*Fluorescent Chemosensor*

# A Colorimetric and Ratiometric Fluorescent Chemosensor with Three Emission Changes: Fluoride Ion Sensing by a Triarylborane–Porphyrin Conjugate**

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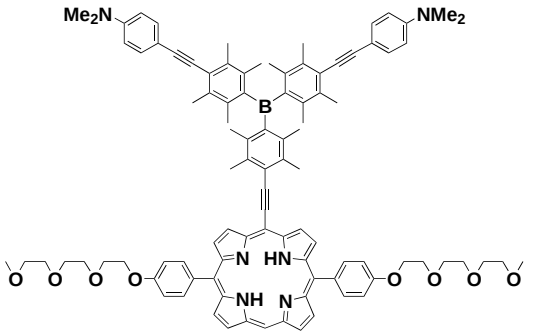
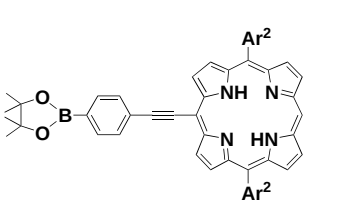
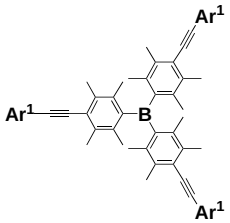
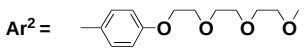
The design of chemosensors for a specific analyte is of great importance for the facile monitoring of analytes.[1,2] Most chemosensors developed so far are colorimetric and/or fluorescent sensors, which efficiently change their photophysical properties ($\lambda_{max}$ shift of the UV/Vis spectrum, change in the quantum yield or emission wavelength, etc) in the presence of the analyte.[1,2] Ratiometric fluorescent probes, in particular, have found widespread use in biological, polymeric, and sensory materials chemistry, where the two emission bands from the covalently linked chromophores, or a chromophore with a dual channel or with a dual signaling pathway, were used to differentiate between the two signals. In the former case, the analyte recognition site was connected to two chromophores (an energy donor and an energy acceptor or chromophores forming an excimer/exciplex) through a covalent bond, and the analyte changes the orientation and/or the dipolar interaction between the chromophores.[2,3] In the latter cases, another signaling channel or signaling pathway is activated in the analyte binding site (which is frequently a part of a chromophore) only when the analyte is bound to the chromophore.[3e,f] In these systems, the chromophores were designed so that the two emission changes would occur in the presence of the analyte. It thus occurred to us that if the analyte induced multiple emissions[4] with different colors from a chemosensor, the perceived color change would be useful not only for the ratiometric method of detection but also for rapid visual sensing. We report herein that a triarylborane–porphyrin conjugate **1** displays colorimetric (purple to green and red to bluish emission) and ratiometric fluorescent responses to fluoride ions with three emission bands at 356, 670, and 692 nm.[5–9]




**1**

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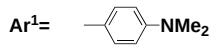


**3**

The triarylborane chromophore (an energy donor: D) and the porphyrin chromophore (an energy acceptor: A) in **1** share a Lewis acidic boron junction that can bind a fluoride ion with subsequent $sp^2$-$sp^3$ hybridization of the boron atom.[10] The change in the hybridization of the boron atom interrupts both the electronic communication and the dipolar interaction between the triarylborane and porphyrin units as well as the internal charge-transfer state between the two chromophores so that each chromophore (D′ and A′) absorbs and emits light independently only in the presence of fluoride ions (Figure 1).[11] This situation could lead to changes in the UV/Vis and fluorescence spectra, from which one could sense the fluoride ion colorimetrically and ratiometrically.

Compound **1** was prepared according to Scheme 1 and identified by $^1$H NMR spectroscopy, MALDI-TOF mass spectrometry, and elemental analysis. Compounds **2** and **3**[10b] were synthesized for control experiments. The Soret band of **1** ([**1**] = 3.00 μM) in THF appears at 436.5 nm, that is, slightly red-shifted relative to that of **2** (430.0 nm), whereas the absorption maxima of the triarylborane moiety (303.0, 322.5, and 392.5 nm) in **1** are identical with those of **3** (Figure 2A). No band attributable to electronic transitions between mixed molecular levels of the triarylborane and porphyrin in **1** was observed. The similarity between the UV/Vis spectrum of **1** and the additive sum of **2** and **3** indicates that the electronic coupling between the two chromophores in the ground state is negligibly small.

