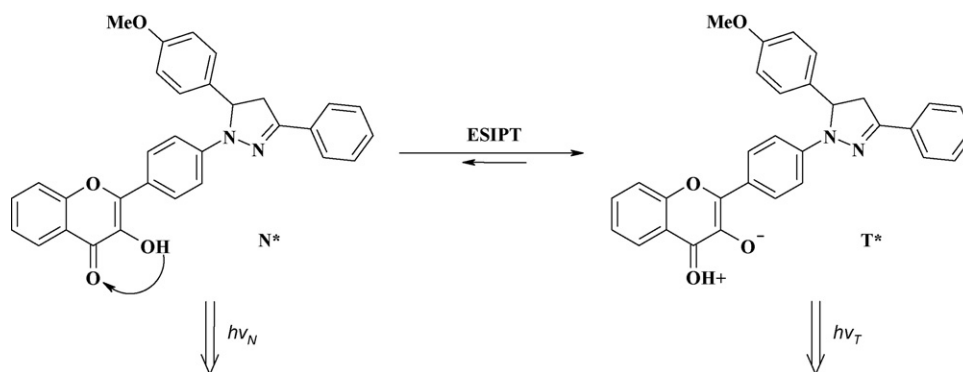


Fig. 2. ESIP process for **2a** and nature of dual-band fluorescence.

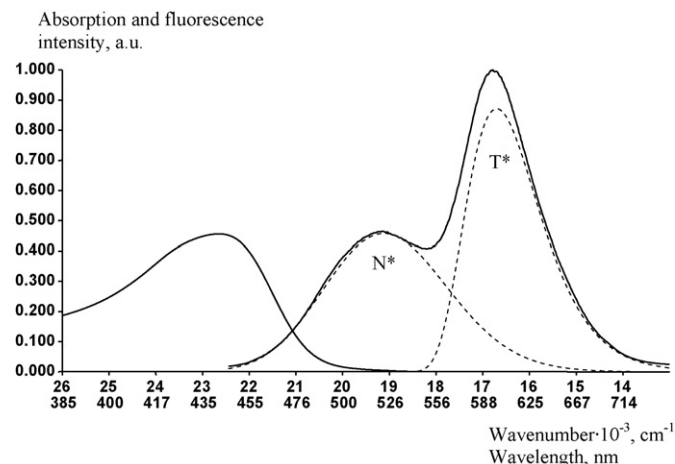


Fig. 3. Absorption and fluorescence ( $\lambda^* = 435$  nm, diluted solution  $< 10^{-5}$  M) spectra of **2a** in 1,2-dichloroethane (solid line). Deconvoluted individual N\* and T\* fluorescence bands (dashed lines).

The electronic excitation of **2a–b** caused simultaneous increase of acidity of the 3-hydroxy group and basicity of 4-carbonyl oxygen atom. This results in the intramolecular proton transfer reaction (Fig. 2) and formation of the so-called phototautomer form (T\*) emitting light at long wavelength region and characterized by the increased Stokes shift value. If the ESIPT rate is not very high the normal form (N\*) emission is being observed at shorter wavelengths compared to phototautomer. In the experimental fluorescence spectrum the emission of N\* and T\* forms usually overlap forming its dual-banded shape with slight vibrational structure, better resolved in nonpolar solvents (Fig. 3, absorption band normalized to the short-wavelength emission one).

In the fluorescence spectra of **2a** and **2b** the high Stokes shift of up to  $7000\text{ cm}^{-1}$  emission band was attributed to the product of the excited state proton transfer reaction—the phototautomer form. The initial normal form fluorescence band has Stokes shift of up to  $5000\text{ cm}^{-1}$  and is almost as intense as the T\* form in polar media. This makes the compounds **2a–b** suitable for dual-band radiometric measurements. High fluorescence quantum yields (up to 0.55) are typical for both dyes as well. Data on absorption and fluorescence

spectral measurements of **2a** and **2b** in nine solvents of different polarity are shown in Table 1.

