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Microwave-Assisted Synthesis and Spectroscopic Properties of 4′-Substituted Rosamine Fluorophores and Naphthyl Analogues

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A series of rosamine fluorophores was obtained by reaction of the appropriate benzaldehyde and 3-(diethylamino)phenol followed by an oxidation step. Both conventional heating and microwave irradiation methods were utilized, and higher yields in a remarkably shorter period of time (10 min) were achieved by using the microwave irradiation protocol under closed vessel conditions (80 °C). The nitro-substituted rosamine was further converted into the corresponding amino derivative through Pd/C-catalysed hydrogenation. The synthetic protocol used for rosamines was also successfully employed to synthesise naphthyl analogues by using 1- and 2-naphthaldehyde. In the latter case, a novel hydroxy analogue was also obtained as a minor product. The photophysical behaviour of all the rosamines was studied in different solvents to rationalize the influence of the substituent groups on the electronic distribution, the effect of steric hindrance caused by the naphthyl ring, and the effect of the solvent. The results demonstrate that the introduction of different substituents in the periphery of the rosamine framework (in particular NO_2 and NH_2 groups) alters the fluorescence properties of the molecule such as emission wavelength and fluorescence quantum yield. All the rosamines are shown to be more fluorescent in dichloromethane than in more polar solvents such as ethanol. The spectroscopic properties of the 4′-carboxy-substituted rosamine, which is particularly attractive for labelling purposes, was also studied at physiological pH.

Introduction

The design of novel fluorophores and fluorescent probes has become a theme of particular attention for the scientific community, mainly because they are indispensable monitoring tools for chemical, biological and environmental purposes.[1] The pursuit of this objective, however, is hindered by the lack of simple and efficient synthetic routes that provide pure compounds with fluorescence properties that are suitable for broad applications.

Rhodamine derivatives are particularly attractive as fluorophores or fluorescent probes because of their excellent photophysical properties,[2–4] and there are several well-established synthetic methods for derivatization of rhodamines that allow the attachment of the fluorophore to almost every molecule of interest.[4] Consequently, these compounds have been used in a range of optical applications, including as dyes for the construction of optic fibre devices,[5] as fluorescence standards,[6] and as chemosensors for metal ion detection.[7] However, although several rhodamine derivatives are commercially available, they are quite expensive and most of the compounds commonly used for further derivatization are only accessible as a mixture of 4′- and 5′-regioisomers (Figure 1), the reactivity of which depends on the position of the functional group in the rhodamine scaffold. In contrast, rhodamine derivatives lacking the carboxylic group in the 2′-position, known as rosamines (Figure 1), can be easily isolated as a single regioisomer and are therefore less problematic to synthesise and purify.

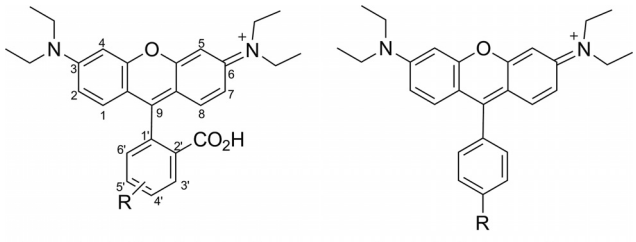

Figure 1. 4′- or 5′-Substituted rhodamines and 4′-substituted rosamines.

From the photophysical point of view, the fluorescence intensity of the rosamine fluorophore is usually enhanced upon binding to another molecule because linkage usually results in a lock of the rotation of the 9-phenyl ring in the new conjugates.[8] As a drawback, the rosamine synthesis

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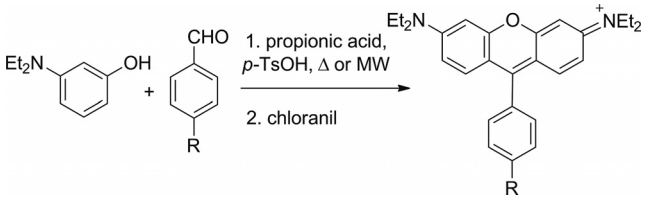
involves the use of high temperatures, which is a problem that can be easily solved through the application of microwave irradiation.[9] The development of methodologies that can be used to access rosamine derivatives and photophysical studies of their properties are therefore crucial for further applications of these compounds. In this context, combinatorial synthesis was recently successfully introduced as a good alternative for the construction of rosamine libraries.[8,10]

The objective of the present work is the implementation of more efficient and straightforward protocols for the synthesis of rosamine derivatives. To achieve this goal we synthesised a series of 4′-substituted rosamines (**1**–**6**) and naphthyl analogues (**7** and **8**) by using two different heating protocols: conventional heating (oil bath) and microwave irradiation, in combination with different oxidation methods. By following these procedures we expected to significantly increase the product yield and reduce the reaction time.

Considering previous work in the field of rosamine synthesis,[9] in which a series of three regioisomerically pure bromo-substituted rosamines were prepared through condensation of 4-bromobenzaldehyde with different phenolic amines (using 60% sulfuric acid, followed by oxidation with chloranil), the present work represents a step forward because a series of regioisomerically pure 4′-substituted rosamines (Table 1, R = H, COOH, OCH_3, Br and NO_2) was prepared from the condensation of different 4-substituted benzaldehydes with 3-(diethylamino)phenol, using propionic acid and a catalytic amount of *p*-toluenesulfonic acid (*p*-TsOH), with subsequent oxidation in chloranil. The amino-substituted rosamine (see below, Scheme 2, R = NH_2) was prepared from the nitro-substituted rosamine through a Pd/C catalyzed hydrogenation reaction. The synthetic protocol was also extended to the preparation of

Table 1. Synthesis of 4′-substituted rosamines (**1**–**5**) using different heating methods, followed by oxidation with chloranil.

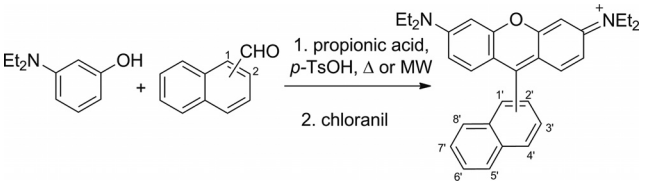


Entry	Rosamine	Method	Temp. [°C]	Time	Yield [%][a]
1	**1**, R = H	oil bath	65	16 h	35
2	**1**, R = H	MW, open vessel	65	180 min	50
3	**1**, R = H	MW, closed vessel	80	10 min	45
4	**2**, R = COOH	oil bath	65	16 h	30
5	**2**, R = COOH	MW, closed vessel	80	10 min	47
6	**3**, R = OCH_3	oil bath	65	16 h	44
7	**3**, R = OCH_3	MW, closed vessel	80	10 min	48
8	**4**, R = Br	oil bath	65	16 h	26
9	**4**, R = Br	MW, closed vessel	80	10 min	49
10	**5**, R = NO_2	oil bath	65	16 h	27
11	**5**, R = NO_2	MW, closed vessel	80	10 min	51

[a] Isolated yield after flash chromatography.

sterically hindered 9-naphthyl rosamines (Table 2). The photophysical properties of the prepared rosamines were investigated by absorption and fluorescence electronic spectroscopy.