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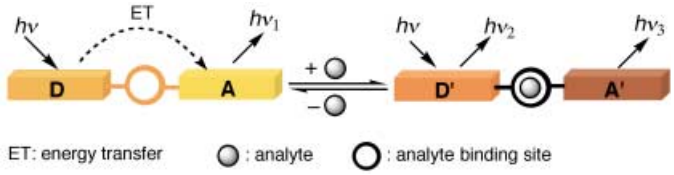



***Figure 1.*** Schematic representation of the different emission processes occurring in **1** on coordination of an analyte.

Compound **1** was titrated with fluoride ions (as a tetrabutylammonium salt, TBAF) in THF at 25 °C and monitored by UV/Vis absorption spectroscopy. As shown in Figure 2 B, the Soret band shifted to a longer wavelength (ca. 480.0 nm). A significant hypsochromic effect was seen upon increasing the concentration of TBAF and this was accompanied by a bathochromic shift (13–20 nm) of the Q band.[12] The hypsochromic and bathochromic shifts of the Soret and Q bands, respectively, were also observed when control compound **2** was titrated with TBAF in THF. Recently, Crossley and Johnston[13] reported that a change in the conjugation in a laterally expanded porphyrin through a redox-induced reaction of a linker results in a similar significant hypsochromic effect of the Soret band together with the bathochromic shift of the Q band. In the case of compound **1**, coordination of a fluoride ion, which generates anionic charge on the boron atom, should change the conjugation or the dipole moment of the durylborane-

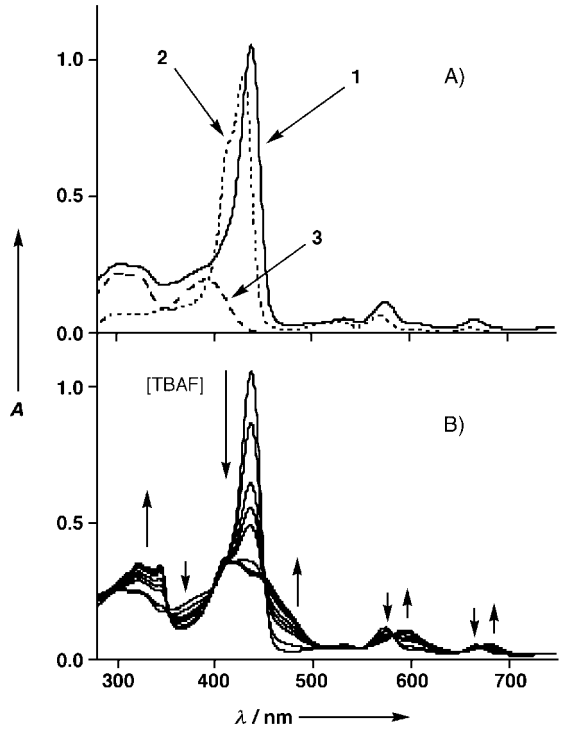
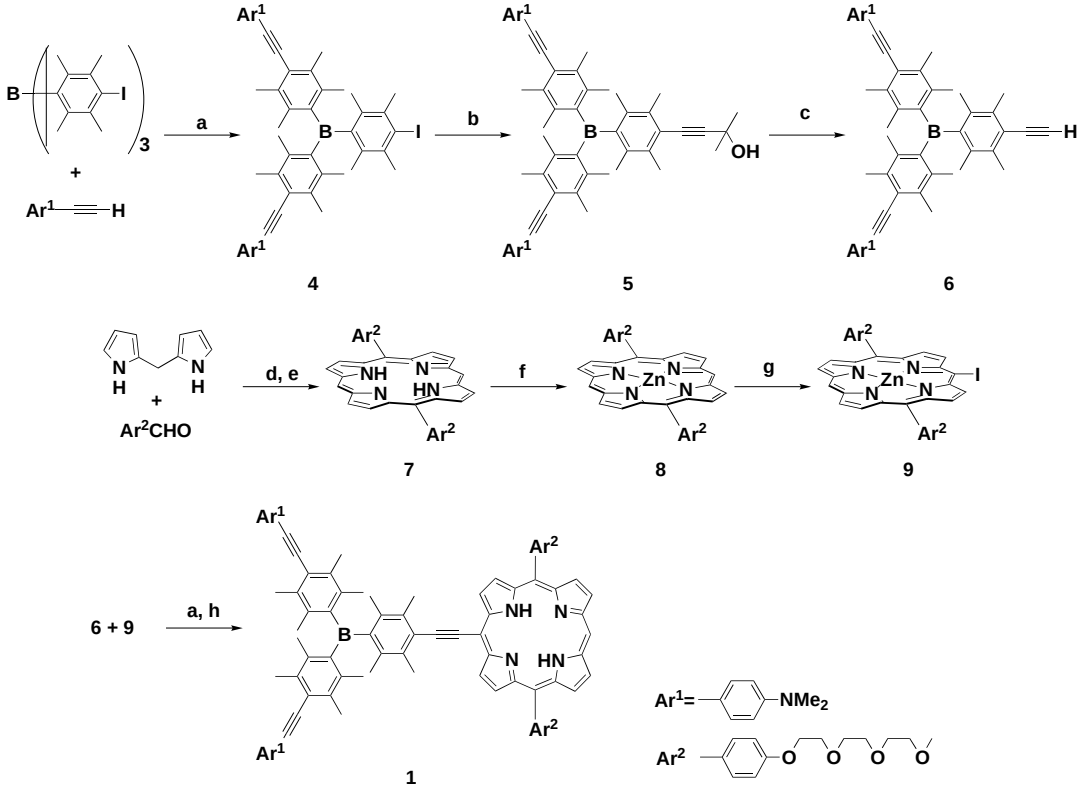