Introduction of 1,3,5-triphenyl-2-pyrazolinic moiety in the molecule of 3-hydroxychromone leads to significant enlargement of the conjugated system and thus moving both absorption and emission spectra towards longer wavelengths. To elucidate the role of 1,3,5-triphenyl-2-pyrazoline unit in the chromophoric system of the investigated molecules, we have made a series of quantum-chemical calculations. First the molecular structure of **2a** and a model dimethylamino-substituted 3-hydroxychromone (**DM3HC**) was optimized with PM6 method. Then the electronic spectra of these compounds were calculated in ZINDO/S scheme using the obtained molecular geometry.

The electronic excitation localization analysis [27] was applied to the studied molecules: the corresponding indices were calculated to the selected molecular fragments and presented in Table 2.

As it follows from the above results, the long-wavelength electronic transitions in both examined molecules are similar in nature. Only the A–D fragments of **2a** take significant part in the electronic excitation, while as both E and F fragments contribution is low. It is quite clear to F, which is not conjugated to the main chromophore. The role of E is probably the increase of the effective electron density on the electron-donor center of the title compounds (nitrogen atom of dimethylamino group:  $-0.21e$  and pyrazoline cycle N<sub>1</sub> and N<sub>2</sub> atoms:  $-0.38e$ ).

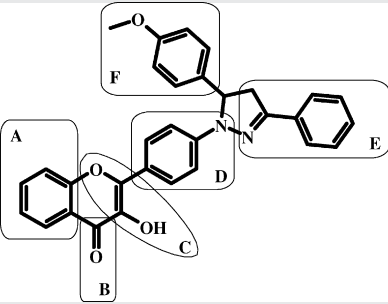
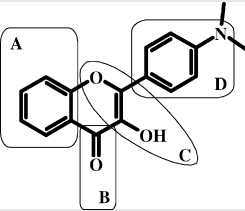
The total amount of the transferred electron density at the electronic excitation ( $\Delta q$ ) of **DM3HC** exceeds that of **2a**, this determines the calculated  $\Delta\mu$  values (vector difference between the dipole moments in the excited and in the ground states): 9.4 D and 7.5 D correspondingly. This causes high sensitivity of their normal forms emission bands to solvent polarity. However, one should also take into account another intramolecular excited state relaxation process, which makes its additional and independent contribution into solvent induced spectral shifts. Our calculations show the disturbance of planarity of **2a** molecule connected with its triphenylpyrazoline unit: the angle between the plane of 2-phenyl and pyrazoline cycle was estimated as  $25^\circ$ , the corresponding angle between the pyrazoline cycle and benzene ring in its position 3– $20^\circ$ . Thus, definite excited state planarization of **2a–b** molecules would take place, which should be regulated by the solvent polarity as well. This might be among the reasons of high sensitivity of **2a–b** spectral parameters to solvent and is in full accordance

Table 1  
Absorption and fluorescence spectral data of **2a** and **2b** in different solvents.