Table 2. Synthesis of 9-naphthyl-substituted rosamines **7** and **8** using different heating conditions, followed by oxidation with chloranil.



Entry	Rosamine	Method	Temp. [°C]	Time	Yield [%][a]
1	**7**, 1-naphthyl	oil bath	65	16 h	15
2	**7**, 1-naphthyl	MW, closed vessel	80	10 min	18
3	**8**, 2-naphthyl	oil bath	65	16 h	30
4	**8**, 2-naphthyl	MW, closed vessel	80	10 min	30

[a] Isolated yield after flash chromatography.

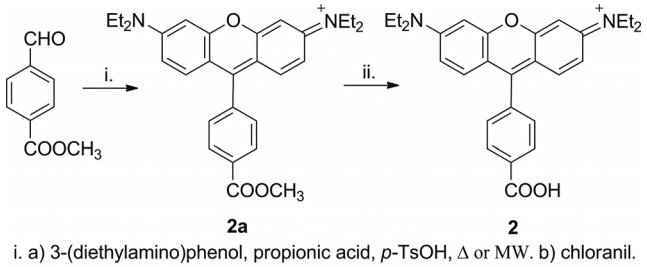
Results and Discussion

To pursue our objective, we chose the synthesis of non-substituted rosamine **1** to optimise the synthetic route for rosamine derivatives. The first attempt was carried out by heating a propionic acid solution of benzaldehyde and 3-(diethylamino)phenol in the presence of *p*TsOH at 65 °C in an oil bath for 16 h, followed by oxidation with chloranil.[11] After purification by flash chromatography, the product was washed with a saturated aqueous solution of NaCl, and rosamine **1** was isolated as a chloride salt in 35% yield (Table 1, entry 1). To improve the outcome of the reaction, the condensation was performed under microwave irradiation in a dedicated single-mode reactor, keeping the oxidation step with chloranil. Initial experiments employed open-vessel microwave conditions and demonstrated that, using the same temperature (65 °C), the reaction provided better yields (50% yield) within a slightly reduced reaction time (180 min) (Table 1, entry 2). By switching microwave irradiation to a closed-vessel system, and increasing the reaction temperature to 80 °C, the reaction took place in only 10 min and gave 45% yield of **1** (Table 1, entry 3). The key difference between the open and closed vessel conditions is that, whereas in an open vessel the reaction temperature is limited by the boiling point of the solvent, in the closed vessel it is possible to heat the solvents under pressure and employ temperatures that are higher than their boiling point. Considering this, experiments using increased reaction temperature were carried out (100 °C and above 140 °C) but an enhancement in the amount of degradation products of the reaction was observed. The use of acetic acid instead of propionic acid was also unsuccessful, resulting in the isolation of only minor amounts of pure rosamine **1**. Furthermore, the use of different oxidizing agents, such as nitrobenzene and H_2O_2, were screened and com-

pared with chloranil, but these oxidants did not provide any improvement in the reaction outcome and were therefore abandoned.

Taking into account the results detailed above, we chose to use closed-vessel microwave heating at 80 °C for 10 min as the optimal conditions to synthesise a range of rosamines with different substituents in the 4′-position of the phenyl ring, employing a variety of 4-substituted benzaldehydes and the same 3-(diethylamino)phenol. In most instances the anticipated rosamines were obtained in relatively good isolated yields. The electron-deficient benzaldehydes, 4-formylbenzoic acid and 4-nitrobenzaldehyde, together with the halogen-substituted benzaldehyde, 4-bromobenzaldehyde and the electron-rich benzaldehyde, 4-methoxybenzaldehyde, provided similar yields (Table 1, entries 5, 11, 9 and 7, respectively).

To evaluate the possibility of improving the yield of the acid rosamine **2** (Scheme 1) an experiment using methyl 4-formylbenzoate instead of 4-formylbenzoic acid was carried out. In fact, by using the conventional protocol, rosamine **2a** (R = $COOCH_3$) was obtained in 18% yield. This value was significantly improved to 59% when microwave irradiation was used as the heating source. Subsequent alkaline-mediated hydrolyses gave the expected rosamine **2** (R = COOH) in 30% overall yield after a fast chromatographic purification. These results lead us to conclude that the synthesis of rosamine **2** using methyl 4-formylbenzoate is not advantageous because, in addition to introducing a further synthetic step, a significant reduction in the overall yield was observed when compared with the yield of 47% obtained using 4-formylbenzoic acid (Table 1, entry 5).



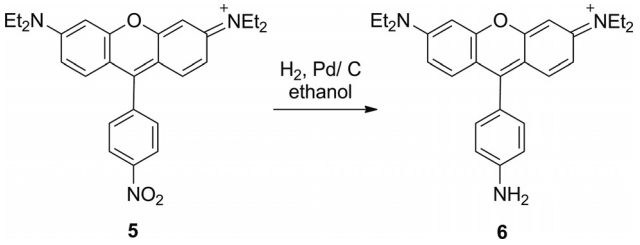
2a **2**

i. a) 3-(diethylamino)phenol, propionic acid, *p*-TsOH, Δ or MW. b) chloranil.
ii. NaOH, MeOH, Δ.

Scheme 1. Alternative synthesis of rosamine **2**.

A comparison of the results obtained under microwave irradiation and those obtained by using a conventional heating protocol at 65 °C for 16 h, demonstrates that microwave irradiation not only provides the best yields but also reduces the reaction time to 10 min.

Our aim was also to perform the reduction of the nitro group of rosamine **5** to the corresponding amine. According to the literature, the reduction of the nitro group to an amino group has been widely explored for fluorescein-type derivatives, and these compounds have been successfully used in the production of pH and ammonia sensors[12] and also for C-terminal labelling of peptides.[13] The reduction step can be carried out under hydrogen and a W-2 Raney nickel catalyst, but this approach furnishes a mixture of aminofluorescein and its analogue after reductive lactone cleavage. A good alternative for such reduction relies on the use of sodium sulphide/sodium hydrosulfide giving only the aminofluorescein derivative.[14] In the present work we were interested in the possibility of using the Pd/C catalysed hydrogenation as a more ecofriendly protocol to perform the reduction of the nitro group in rosamine **5**. Therefore, a solution of rosamine **5** (R = NO_2) in ethanol was placed under a hydrogen atmosphere (5 bar) over 10% Pd/C for 15 h (Scheme 2). Under these conditions, after purification by flash chromatography and washing with a saturated aqueous solution of NaCl, the expected rosamine **6**, having Cl^- as counter anion, was isolated in 20% yield.



5 **6**

Scheme 2. Synthesis of amino-substituted rosamine **6**.