***Figure 2.*** A) UV/Vis absorption spectra of compounds **1**–**3** (3.0 μM) in THF and B) dependence of the UV/Vis spectra on the concentration of fluoride ions; [**1**] = 3.0 μM, [TBAF] = 0–0.10 mM, in THF at 25 °C.




***Scheme 1.*** Reaction and conditons: a) $[Pd(PPh_3)Cl_2]$, CuI, THF, $(iPr)_2NH$; b) 3-methyl-1-butyn-3-ol, $[Pd(PPh_3)_2Cl_2]$, CuI, THF, $(iPr)_2NH$; c) NaOH, toluene; d) TFA, $CH_2Cl_2$; e) DDQ, $CH_2Cl_2$; f) $Zn(OAc)_2$, $CHCl_3$, MeOH, g) $AgPF_6$, $I_2$, $CHCl_3$, pyridine; h) TFA, $CH_2Cl_2$. DDQ = 2,3-dichloro-5,6-dicyano-1,4-benzoquinone, TFA = trifluoroacetic acid.

linked porphyrin moiety. In contrast to the porphyrin moiety, a decrease (to 392.5 nm) and an increase (to 323.0 and 343.4 nm) in the intensities of the triarylborane absorption bands in **1** were observed. These trends are the same as those observed for **3**, and the result is interpreted as a loss of π conjugation through the boron atom.[9] These results support the view that the two chromophores, the aryl borane (D′) and the porphyrin (A′), generate their absorption bands independently in the presence of fluoride ions. The change in the absorption spectra resulted in a change in the color of the solution from purple to green (Figure 3). The stoichiometry in the reaction between **1** and TBAF was confirmed to be 1:1

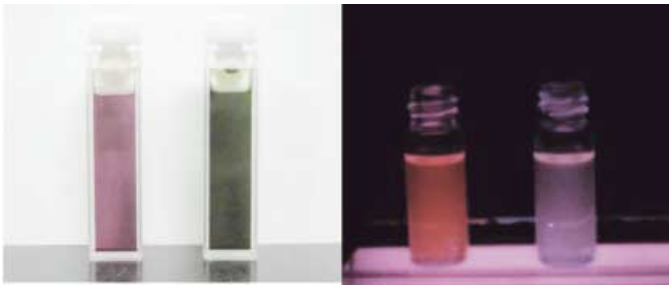


***Figure 3.*** Color changes observed in samples of **1** and TBAF in THF. Left to right: **1**, **1**·TBAF, visible emission of **1**, and emission of **1**·TBAF.