	Solvent	$\nu_{abs}$ ( $\text{cm}^{-1}$ )	$\nu_{fl}^N$ ( $\text{cm}^{-1}$ )	$\Delta\nu_{ST}^N$ ( $\text{cm}^{-1}$ )	$\nu_{fl}^T$ ( $\text{cm}^{-1}$ )	$\Delta\nu_{ST}^T$ ( $\text{cm}^{-1}$ )	$\phi$
<b>2a</b>	Hexane	23,520	21,585	1935	17,300	6220	0.48
	Toluene	22,960	20,180	2780	16,990	5970	0.55
	1,4-Dioxane	23,320	20,640	2680	16,915	6405	0.45
	Ethyl acetate	23,340	19,615	3725	16,785	6555	0.39
	1,2-Dichloroethane	22,660	19,060	3600	16,705	5955	0.30
	Acetone	23,180	19,920	3260	16,905	6275	0.39
	Acetonitrile	23,380	18,420	4960	16,440	6940	0.48
	Ethanol	22,900	17,670	5230	15,960	6940	0.38
	Water	22,200	17,000	5200	–	–	0.031
<b>2b</b>	Hexane	20,980	19,980	1000	17,290	3690	0.20
	Toluene	21,140	19,890	1250	16,960	4180	0.31
	1,4-Dioxane	21,200	19,120	2080	16,670	4530	0.24
	Ethyl acetate	21,300	18,780	2520	16,640	4660	0.25
	1,2-Dichloroethane	20,720	18,980	1740	16,490	4230	0.33
	Acetone	20,960	17,980	2980	16,600	4360	0.28
	Acetonitrile	20,860	18,330	2530	16,315	4545	0.24
	Ethanol	20,520	17,480	3040	15,995	4525	0.19
	Water	19,770	15,300	4470	–	–	0.014

$\nu_{abs}$ ,  $\nu_{fl}^N$ ,  $\nu_{fl}^T$  – positions of absorption, normal and phototautomer forms fluorescence maxima (deconvoluted onto individual emission bands as described in Section 2) respectively;  $\Delta\nu_{ST}^N$ ,  $\Delta\nu_{ST}^T$  – normal and phototautomer forms fluorescence Stokes shifts;  $\phi$  – total fluorescence quantum yield.

**Table 2**Calculated parameters of  $S_0$ – $S_1$  electronic transitions for **2a** and model 2-(4'-dimethylaminophenyl)-3-hydroxychromone.

Comp.	Index	A	B	C	D	E	F	
<b>2a</b>		$L$	0.18	0.20	0.17	0.36	0.05	0.04
	$\Delta q$	-0.210	-0.240	-0.044	0.402	0.029	0.047	
<b>DM3HC</b>		$L$	0.18	0.22	0.23	0.37		-
	$\Delta q$	-0.217	-0.273	0.025	0.449			-

$L$  – electronic excitation localization numbers [25] indicating the participation of an atom or a fragment of the molecule in the electronic transition and thus – in the formation of the excited state;  $\Delta q$  – changes in electron density on the structural fragment at the electronic excitation.

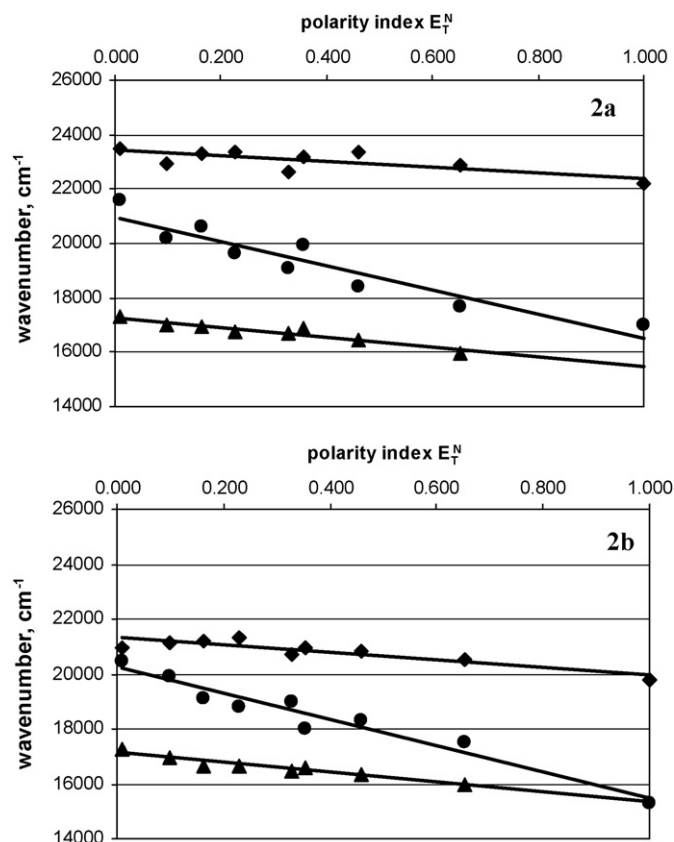
with the experimental observation of slightly lower or comparative solvatofluorochromism of **DM3HC** in respect to **2a–b** [28].