A similar comparative study of the reaction under conventional heating and microwave irradiation protocols was carried out to synthesise the sterically hindered 9-naphthyl analogues **7** and **8** (Table 2). When 1-naphthaldehyde was used (Table 2, entries 1 and 2), the desired rosamine **7** was obtained in low yield (15% in oil bath and 18% in microwave irradiation). In contrast, the less sterically hindered 2-naphthaldehyde gave the desired rosamine **8** in a considerably higher yield of 30%, regardless of which heating source was used (Table 2, entries 3 and 4).

It is important to mention that, based on the progress of the reactions (which were monitored by TLC), in general the proposed protocol for the synthesis of rosamine fluorophores also affords minor amounts of other compounds. Some of these minor compounds had a purple colour and R_f values close to those of rosamine. Particularly, in the synthesis of rosamine **8**, a purple compound was obtained in a larger amount, allowing its isolation and characterization. A detailed NMR analysis (see below) of this minor compound allowed us to identify compound **8a** as the hydroxyl analogue shown in Figure 2. This hydroxylated compound is probably formed during the oxidation step with chloranil.

The prepared rosamines were characterized by NMR, UV/Vis and fluorescence spectroscopy, mass spectrometry and elemental analysis. For the 4′-substituted rosamines series **1**–**6**, the ^1H NMR spectra showed the presence of signals that are typical of the xanthene scaffold: (i) a triplet at 1.31–1.35 ppm and a quartet at 3.66–3.69 ppm, corresponding to the resonance of the ethyl groups; (ii) a doublet at 6.73–6.98 ppm corresponding to the resonance of 4-H and 5-H protons; (iii) a double doublet at 6.95–7.09 Hz attributed to the resonance of 2-H and 7-H protons, and (iv) a relatively deshielded doublet at 7.21–7.65 ppm due to the resonance of 1-H and 8-H protons. Much more dependent

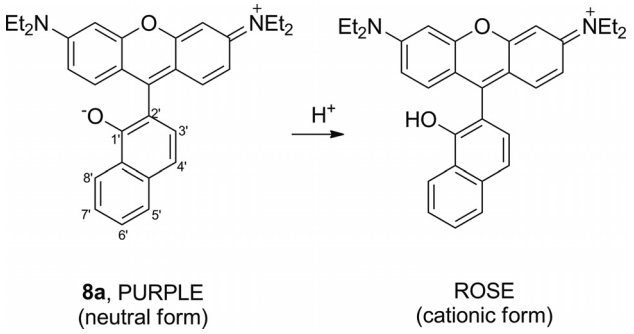


Figure 2. Structure of hydroxy analogue **8a** and its protonated form.

on the nature of the 4′-substituent group are signals from the protons of the phenyl ring. For electron-withdrawing groups, such as CO_2H and NO_2, and for the halogen Br, the 2′-H and 6′-H protons appear at 7.28–7.64 ppm and 3′-H and 5′-H protons appear at 7.77–8.50 ppm. However for the electron-donating groups OCH_3 and NH_2, the 2′-H and 6′-H protons appear at δ = 7.35 and 7.26 ppm but 3′-H and 5′-H protons appear more protected at δ = 7.15 and 6.91 ppm, respectively. These chemical shifts are summarized in Table 3. Supplementary ^{13}C NMR spectroscopic data for the 4′-substituted rosamines series **1**–**6** are summarized in Table S1 in the Supporting Information.

Table 3. Comparison of ^1H NMR chemical shift values (ppm) of rosamines **1**–**6**, recorded in $CDCl_3$ (except **2** and **6**, which were recorded in CD_3OD).

Rosamine	1,8-H	2,7-H	4,5-H	2′,6′-H	3′,5′-H	CH_2	CH_3
1, R = H	7.36	6.95	6.86	7.37–7.39	7.61–7.64	3.67	1.34
2, R = CO_2H	7.40	7.05	6.98	7.49	8.22	3.69	1.32
3, R = OCH_3	7.46	6.96	6.83	7.35	7.15	3.66	1.34
4, R = Br	7.31	6.95	6.73	7.28	7.77	3.66	1.33
5, R = NO_2	7.21	7.03	6.89	7.64	8.50	3.69	1.35
6, R = NH_2	7.65	7.09	6.92	7.26	6.91	3.68	1.31

For 9-naphthyl analogues **7** and **8**, the ^1H NMR spectra also showed the characteristic signals of the xanthene scaffold and, particularly for rosamine **7**, the signals corresponding to the resonance of protons 2,7-H and 1,8-H appear relatively shifted to higher fields, at δ = 6.77 and 7.05 ppm, respectively. This alteration in the chemical shifts arises from the influence of the steric hindrance imparted by the naphthyl ring linked to the xanthene scaffold through position 1′. For rosamine **8**, the naphthyl ring is connected through the 2′-position and, therefore, has little influence on the chemical shifts of protons 2,7-H and 1,8-H, which appear now at δ = 6.98 and 7.47 ppm, respectively. These chemical shifts are summarized in Table 4.

In regard to the minor isolated compound **8a**, the ESI mass spectrum, which revealed the molecular ion $M^{+\cdot}$ at *m*/*z* 465, and the elemental analysis, are both consistent with the presence of an additional hydroxyl group in the periphery of the rosamine. This observation is also in agreement with the ^1H NMR spectrum, which shows all the typical signals of the xanthene unit, suggesting that the additional hydroxyl group must be present in the naphthyl unit. In fact, from the group of signals at 7.68–7.96 ppm, we were able to distinguish two doublets at δ = 7.71 ppm and 7.94 ppm (J = 9.2 Hz) that, according to the COSY spectrum, are correlated with each other; these signal were attributed to the resonance of 4′-H and 3′-H, respectively. Further distinguished protons are: (i) 6′-H and 7′-H as a multiplet at 7.68–7.77 ppm, and (ii) 5′-H and 8′-H as a multiplet at 7.93–7.95 ppm and a doublet at δ = 8.72 ppm. This is only compatible with the presence of the hydroxyl group in position 1′ of the naphthyl ring, confirming the structure of compound **8a** (Figure 2). A few drops of trifluoroacetic acid (TFA) were added to the NMR tube, providing an immediate colour change of the solution from purple to rose. This composition of the solution during the colour change was followed by NMR spectroscopic analysis, which revealed the appearance of a broad singlet at δ = 9.41 ppm that was assigned as arising from the proton of the OH group. Furthermore, as a result of oxygen atom protonation, all aromatic and aliphatic signals of the xanthene and naphthyl units were significantly shifted to higher chemical shift values. Further studies concerning the behaviour of this compound with pH will be conducted and presented in later works.

Table 4. Comparison of ^1H NMR chemical shift values (ppm) of rosamines **7** and **8**, recorded in $CDCl_3$ and CD_3OD, respectively.