from a plot of the mole ratio versus absorption. A standard curve-fitting method was utilized for the $A_{436.5}$ versus [TBAF] plot to evaluate the association constant for the 1:1 complex, which was estimated to be 99700 $M^{-1}$. This value is comparable with those previously determined for triarylboranes and fluoride ions.[10] No change in the Soret band, Q band, or the tridurylborane absorption was observed upon exposure of **1** to larger halides, acetate, and hydroxide ions. Apparently, only the smaller anion, the fluoride ion, can fit in the space around the triduryl-surrounded Lewis acidic boron atom.

The coordination of the fluoride ion to the boron center was confirmed by NMR spectroscopy. A *meso*-H proton signal and pyrrole β-proton signals of the porphyrin unit as well as methyl proton signals of the duryl group are shifted to higher magnetic fields in the $^1$H NMR spectra of [**1**]:[TBAF] = 1:0 and 1:2 in [$D_8$]THF at 25 °C ([**1**] = 1.00 mM; see the Supporting Information). A $^{19}$F signal was shifted to a lower magnetic field ($\Delta\delta = 8.40$ ppm) relative to free TBAF in the $^{19}$F NMR spectra as a result of its coordination to the boron center (see the Supporting Information).

The fluorescence spectrum of **1** (0.5 μM) in THF was recorded with excitation at an isosbestic point (294 nm, see the Supporting Information) where the selectivity of the triarylborane absorption over that of the porphyrin ring was 3:1, as estimated from the absorbance of compounds **2** and **3**. Compound **1** gives the porphyrin emission band (670 nm) without the triarylborane emission band that should appear at 515 nm, as seen in the emission spectrum of **3** (see the Supporting Information). The same spectrum was obtained in a nonpolar solvent (benzene). The intermolecular energy transfer is negligible at such a low concentration, since the fluorescence spectrum for an equimolar mixture (0.5 μM each) of **2** and **3** was equivalent to the sum of the two individual fluorescence spectra. Furthermore, the excitation spectrum of **1** shows an intense triarylborane absorption band as well as the porphyrin band. The findings clearly show that efficient transfer of energy from the triarylborane to the porphyrin chromophore takes place in the absence of fluoride ions.

The addition of fluoride ions to a solution of **1** in THF results in a substantial increase in the intensity of the two emission bands at 356 nm and 692 nm along with a decrease in the intensity of the emission band at 670 nm (Figure 4). The

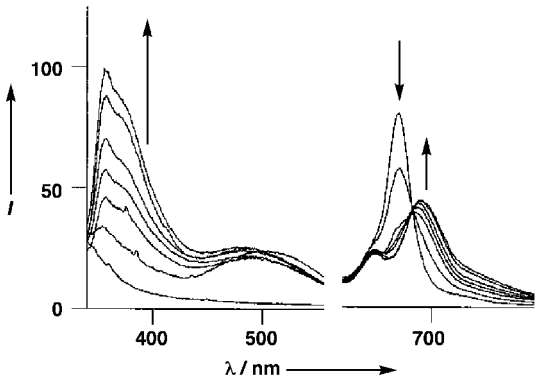



***Figure 4.*** Changes in the emission spectra upon addition of TBAF to solutions of THF at 25 °C; excitation wavelength 294 nm.