Difference in the excited state electron density redistribution between **2a–b** and **DM3HC** should affect the ESIPT reaction as well: according to our calculations the  $S_1$  state acidity of **2a** hydroxyl group should increase less than in the case of the model chromone. As we consider this factor to be crucial [8,29], we can conclude that the ESIPT reaction should be slower in the case of **2a–b** compared to that of **DM3HC**. This circumstance should increase **2a–b**  $N^*/T^*$  emission bands intensity ratio and make the normal form band better resolved in the low polar solvents.

Solvatochromic and solvatofluorochromic properties, as well as normal-to-tautomer emission intensity ratio dependence on solvent polarity were investigated (see Fig. 4) using a normalized Reichardt polarity index  $E_T^N$  [30] which is widely used for estimation of media polarity in numerous investigations of chemical and biological systems.

Both dyes are characterized by a slight bathochromic shift of their long-wavelength absorption bands with the increase of the solvent polarity, which however does not exceed  $1000\text{ cm}^{-1}$  between hexane and water. Interestingly, the normal fluorescence band possesses very distinct solvatofluorochromism, showing bathochromic shift of over  $4500\text{ cm}^{-1}$  on going from hexane to water. This makes **2a** one of the most effective solvatofluorochromic compounds among currently known 3-hydroxychromones [14,17,18,35]. The compound **2b** shows similar spectral behavior, but the bathochromic shift of its normal fluorescence band is somewhat smaller (around  $3500\text{ cm}^{-1}$ ) at analogous conditions.

Spectral behavior of the phototautomer fluorescence band of compounds **2a–b** is not typical to most of 3-hydroxychromone derivatives. It is well known that, due to lower charge separation in comparison to that of the normal form, the phototautomer fluorescence band is practically insensitive to media polarity [31]. In contrary, the phototautomer fluorescence bands of both investigated compounds are characterized by a distinct sensitivity to



**Fig. 4.** Positions of absorption ( $\blacklozenge$ ), normal ( $\bullet$ ) and phototautomer ( $\blacktriangle$ ) fluorescence maxima versus solvent polarity index  $E_T^N$  for **2a** and **2b**.