Rosamine	1,8-H	2,7-H	4,5-H	H-naphthyl	CH_2	CH_3
7, 1-naphthyl	7.05	6.77	6.94	7.31–7.45 (2′,6′,8′-H) 7.57 and 7.69 (3′,7′-H) 8.01 and 8.10 (4′,5′-H)	3.65	1.33
8, 2-naphthyl	7.47	6.98	6.91	7.52 (3′-H) 7.66–7.73 and 7.95–8.06 (1′,5′,6′,7′,8′-H) 8.14 (4′-H)	3.68	1.36

Figure 3 shows the normalized absorption and fluorescence spectra of rosamines **1**–**8a** in ethanol (for normalized absorption and emission spectra of all rosamines in dichloromethane see the Supporting Information). The corresponding spectral parameters [$\lambda_{max(abs)}$, $\lambda_{max(em)}$], quantum yield (ϕ_F) and absorption extinction coefficients (ε) of the six 9-aryl rosamines **1**–**6** and the three 9-naphthyl rosamines **7**–**8a** in the different solvents used are listed in Table 5.

Analysis of part A of Figure 3 shows that the spectra are quite similar, with the exception of that for compound **8a**. The absorption maxima are only slightly shifted (peaks are in the 556–564 nm range), which is characteristic of this kind of compound.[15] For three of the compounds a bigger shift was observed. For rosamine **5** (R = NO_2) a large redshift (λ_{max} = 566 nm) occurred in the absorption spectrum; for rosamine **6** (R = NH_2) a blueshift (λ_{max} = 547 nm) occurred, and for rosamine **8a**, a significantly different absorption spectra was observed together with a large blueshift (λ_{max} = 523 nm) (this was also observed in dichloromethane; for details, see the Supporting Information). The same trend was observed for emission fluorescence spectra (see Figure 3, B) with maximum of emission occurring in the 571–581 nm range.

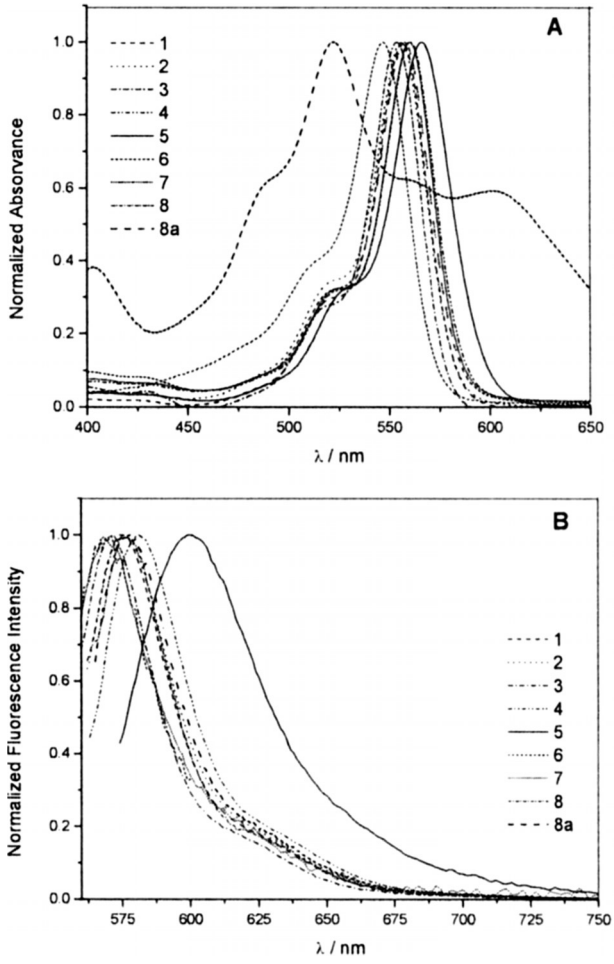


Figure 3. Normalized absorption spectra (**A**) and fluorescence emission spectra (**B**) of rosamines **1**–**8a** in ethanol.

Regarding the spectral characteristics of rosamine **5** (R = NO_2), the emission redshift was observed in ethanol and dichloromethane, which have different polarities and polarizabilities, thus indicating that the shift must be a direct consequence of introducing the NO_2 group into the phenyl ring. The NO_2 group is a well-known electron acceptor and, consequently, this substitution in the 4′-position of the phenyl ring will: (1) induce a charge shift leading to a large dipole moment of the excited state, which interacts with the solvent molecules to reduce the energy of the excited state resulting in a redshift, or (2) allow rosamine **5** to form an internal charge transfer state or a twisted internal charge transfer by NO_2 rotation, which, following excitation, might result in an increase in charge separation within the fluorophore.[3,16]

Regarding the spectrum of rosamine **8a**, a considerably different absorption spectrum was obtained that showed a progression of peaks in the 400–650 nm range, with a high (ca. 30 nm) hypsochromic displacement, which can be due to the molecule asymmetry associated with the presence of a hydroxyl group in the naphthyl ring. The introduction of a naphthyl unit with a hydroxyl group induces a strong blueshift and a noticeable decrease in the molar extinction

Table 5. Photophysical parameters for rosamines **1**–**8a** in ethanol, dichloromethane and MOPS (only for rhodamine B and rosamine **2**). The molar absorption coefficient ε and fluorescence quantum yield ϕ_F were determined.[19] Rhodamine B values were also determined and are included for comparison.

Rosamine	Solvent	$\lambda_{max(abs)}$ [nm]	$\lambda_{max(em)}$ [nm]	ε [cm^{-1} M^{-1}] × 10^4	ϕ_F
1, R = H	EtOH	557	574	8.30	0.39
	CH_2Cl_2	558	573	3.55	0.56
2, R = CO_2H	EtOH	556	576	4.13	0.28
	CH_2Cl_2	562	579	2.51	0.44
	MOPS	559	583	2.98	0.15
3, R = OCH_3	EtOH	564	571	8.64	0.28
	CH_2Cl_2	555	569	6.88	0.37
4, R = Br	EtOH	560	581	10.28	0.23
	CH_2Cl_2	562	576	6.42	0.38
5, R = NO_2	EtOH	566	600	6.62	0.05
	CH_2Cl_2	570	596	8.07	0.32
6, R = NH_2	EtOH	547	570	5.98	0.01
	CH_2Cl_2	550	565	4.43	0.20
7, 1-naphthyl	EtOH	560	576	5.48	0.20
	CH_2Cl_2	561	575	6.85	0.37
8, 2-naphthyl	EtOH	558	577	5.10	0.22
	CH_2Cl_2	560	575	2.58	0.38
8a,	EtOH	523	578	1.77	0.03
OH-analogue	CH_2Cl_2	525	574	2.24	0.05
Rhodamine B	EtOH	543	565	3.25	0.49[a]
	CH_2Cl_2	555	574	11.2	0.52
	MOPS	554	575	9.35	0.19

[a] See ref.[20]

coefficient when compared with all the other rosamines and which in ethanol has the value of 17700 M^{-1} cm^{-1}. Because the absorption spectra of rosamine **8a** in ethanol and dichloromethane are concentration-independent (results not shown), self-aggregation of the rosamine leading to blue-shifted non-fluorescent species, as reported for highly concentrated rhodamine solutions,[17] can be ruled out. Therefore, the observed behaviour can possibly arise from the existence of different forms in solution of the rosamine **8a** with different optical properties.