appearance of the emission band at 356 nm was the same response to fluoride ions as that of **3**. The longer wavelength shift of 22 nm in the porphyrin emission can be attributed to the lower energy of the Q band in the ground state. A visible change in the emission from a red to bluish color was also observed (Figure 3). Compound **1** showed a ratiometric response to fluoride ions at two different wavelengths (356 and 692 nm) when normalized against the emission at 670 nm (see the Supporting Information). The excitation spectra of **1** with added fluoride ions revealed that the absorbance of the aryl borane still participates in the appearance of the porphyrin emission at 692 nm. This observation means that the energy transfer from the aryl borane moiety to the porphyrin unit occurs even after complexation with a fluoride ion.[14] The fluorescence decay of the emission band of the aryl borane moiety in **1** was evaluated to be shorter than 100 ps (515 nm) and 0.53 ns (380 nm) without and with the guest fluoride ion, respectively. A shorter lifetime at the 515 nm emission without fluoride ions than that of **3** (4.52 ns) could be attributed to an efficient Dexter-type energy transfer from the aryl borane to the porphyrin moiety in **1**. In the presence of fluoride ions, the lifetime of 0.53 ns is similar to that of the **3**·fluoride ion complex (monitored at 380 nm, 0.39 ns). This finding together with the excitation spectrum of the **1**·fluoride ion complex enables one to suppose that energy transfer from the aryl borane moiety to the porphyrin unit in **1** takes place to some extent in the presence of fluoride ions. The result suggests, therefore, that the guest fluoride ion can switch the energy-transfer pathway to make it possible to monitor the

binding event through the changes in the three emissions (Figure 5).

In conclusion, we have demonstrated that **1** displays a colorimetric (purple to green and red to bluish emission) and a ratiometric response (by utilizing changes in three emissions) that are useful for the detection of fluoride ions. The mechanism for the increase in the two emission bands and not the third emission band was assumed by the finding that the coordination of a fluoride ion to the boron center in **1** caused perturbation in the energy transfer pathway and the π conjugation. Thus, two chromophores sharing a recognition unit linked though a conjugate spacer would become a versatile molecular design scheme to achieve the monitoring of multiple emissions useful for signal differentiation.

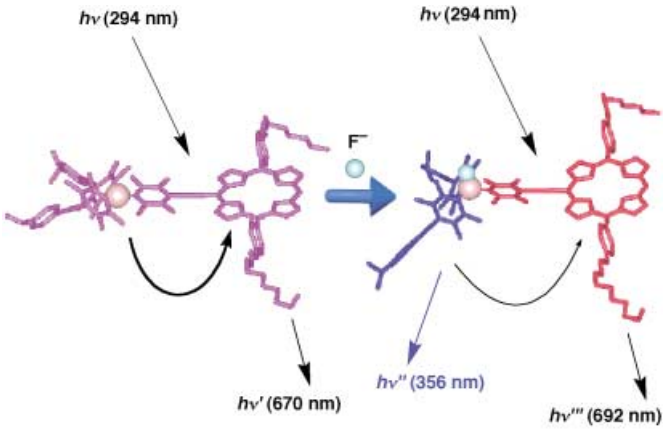



***Figure 5.*** Effects of the coordination of a fluoride ion on the emissions from **1** on excitation at 294 nm.

## *Experimental Section*

All starting materials and solvents were purchased from Tokyo Kasei Chemicals or Wako Chemicals, and used as received. The $^1$H NMR spectra were recorded either on a Brucker AC 250 (250 MHz) or Brucker DRX 600 (600 MHz) spectrometer. Chemical shifts are reported in ppm downfield from tetramethylsilane as the internal standard. Mass spectral data were obtained by using a Perseptive Voyager RP MALDI-TOF spectrometer. UV/Vis and fluorescent spectra were recorded with a Shimadzu UV-2500 PC and Hitachi F-4500 spectrophotometer.

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**Keywords:** fluorescent probes · fluorides · molecular recognition · porphyrinoids · sensors

[1] a) A. P. de Silva, D. B. Fox, A. J. M. Huxley, T. S. Moody, *Coord. Chem. Rev.* **2000**, *205*, 41; b) L. Prodi, F. Bolletta, M. Montaliti, N. Zaccheroni, *Coord. Chem. Rev.* **2000**, *205*, 59; c) V. Amendola, L. Fabbrizzi, M. Licchelli, C. Mangano, P. Pallavicini, L. Parodi, A. Poggi, *Coord. Chem. Rev.* **2000**, *192*, 649; d) J. P. Desvergne, A. W. Czarnik, *NATO ASI Ser. Ser. C* **1997**, *492*.

[2] J. R. Lakowicz, *Priciples of Fluorescence Spectroscopy*, 2nd ed., Plenum, New York, **1999**.