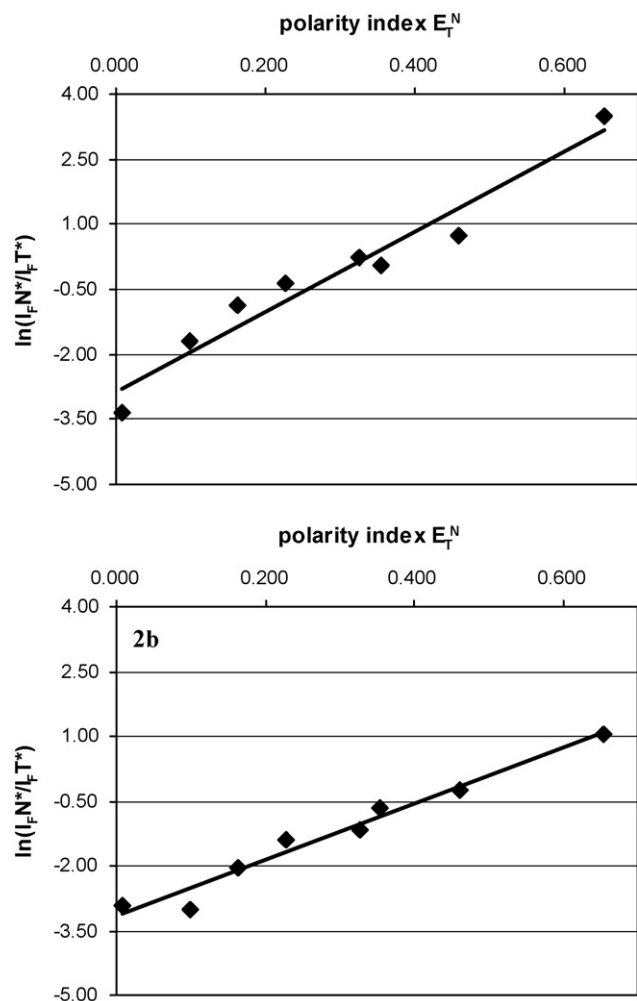


Fig. 5. Normal-to-phototautomer emission intensity logarithm dependence on solvent polarity for **2a** and **2b**.

solvent polarity and exhibit relatively high positive solvatofluorochromism, showing bathochromic shifts of over  $1500\text{ cm}^{-1}$  on going from hexane to acetonitrile and ethyl alcohol. This property allows to keep the band separation suitable for dual-band ratiometric measurements in a wider range of solvent polarities. A possibility for several substituted 3-hydroxychromones to exhibit sensitivity of the phototautomer emission to the solvent polarity was particularly discussed in [32]. Similar effect was rarely observed to several other classes of ESIPT compounds [17,33].

As it was already shown for a number of other 3-hydroxychromone derivatives [17,34], both synthesized compounds show strong dependence of the normal-to-phototautomer emission intensity ratio on the solvent polarity. This characteristic is crucial for implementation of these compounds as ratiometric probes. From a general approach, a possibility of intermolecular hydrogen bonded associates formation in different polar, especially protic solvents, presents a concurrence to the intramolecular H-bonds and affects the ESIPT process. These specific intermolecular interactions lead to the decrease of the phototautomer emission intensity. The demand to obtain a linear plot of the  $N^*/T^*$  intensity ratio on the solvent polarity led to the logarithmic function as a most suitable to linearize their mutual correlation [14].

As one can see from Fig. 5, both investigated compounds show good linear plots of the normal-to-phototautomer emission intensity ratio logarithm upon the solvent polarity. Introduction of 1,3,5-triphenyl-2-pyrazoline moiety not only preserved this tendency, but also allowed to get a fairly better response than the one of 3-hydroxyflavone, being as high as for several previously obtained derivatives [14,35,36].

To demonstrate a good prospects of application of the synthesized compounds for analysis of water content of organic solvents, compound **2a** in dioxane and acetone was titrated by water (Fig. 6). Increasing water concentration led to increase of the normal fluorescence intensity with long-wavelength shifting of its band maximum, together with the decrease of phototautomer emission intensity. These effects are in full accordance with previously published experimental data [28,37], and further investigation can