The ϕ_F values of rosamines **1**–**6** in ethanol are strongly dependent on the nature of the substituent introduced in the 4′-position of the rosamine scaffold. Compared with rhodamine B, all the tested substituents elicited a decrease in ϕ_F. Even the unsubstituted rosamine **1** was found to have a relatively lower ϕ_F value. These results are supported by the fact that while in rhodamine B, which carries the 2′-carboxylic acid group, the rotation of the 9-phenyl ring is constrained, in rosamine derivatives the lack of that 2′-carboxylic acid group increases the flexibility of the structure. This peculiar feature of rosamine is particularly attractive if a specific macromolecule or a specific material binding event can be found to lock this flexibility and induce a fluorescence enhancement.[8] Particularly, the introduction of NO_2 (strongly electron-accepting group) and NH_2 (strongly electron-donating group), significantly lowered the value of ϕ_F. However, the introduction of the COOH group resulted in a slight decrease in ϕ_F. Furthermore, a slight decrease in ϕ_F was observed for OCH_3 and Br. These results are in agreement with the results obtained

for a series of fluorescein-substituted derivatives.[18] Similar results in absorption and emission spectra are obtained when CH_2Cl_2 was used as solvent (see the Supporting Information).

The spectral characteristics in the two different solvents are slightly different in respect of the bands and maxima shifts in the UV/Vis absorption maxima and fluorescence intensity emission maxima. However, significant changes in ϕ_F values are observed. There is a general increase in ϕ_F values for all the rosamines **1**–**8a** in CH_2Cl_2 in the range from 1.3 to 20 times higher, respectively, for rosamine **3** and rosamine **6**. The use of CH_2Cl_2 dramatically changes the ϕ_F value of rosamine **5** and rosamine **6**, and, in the case of rosamine **5**, approximates its fluorescence quantum yield to those determined for the other rosamines, revealing that in a more polar solvent the presence of the NO_2 group does not affect the ϕ_F value as significantly. Considering the case of rosamine **8a**, the solvent change does not significantly increase its ϕ_F value, probably due to the fact that this rosamine is an asymmetric molecule. The general increase in ϕ_F values with an increase in the dielectric constant of the solvents was previously verified in other studies, considering other substituents in the xanthene ring and other solvents.[9] Moreover, because this solvent dependence (CH_2Cl_2 vs. EtOH) is higher for rosamines than for Rhodamine B, this result demonstrates that the fluorescence of rosamine is more sensitive to changes in the solvent environment than Rhodamine B, which is particularly important because it could be used to detect different polarity environments.

Considering future biolabeling applications of rosamine **2**, studies of its photophysical parameters were performed in MOPS (pH 7.4). The values obtained showed a redshift in the fluorescence intensity emission wavelength; the decrease in ϕ_F value follows the expected order[20] and is consistent with the higher dielectric constant of the solvent (MOPS > EtOH > CH_2Cl_2).

Conclusions

This work has established a simple and efficient protocol for the synthesis of a series of rosamine derivatives bearing different electron donor and sterically hindered groups. The yields were higher and the time of the reactions were considerably shorter when microwave irradiation was used instead of conventional heating.

Different substituents resulted in rosamines with different photophysical parameters, which can be used to study environmental differences such as polarity. Moreover, these rosamines could be engaged in facile coupling reactions with various substrates that may include material surfaces to construct optical devices in a less expensive and more efficient way.

We have also shown that the condensation of 2-naphthaldehyde with 3-(diethylamino)phenol, followed by an oxidation step with chloranil, affords the expected naphthyl derivative and a novel hydroxy analogue. This analogue exhibits colour changes in response to changes in the pH. Further studies concerning the behaviour of this compound with the pH and its potential application as a chemosensor are underway in our laboratory.

Experimental Section

General: Reagents and solvents were purchased as reagent-grade and used without further purification unless otherwise stated. NMR spectra were recorded with a Bruker Avance III 400 spectrometer (400.15 MHz for ^1H and 100.63 MHz for ^{13}C). Chemical shifts (δ) are reported in ppm and coupling constants (J) in Hz; the internal standard was TMS. Unequivocal ^1H assignments were made with the aid of 2D gCOSY ($^1H/^1H$), whereas ^{13}C assignments were made on the basis of 2D gHSQC ($^1H/^{13}C$) and gHMBC experiments (delay for long range J C/H couplings were optimized for 7 Hz). Mass spectra were acquired by the Unidade De Espectrometria De Masas of Santiago de Compostela and microanalyses were acquired by the Unidad De Análisis Elemental of Santiago de Compostela. Flash chromatography was carried out using silica gel Merck (230–400 mesh).

Electronic absorption spectra were recorded with a Varian Cary bio50 spectrophotometer, using quartz cells with 1 cm path length. Rosamine stock solutions were prepared in ethanol. Solutions in a 10^{-5}–10^{-7} M concentration range of the compounds were prepared for molar absorptivity coefficient determination.

Generally, fluorescence quantum yield determination was done as described.[16] Electronic absorption spectra were recorded with a Varian Cary bio50 spectrophotometer, equipped with a Varian Cary single cell Peltier accessory, using quartz cells with 1 cm path length, thermostated at 25 °C. Rosamine stock solutions were prepared in ethanol. Rhodamine B was used as standard for quantum yield determination. Steady-state fluorescence measurements were carried out with a Varian spectrofluorometer, model Cary Eclipse, equipped with a constant-temperature cell holder (Peltier single cell holder) with 5 mm slit width for excitation and emission. All emission spectra were recorded at 25 °C using the maximum λ_{exc} and the appropriate λ_{em} range for each rosamine and considering the different solvents used.

General Procedure for the Synthesis of Rosamines

(a) Conventional Heating: A solution of 3-(diethylamino)phenol (0.28 g, 1.72 mmol) with the appropriate benzaldehyde (0.86 mmol) and *p*TsOH (18.0 mg, 0.10 mmol) in propionic acid (10 mL) was stirred at 65 °C for ca. 16 h. After cooling to room temperature, the mixture was poured into aq. 3 M NaOAc (100 mL). The resulting suspension was extracted with chloroform and the combined organic extracts were dried (Na_2SO_4) and the solvent evaporated. The resulting solid was dissolved in a mixture of methanol (20 mL) and chloroform (20 mL), to which chloranil (0.11 g, 0.43 mmol) was added. The mixture was vigorously stirred for 2 h and concentrated in vacuo. The residue was purified by flash chromatography using a mixture of chloroform/methanol (9:1). The rosamine was then washed with a saturated aqueous solution of NaCl, extracted with chloroform, dried (Na_2SO_4), and the solvent was evaporated in vacuo.

(b) Microwave Irradiation: A solution of 3-(diethylamino)phenol (0.14 g, 0.86 mmol) with the appropriate benzaldehyde (0.43 mmol) and *p*TsOH (10.0 mg, 0.05 mmol) in propionic acid (5 mL) was placed in a 10 mL reaction vial, which was then sealed and placed in the cavity of a CEM microwave reactor. The reaction was irradiated at 80 °C (1 min ramp to 80 °C and 10 min hold at 80 °C, using

100 W maximum power). The work-up and the oxidation reaction were performed by using a similar procedure to that described above.

Rosamine 1: ^{1}H NMR (400.15 MHz, $CDCl_3$): δ = 1.34 (t, J = 7.2 Hz, 12 H, 4× CH_3), 3.67 (q, J = 7.2 Hz, 8 H, 4× CH_2), 6.86 (d, J = 2.4 Hz, 2 H, 4-H and 5-H), 6.95 (dd, J = 9.6, 2.4 Hz, 2 H, 2-H and 7-H), 7.36 (d, J = 9.6 Hz, 2 H, 1-H and 8-H), 7.37–7.39 (m, 2 H, 2′-H and 6′-H), 7.61–7.64 (m, 3 H, 3′-H, 4′-H and 5′-H) ppm. ^{13}C NMR (100.63 MHz, $CDCl_3$): δ = 12.8 (CH_3), 46.4 (CH_2), 96.7 (C-4 and C-5), 113.5 (C-1a and C-8a), 114.4 (C-2 and C-7), 129.1 (C-3′ and C-5′), 129.5 (C-2′ and C-6′), 130.5 (C-4′), 131.9 (C-1′), 132.3 (C-1 and C-8), 155.7 (C-3 and C-6), 157.5 (C-9), 158.2 (C-4a and C-5a) ppm. MS (FAB$^+$): m/z = 399 [M]$^{+\cdot}$. $C_{27}H_{31}ClN_2O{\cdot}2H_2O{\cdot}CHCl_3$ (590.42): calcd. C 56.96, H 6.15, N 4.74; found C 57.08, H 6.20, N 4.77.

Rosamine 2: ^{1}H NMR (400.15 MHz, [D$_4$]CD_3OD): δ = 1.32 (t, J = 7.2 Hz, 12 H, 4× CH_3), 3.69 (q, J = 7.2 Hz, 8 H, 4× CH_2), 6.98 (d, J = 2.4 Hz, 2 H, 4-H and 5-H), 7.05 (dd, J = 9.6, 2.4 Hz, 2 H, 2-H and 7-H), 7.40 (d, J = 9.6 Hz, 2 H, 1-H and 8-H), 7.49 (d, J = 8.4 Hz, 2 H, 2′-H and 6′-H), 8.22 (d, J = 8.4 Hz, 2 H, 3′-H and 5′-H) ppm. ^{13}C NMR (100.63 MHz, [D$_4$]CD_3OD): δ = 12.8 (CH_3), 45.9 (CH_2), 97.4 (C-4 and C-5), 114.4 (C-1a and C-8a), 115.6 (C-2 and C-7), 130.4 (C-2′ and C-6′), 130.7 (C-3′ and C-5′), 133.1 (C-1 and C-8), 135.6 (C-1′), 140.0 (C-4′), 157.2 (C-3 and C-6), 158.8 (C-9), 159.6 (C-4a and C-5a), 173.0 (COOH) ppm. HRMS (ESI): m/z calcd for $C_{28}H_{31}N_2O_3$ [M]$^{+\cdot}$ 443.2330; found 443.2329.

Rosamine 3: ^{1}H NMR (400.15 MHz, $CDCl_3$): δ = 1.34 (t, J = 7.2 Hz, 12 H, 4× CH_3), 3.66 (q, J = 7.2 Hz, 8 H, 4× CH_2), 3.95 (s, 3 H, OCH_3), 6.83 (d, J = 2.4 Hz, 2 H, 4-H and 5-H), 6.96 (dd, J = 9.6, 2.4 Hz, 2 H, 2-H and 7-H), 7.15 (d, J = 8.8 Hz, 2 H, 3′-H and 5′-H), 7.35 (d, J = 8.8 Hz, 2 H, 2′-H and 6′-H), 7.46 (d, J = 9.6 Hz, 2 H, 1-H and 8-H) ppm. ^{13}C NMR (100.63 MHz, $CDCl_3$): δ = 12.7 (CH_3), 46.2 (CH_2), 55.7 (OCH_3), 96.5 (C-4 and C-5), 113.4 (C-1a and C-8a), 114.1 (C-2 and C-7), 114.6 (C-3′ and C-5′), 123.4 (C-1′), 131.4 (C-2′ and C-6′), 132.3 (C-1 and C-8), 155.4 (C-3 and C-6), 157.7 (C-9), 158.1 (C-4a and C-5a), 161.5 (C-4′) ppm. MS (FAB$^+$): m/z = 429 [M]$^{+\cdot}$. $C_{28}H_{33}ClN_2O_2{\cdot}7/2H_2O$: calcd. C 63.68, H 7.63, N 5.30; found C 63.32, H 7.60, N 5.20.

Rosamine 4: ^{1}H NMR (400.15 MHz, $CDCl_3$): δ = 1.33 (t, J = 7.2 Hz, 12 H, 4× CH_3), 3.66 (q, J = 7.2 Hz, 8 H, 4× CH_2), 6.73 (d, J = 2.4 Hz, 2 H, 4-H and 5-H), 6.95 (dd, J = 9.6, 2.4 Hz, 2 H, 2-H and 7-H), 7.28 (d, J = 8.4 Hz, 2 H, 2′-H and 6′-H), 7.31 (d, J = 9.6 Hz, 2 H, 1-H and 8-H), 7.77 (d, J = 8.4 Hz, 2 H, 3′-H and 5′-H) ppm. ^{13}C NMR (100.63 MHz, $CDCl_3$): δ = 12.7 (CH_3), 46.3 (CH_2), 96.7 (C-4 and C-5), 113.1 (C-1a and C-8a), 114.5 (C-2 and C-7), 125.0 (C-4′), 130.7 (C-1′), 131.0 (C-2′ and C-6′), 131.7 (C-1 and C-8), 132.4 (C-3′ and C-5′), 155.6 (C-3 and C-6), 155.7 (C-9), 158.1 (C-4a and C-5a) ppm. MS (FAB$^+$): m/z = 479 [M]$^{+\cdot}$. $C_{27}H_{30}BrClN_2O{\cdot}3/2H_2O$: calcd. C 59.95, H 6.15, N 5.18; found C 60.25, H 6.08, N 5.16.

Rosamine 5: ^{1}H NMR (400.15 MHz, $CDCl_3$): δ = 1.35 (t, J = 7.2 Hz, 12 H, 4× CH_3), 3.69 (q, J = 7.2 Hz, 8 H, 4× CH_2), 6.89 (d, J = 2.4 Hz, 2 H, 4-H and 5-H), 7.03 (dd, J = 9.6, 2.4 Hz, 2 H, 2-H and 7-H), 7.21 (d, J = 9.6 Hz, 2 H, 1-H and 8-H), 7.64 (d, J = 8.6 Hz, 2 H, 2′-H and 6′-H), 8.50 (d, J = 8.6 Hz, 2 H, 3′-H and 5′-H) ppm. ^{13}C NMR (100.63 MHz, $CDCl_3$): δ = 12.9 (CH_3), 46.5 (CH_2), 97.0 (C-4 and C-5), 113.0 (C-1a and C-8a), 115.1 (C-2 and C-7), 124.4 (C-3′ and C-5′), 130.9 (C-2′ and C-6′), 131.4 (C-1 and C-8), 138.6 (C-1′), 149.0 (C-4′), 153.8 (C-9), 155.9 (C-3 and C-6), 157.9 (C-4a and C-5a) ppm. MS (FAB$^+$): m/z = 444 [M]$^{+\cdot}$. $C_{27}H_{30}ClN_3O_3{\cdot}8/3H_2O$: calcd. C 61.41, H 6.74, N 7.96; found C 61.15, H 6.55, N 7.62.