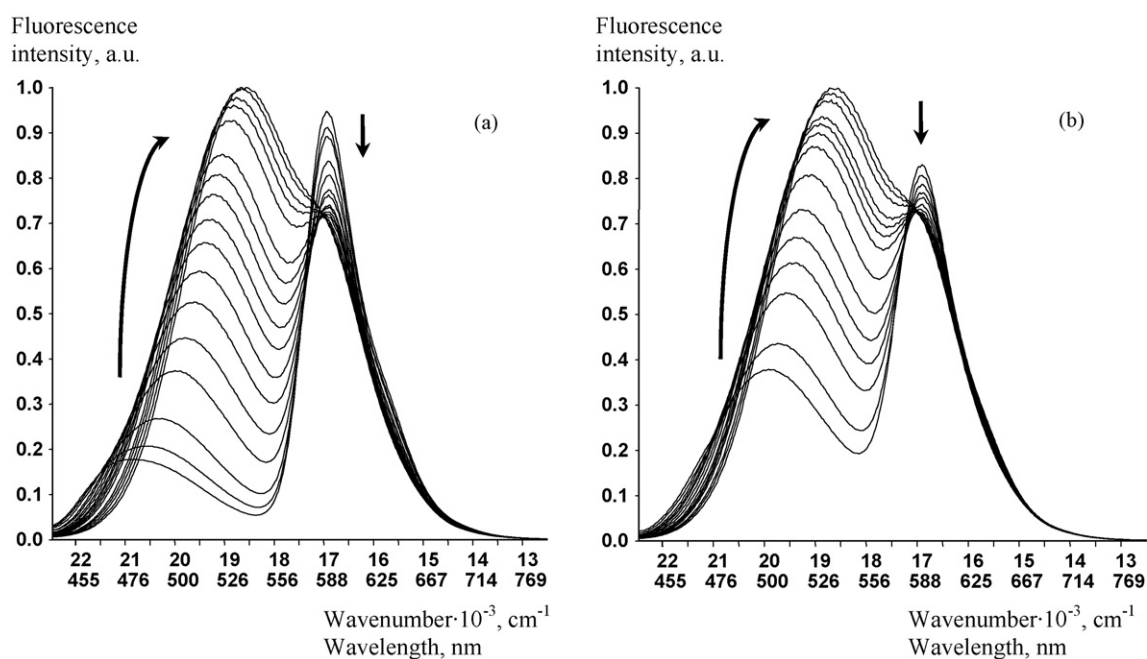


Fig. 6. Emission of **2a** in dioxane (a) and acetone (b) with different water additions (step 1 vol%).

make **2a** and **2b** promising indicators sensitive to polar and protic solvent admixtures.

#### 4. Conclusion

Two novel 3-hydroxychromone derivatives with a substituted 1,3,5-triphenyl-2-pyrazoline moiety were synthesized. As it was suggested, introduction of a strong electron donor fragment to the position 2 of the 3-hydroxychromone significantly increased the charge-transfer character of the normal form. This makes the normal fluorescence band much more intense and increases its sensitivity to the solvent polarity. Extremely high solvatofluorochromism of the normal emission band of the compound **2a** makes it one of the most effective solvatofluorochromic dyes in the 3-hydroxychromone family. Good response of the normal-to-phototautomer ratio to the solvent polarity makes both compounds prospective for their application as ratiometric fluorescent probes. Sensitivity of the phototautomer form emission of both investigated compounds to the solvent polarity allows to keep the band separation suitable for dual-band ratiometric measurements in a wider range of solvent polarities.