Rosamine 7: ^{1}H NMR (400.15 MHz, $CDCl_3$): δ = 1.33 (t, J = 7.2 Hz, 12 H, 4× CH_3), 3.65 (q, J = 7.2 Hz, 8 H, 4× CH_2), 6.77 (dd, J = 9.6, 2.4 Hz, 2 H, 2-H and 7-H), 6.94 (d, J = 2.4 Hz, 2 H, 4-H and 5-H), 7.05 (d, J = 9.6 Hz, 2 H, 1-H and 8-H), 7.31–7.45 (m, 3 H, 2′-H, 6′-H and 8′-H), 7.57 and 7.69 (2 t, J = 8.0 Hz, 2 H, 3′-H and 7′-H), 8.01 and 8.10 (2 d, J = 8.4 Hz, 2 H, 4′-H and 5′-H) ppm. ^{13}C NMR (100.63 MHz, $CDCl_3$): δ = 12.8 (CH_3), 46.4 (CH_2), 96.9 (C-4 and C-5), 114.3 (C-2 and C-7), 114.4, 125.2, 125.3, 127.1 and 127.8 (C-2′, C-3′, C-6′, C-7′ and C-8′), 128.9 (C-4′ or C-5′), 129.6, 130.6 (C-4′ or C-5′), 131.6, 132.1 (C-1 and C-8), 133.5, 155.8 (C-3 and C-6), 156.7 (C-9), 158.1 (C-4a and C-5a) ppm. MS (FAB$^+$): m/z = 449 [M]$^{+\cdot}$. $C_{31}H_{33}ClN_2O{\cdot}1/2H_2O{\cdot}1/2CHCl_3$: calcd. C 68.32, H 6.28, N 5.06; found C 68.48, H 6.16, N 4.44.

Rosamine 8: ^{1}H NMR (400.15 MHz, CD_3OD): δ = 1.36 (t, J = 7.2 Hz, 12 H, 4× CH_3), 3.68 (q, J = 7.2 Hz, 8 H, 4× CH_2), 6.91 (d, J = 2.4 Hz, 2 H, 4-H and 5-H), 6.98 (dd, J = 9.4, 2.4 Hz, 2 H, 2-H and 7-H), 7.47 (d, J = 9.4 Hz, 2 H, 1-H and 8-H), 7.52 (dd, J = 8.4, 1.6 Hz, 2 H, 3′-H), 7.66–7.73 and 7.95–8.06 (2 m, 5 H, 1′-H, 5′-H, 6′-H, 7′-H and 8′-H), 8.14 (d, J = 8.4 Hz, 1 H, 4′-H) ppm. ^{13}C NMR (100.63 MHz, CD_3OD): δ = 12.8 (CH_3), 46.5 (CH_2), 96.9 (C-4 and C-5), 114.1 (C-1a and C-8a), 114.7 (C-2 and C-7), 126.7 (C-3′), 128.1, 128.50, 128.54, 128.8, 129.4 (C-4′), 129.7, 130.0, 132.9 (C-1 and C-8), 133.2, 134.4, 156.2 (C-3 and C-6), 158.5 (C-9), 158.7 (C-4a and C-5a) ppm. MS (FAB$^+$): m/z = 449 [M]$^{+\cdot}$. $C_{31}H_{33}ClN_2O{\cdot}3/2H_2O{\cdot}1/2CHCl_3$: calcd. C 66.17, H 6.43, N 4.90; found C 66.59, H 6.38, N 4.51.

Rosamine 8a: ^{1}H NMR (400.15 MHz, $CDCl_3$): δ = 1.30 and 1.35 (2 t, J = 7.2 Hz, 12 H, 4× CH_3), 3.62 and 3.50 (2 q, J = 7.2 Hz, 8 H, 4× CH_2), 6.35 (dd, J = 8.8, 2.4 Hz, 1 H, 2-H), 6.74 (d, J = 2.4 Hz, 1 H, 5-H), 6.93 (dd, J = 9.6, 2.4 Hz, 1 H, 7-H), 6.99 (d, J = 8.8 Hz, 1 H, 1-H), 7.21–7.26 (m, 1 H, 4-H), 7.68–7.77 (m, 2 H, 6′-H and 7′-H), 7.71 (d, J = 9.2 Hz, 1 H, 4′-H), 7.89 (d, J = 8.0 Hz, 1 H, 8-H), 7.93–7.95 (m, 1 H, 5′-H or 8′-H), 7.94 (d, J = 9.2 Hz, 1 H, 3′-H), 8.72 (d, J = 8.0 Hz, 1 H, 5′-H or 8′-H) ppm. ^{1}H NMR (400.15 MHz, $CDCl_3$ + TFA): δ = 1.35–1.48 (m, 12 H, 4× CH_3), 3.74–3.85 (m, 8 H, 4× CH_2), 7.18 (d, J = 2.0 Hz, 1 H), 7.26–7.28 (m, 1 H), 7.36 (d, J = 8.8 Hz, 2 H), 7.53–7.55 (m, 2 H), 7.58 (d, J = 8.8 Hz, 1 H), 7.87 (d, J = 9.2 Hz, 1 H), 7.92 (d, J = 7.2 Hz, 1 H), 7.97 (dd, J = 6.8, 7.2 Hz, 1 H), 8.07 (d, J = 8.0 Hz, 1 H), 8.91 (d, J = 8.4 Hz, 1 H), 9.41 (br. s, 1 H) ppm. ^{13}C NMR (100.63 MHz, $CDCl_3$): δ = 13.0 (CH_3), 44.8 and 46.4 (CH_2), 95.7, 100.5, 103.6, 107.8, 115.6, 117.4, 118.7, 122.9, 124.0, 125.5, 126.1, 127.8, 128.1, 131.3, 133.7, 135.2, 136.4, 152.8, 156.1, 158.2, 159.2, 161.0 ppm. MS (FAB$^+$): m/z = 465 [M]$^{+\cdot}$. $C_{31}H_{33}ClN_2O_2{\cdot}2H_2O{\cdot}5/2CHCl_3$: calcd. C 48.16, H 4.77, N 3.35; found C 48.19, H 4.43, N 3.46.

Rosamine 6: A solution of rosamine-NO_2 (250 mg, 0.522 mmol) in ethanol (40 mL) was placed into a hydrogenation vessel. The air was displaced with N_2, a catalytic amount of 10% Pd/C (w/w) was added and the mixture was shaken at room temperature with H_2 at 5 bar for 15 h. The resulting mixture was filtered to remove the catalyst and the solvent was evaporated under reduced pressure. The resulting residue was purified by flash chromatography using a mixture of chloroform/methanol (9:1) as eluent. The rosamine was then washed with a saturated aqueous solution of NaCl, extracted with chloroform, dried (Na_2SO_4), and the solvent was evaporated in vacuo to give rosamine-NH_2 (47.0 mg, 20%). ^{1}H NMR (400.15 MHz, CD_3OD): δ = 1.31 (t, J = 7.2 Hz, 12 H, 4× CH_3), 3.68 (q, J = 7.2 Hz, 8 H, 4× CH_2), 6.91 (d, J = 8.4 Hz, 2 H, 3′,5′-H,), 6.92 (d, J = 2.4 Hz, 2 H, 4,5-H), 7.09 (dd, J = 9.6, 2.4 Hz, 2 H, 2,7-H), 7.26 (d, J = 8.4 Hz, 2 H, 2′,6′-H), 7.65 (d, J = 9.6 Hz, 2 H, 1,8-H) ppm. ^{13}C NMR (100.63 MHz, CD_3OD): δ = 12.3

(CH_3), 46.2 (CH_2), 96.8 (C-4 and C-5), 113.8 (C-1a and C-8a), 114.4 (C-2 and C-7), 114.7 (C-3′ and C-5′), 120.3 (C-1′), 132.6 (C-2′ and C-6′), 133.2 (C-1 and C-8), 152.2 (C-4′), 156.3 (C-3 and C-6), 159.1 (C-4a and C-5a), 160.0 (C-9) ppm. MS (FAB^+): *m*/*z* = 414 $[M]^{+\cdot}$.

Supporting Information (see footnote on the first page of this article): Selected NMR spectra (^1H, ^{13}C, COSY, HSQC, and HMBC) of all synthesized derivatives, ^{13}C NMR spectroscopic data for the 4′-substituted rosamine series **1**–**6**, absorption and fluorescence spectra of rosamines **1**–**8a** in dichloromethane and absorption and fluorescence spectra of rosamine **2** in MOPS.

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[1] a) M. Dutta, D. Das, *Trends Anal. Chem.* **2012**, *32*, 113–132; b) T. Ueno, T. Nagano, *Nat. Methods* **2011**, *8*, 642–645; c) L. M. Wysockia, L. D. Lavis, *Curr. Opin. Cell Biol.* **2011**, *15*, 752–759; d) L. D. Lavis, R. T. Raines, *ACS Chem. Biol.* **2008**, *3*, 142–155.

[2] R. P. Haugland, in: *Handbook of Fluorescent Probes and Research Chemicals* (Eds.: M. T. Z. Spence), 9th ed., *Molecular Probes*, Eugene, OR, USA, **2002**.

[3] J. R. Lakowicz, in: *Principles of Fluorescence Spectroscopy*, 3rd ed., Springer, Berlin, Heidelberg, **2006**.

[4] a) X. Chen, T. Pradhan, F. Wang, J. S. Kim, J. Yoon, *Chem. Rev.* **2012**, *112*, 1910–1956; b) M. Beija, C. A. M. Afonso, J. M. G. Martinho, *Chem. Soc. Rev.* **2009**, *38*, 2410–2433.

[5] a) H. A. S. Al-Shamiri, M. T. H. Abou Kana, *Appl. Phys. B* **2010**, *101*, 129–135; b) C. McDonagh, C. S. Burke, B. D. MacCraith, *Chem. Rev.* **2008**, *108*, 400–422.

[6] T. J. V. Prazeres, A. Fedorov, S. P. Barbosa, J. M. G. Martinho, M. N. Berberan-Santos, *J. Phys. Chem. A* **2008**, *112*, 5034–5039.

[7] a) M. Formica, V. Fusi, L. Giorgi, M. Micheloni, *Coord. Chem. Rev.* **2012**, *256*, 170–192; b) G. Aragay, J. Pons, A. Merkoçi, *Chem. Rev.* **2011**, *111*, 3433–3458; c) L.-J. Fan, Y. Zhang, C. B. Murphy, S. E. Angell, M. F. L. Parker, B. R. Flynn, W. E. Jones Jr., *Coord. Chem. Rev.* **2009**, *253*, 410–422; d) H. N. Kim, M. H. Lee, H. J. Kim, J. S. Kim, J. Yoon, *Chem. Soc. Rev.* **2008**, *37*, 1465–1472.

[8] Y. H. Ahn, J. S. Lee, Y. T. Chang, *J. Comb. Chem.* **2008**, *10*, 376–380.

[9] G.-S. Jiao, J. C. Castro, L. H. Thoresen, K. Burgess, *Org. Lett.* **2003**, *5*, 3675–3677.

[10] a) Y. H. Ahn, J. S. Lee, Y. T. Chang, *J. Am. Chem. Soc.* **2007**, *129*, 4510–4511; b) Y. K. Kim, H.-H. Ha, J.-S. Lee, X. Bi, Y.-H. Ahn, S. Hajar, S. J.-J. Lee, Y.-T. Chang, *J. Am. Chem. Soc.* **2010**, *132*, 567–575; c) J. Li, H.-H. Ha, L. Guo, D. Coomber, Y.-T. Chang, *Chem. Commun.* **2010**, *46*, 2932–2934.

[11] S. Iyoshi, M. Taki, Y. Yamamoto, *Inorg. Chem.* **2008**, *47*, 3946–3948.

[12] a) A. Lobnik, I. Oehme, I. Murkovic, O. S. Wolfbeis, *Anal. Chim. Acta* **1998**, 159–165; b) A. Lobnik, O. S. Wolfbeis, *Sens. Actuators B* **1998**, *51*, 203–207; c) X. Chen, L. Lin, P. Li, Y. Dai, X. Wang, *Anal. Chim. Acta* **2004**, *506*, 9–15.

[13] V. Uryga-Polowy, D. Kosslick, C. Freund, J. Rademann, *Chem. Biol. Chem.* **2008**, *9*, 2452–2462.

[14] R. M. McKinney, F. C. Churchill, *J. Chem. Soc. C* **1970**, *5*, 654–656.

[15] L. C. Abbott, P. MacFaul, L. Jansen, J. Oakes, J. R. Lindsay Smith, J. N. Moore, *Dyes Pigm.* **2001**, *48*, 49–56.

[16] T. Gunaratne, J. R. Challa, M. C. Simpson, *ChemPhysChem* **2005**, *6*, 1157–1163.

[17] K. Kemnitz, K. Yoshihara, *J. Phys. Chem.* **1991**, *95*, 6095.

[18] X.-F. Zhang, *Photochem. Photobiol. Sci.* **2010**, *9*, 1261–1268.

[19] S. Fery-Forgues, D. Lavabre, *J. Chem. Educ.* **1999**, *76*, 1260–1264.

[20] K. G. Casey, E. L. Quitevis, *J. Phys. Chem.* **1988**, *92*, 6590–6594.

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