#### References

- [1] A. Sytnik, D. Gormin, M. Kasha, Interplay between excited-state intramolecular proton transfer and charge transfer in flavonols and their use as protein-binding-site fluorescent probes, *Proc. Natl. Acad. Sci. U.S.A.* 91 (1994) 11968–11972.
- [2] P.T. Chou, D. McMorro, T.J. Aartsma, M. Kasha, The proton-transfer laser. Gain spectrum and amplification of spontaneous emission of 3-hydroxyflavone, *J. Phys. Chem.* 88 (1984) 4596.
- [3] M. Kasha, Excited state proton transfer spectroscopy and proton-transfer lasers, *Acta Phys. Polon.* 71A (5) (1987) 717–729.
- [4] M.D. Cohen, G.M. Schmidt, Photochromy and thermochromy of anils, *J. Phys. Chem.* 66 (1962) 2242–2245.
- [5] M.E. Kletskii, A.A. Milov, A.V. Metelitsa, M.I. Knyazhansky, Role of structural flexibility in the fluorescence and photochromism of salicylideneaniline: the general scheme of phototransformations, *J. Photochem. Photobiol. A: Chem.* 110 (1997) 267–270.
- [6] A. Mordzinski, Excited state intramolecular proton transfer: the structural and dynamic aspects, *Inst. Chem. Phys. PAN. Warszawa* (1990) 71.
- [7] N.J. Emptage, Fluorescent imaging in living systems, *Curr. Opin. Pharmacol.* 1 (2001) 521–525.
- [8] A.D. Roshal, A.V. Grigorovich, A.O. Doroshenko, V.G. Pivovarenko, A.P. Demchenko, Flavonols and crown-flavonols as metal cation helators. The different nature of Ba<sup>2+</sup> and Mg<sup>2+</sup> complexes, *J. Phys. Chem. A* 102 (1998) 5907–5914.
- [9] A.D. Roshal, A.V. Grigorovich, A.O. Doroshenko, V.G. Pivovarenko, A.P. Demchenko, Flavonols as metal-ion chelators: complex formation with Mg<sup>2+</sup> and Ba<sup>2+</sup> cations in the excited state, *J. Photochem. Photobiol. A: Chem.* 127 (1999) 89–100.
- [10] J.A. Organero, L. Tormo, M. Sanz, A. Roshal, A. Douhal, Complexation effect of  $\gamma$ -cyclo-dextrin on a hydroxyflavone derivative: formation of excluded and included anions, *J. Photochem. Photobiol. A: Chem.* 188 (2007) 74–82.
- [11] M. Sanz, J.A. Organero, A. Douhal, Proton and charge transfer reactions dynamics of a hydroxyflavone derivative in a polar solvent and in a cyclodextrin nanocavity, *Chem. Phys.* 338 (2007) 135–142.
- [12] J.L. Suarez-Rodriguez, M.E. Diaz-Garcia, Flavonol fluorescent flow-through sensing based on a molecular imprinted polymer, *Anal. Chim. Acta* 405 (2000) 67–76.
- [13] J. Guharay, P.K. Sengupta, Excited-state proton transfer and dual fluorescence of robinetin in different environments, *Spectrochim. Acta A* 53 (1997) 905–912.
- [14] A.S. Klymchenko, A.P. Demchenko, Multiparametric probing of molecular interactions with fluorescent dye exhibiting excited state intramolecular proton transfer, *Phys. Chem. Chem. Phys.* 5 (2003) 461–468.
- [15] S. Ercelen, A.S. Klymchenko, A.P. Demchenko, Novel two-color fluorescence probe with extreme specificity to bovine serum albumin, *FEBS Lett.* 538 (2003) 25–28.
- [16] D.A. Svehkarev, V.N. Baumer, Z.A. Syzova, A.O. Doroshenko, New benzimidazole 3-hydroxychromone derivative with two alternative mechanisms of the excited state intramolecular proton transfer reaction, *J. Mol. Struct.* 882 (2008) 63–69.
- [17] A.S. Klymchenko, T. Ozturk, A.P. Demchenko, Synthesis of furanochromones: a new step in improvement of fluorescence properties, *Tetrahedron Lett.* 43 (2002) 7079–7082.
- [18] A.S. Klymchenko, Y. Mely, 7-(2-Methoxycarbonylvinyl)-3-hydroxychromones. New dyes with red-shifted dual emission, *Tetrahedron Lett.* 45 (2004) 8391–8394.
- [19] S.V. Avilov, C. Bode, F.G. Toelgyesi, A.S. Klymchenko, J. Fidy, A.P. Demchenko, Temperature effects on alpha-crystalline structure probed by 6-bromomethyl-2-(2-furanyl)-3-hydroxychromone, an environmentally sensitive two-wavelength fluorescent dye covalently attached to the single Cys residue, *Int. J. Biol. Macromol.* 36 (2005) 290–298.
- [20] A.S. Klymchenko, D.A. Yushchenko, Y. Mely, Tuning excited state intramolecular proton transfer in 3-hydroxyflavone derivative by reaction of its isothiocyanate group with an amine, *J. Photochem. Photobiol. A: Chem.* 192 (2007) 93–97.
- [21] J. Algar, J.P. Flynn, New synthesis of flavonols, *Proc. Roy. Irish. Acad. Sci.* 42B (1934) 1–8.
- [22] M.A. Smith, R.M. Neumann, R.A. Webb, A modification of the Algar–Flynn–Oyamada preparation of flavonols, *J. Heterocycl. Chem.* 5 (1968) 425–426.
- [23] D.B. Siano, D.E. Metzler, Band shapes of the electronic spectra of complex molecules, *J. Chem. Phys.* 51 (5) (1969) 1856–1861.
- [24] J.J.P. Stewart, Optimization of parameters for semiempirical methods V: modification of NDDO approximations and application to 70 elements, *J. Mol. Model* 13 (2007) 1173–1213.
- [25] J.J.P. Stewart, MOPAC2007, Stewart Computational Chemistry, Colorado Springs, CO, USA, 2007, <<http://OpenMOPAC.net>>.
- [26] J.E. Ridley, M.C. Zerner, An intermediate neglect of differential overlap technique for spectroscopy: pyrrole and azines, *Theor. Chim. Acta* 32 (2) (1973) 111–124.
- [27] A.V. Luzanov, The structure of the electronic excitation of molecules in quantum-chemical models, *Russ. Chem. Rev.* 49 (1980) 1033–1048.
- [28] G. Duportail, A. Klymchenko, Y. Mely, A. Demchenko, Neutral fluorescence probe with strong ratiometric response to surface charge of phospholipid membranes, *FEBS Lett.* 508 (2001) 196–200.
- [29] A.O. Doroshenko, E.A. Posokhov, A.A. Verezubova, L.M. Ptyagina, V.T. Skripkina, V.M. Shershukov, Radiationless deactivation of the excited phototautomer form and molecular structure of ESIPT-compounds, *Photochem. Photobiol. Sci.* 1 (2) (2002) 92–99.
- [30] C. Reichardt, Solvatochromic dyes as solvent polarity indicators, *Chem. Rev.* 94 (1994) 2319–2358.
- [31] J. Catalan, J.C. Del Valle, C. Diaz, J. Palomar, J.L.G. De Paz, M. Kasha, Solvatochromism of fluorophores with an intramolecular hydrogen bond and their use as probes in biomolecular cavity sites, *Int. J. Quant. Chem.* 72 (1999) 421–438.
- [32] P.-T. Chou, M.L. Martinez, J.H. Clements, Reversal of excitation behavior of proton-transfer vs. charge-transfer by dielectric perturbation of electronic manifolds, *J. Phys. Chem.* 97 (1993) 2618–2622.
- [33] E.L. Roberts, J. Dey, I.M. Warner, Excited-state intramolecular proton transfer of 2-(2'-hydroxyphenyl)benzimidazole in cyclodextrins and binary solvent mixtures, *J. Phys. Chem. A* 101 (1997) 5296–5301.
- [34] A.S. Klymchenko, T. Ozturk, V.G. Pivovarenko, A.P. Demchenko, Synthesis and spectroscopic properties of benzo- and naphthofuryl-3-hydroxychromones, *Can. J. Chem.* 79 (2001) 358–363.
- [35] S. Ercelen, A.S. Klymchenko, A.P. Demchenko, Ultrasensitive fluorescent probe for the hydrophobic range of solvent polarities, *Anal. Chim. Acta* 464 (2002) 271–287.
- [36] S.M. Dennison, J. Guharay, P.K. Sengupta, Excited-state intramolecular proton transfer (ESIPT) and charge transfer (CT) fluorescence probe for model membranes, *Spectrochim. Acta A* 55 (1999) 1127–1132.
- [37] W. Liu, Y. Wang, W. Jin, G. Shen, R. Yu, Solvatochromogenic dye for the detection of water in acetone, *Anal. Chim. Acta* 383 (1999) 299–307.