[3] For selected recent examples, see a) S. Maruyama, K. Kikuchi, T. Hirano, Y. Urano, T. Nagano, *J. Am. Chem. Soc.* **2002**, *124*, 10650; b) J. Raker, T. E. Glass, *J. Org. Chem.* **2002**, *67*, 6113; c) F. Würthner, S. Ahmed, C. Thalacker, T. Debaerdemaeker, *Chem. Eur. J.* **2002**, *8*, 4742; d) J. Kim, D. T. McQuade, A. Rose, Z. Zhu, T. M. Swager, *J. Am. Chem. Soc.* **2001**, *123*, 11488; e) J. V. Mello, N. S. Finney, *Angew. Chem.* **2001**, *113*, 1584; *Angew. Chem. Int. Ed.* **2001**, *40*, 1536; f) K. Choi, A. D. Hamilton, *Angew. Chem.* **2001**, *113*, 4030; *Angew. Chem. Int. Ed.* **2001**, *40*, 3912; g) J.-S. Yang, C.-S. Lin, C.-Y. Hwang, *Org. Lett.* **2001**, *3*, 889; h) S. Deo, H. A. Godwin, *J. Am. Chem. Soc.* **2000**, *122*, 174; i) A. P. de Silva, J. Eilers, G. Zlokarnik, *Proc. Natl. Acad. Sci. USA* **1999**, *96*, 8336.

[4] a) Y.-A. Lee, J. E. McGarrah, R. J. Lachicotte, R. Eisenberg, *J. Am. Chem. Soc.* **2002**, *124*, 10662; b) H. Fu, B. H. Loo, D. Xiao, R. Xie, X. Ji, J. Yao, B. Zhang, L. Zhang, *Angew. Chem.* **2002**, *114*, 1004; *Angew. Chem. Int. Ed.* **2002**, *41*, 962.

[5] For reviews on anion receptors, see a) P. D. Beer, P. A. Gale, *Angew. Chem.* **2001**, *113*, 502; *Angew. Chem. Int. Ed.* **2001**, *40*, 486; b) P. A. Gale, *Coord. Chem. Rev.* **2000**, *199*, 181; c) T. S. Snoeden, E. V. Anslyn, *Curr. Opin. Chem. Biol.* **1999**, *3*, 740; d) P. D. Beer, *Acc. Chem. Res.* **1998**, *31*, 71; d) F. P. Schmidtchen, M. Berger, *Chem. Rev.* **1997**, *97*, 1609; e) J. Scheerder, J. F. J. Engbersen, D. N. Reinhoudt, *Recl. Trav. Chim. Pays-Bas* **1996**, *115*, 307.

[6] For recent anion sensors, see a) P. Piatek, J. Jurczak, *Chem. Commun.* **2002**, 2450; b) J.-H. Liao, C.-Y. Chen, J.-M. Fang, *Org. Lett.* **2002**, *4*, 561; c) A. Ojida, Y. Mito-oka, M. Inoue, I. Hamachi, *J. Am. Chem. Soc.* **2002**, *124*, 6256; d) J. R. Blas, M. Marquez, J. L. Sessler, F. J. Luque, M. Orozco, *J. Am. Chem. Soc.* **2002**, *124*, 12796; e) J. L. Sessler, H. Maeda, T. Mizuno, V. M. Lynch, H. Furuta, *Chem. Commun.* **2002**, 862; f) K. Choi, A. D. Hamilton, *J. Am. Chem. Soc.* **2001**, *123*, 2456; g) D. H. Lee, K. H. Lee, J. I. Hong, *Org. Lett.* **2001**, *3*, 5; h) P. D. Beer, N. Berry, M. G. B. Drew, O. D. Fox, M. E. Padilla-Tosta, S. Patell, *Chem. Commun.* **2001**, 199; i) M. J. Deetz, M. Shang, B. D. Smith, *J. Am. Chem. Soc.* **2000**, *122*, 6201; j) Y. Kubo, M. Tsukahara, S. Ishihara, S. Tokita, *Chem. Commun.* **2000**, 653; k) S. Sasaki, M. Mizuno, K. Naemura, Y. Tobe, *J. Org. Chem.* **2000**, *65*, 275; l) H. Miyaji, P. Anzenbachlar, Jr., J. L. Sesslar, E. R. Bleasdale, P. A. Gale, *Chem. Commun.* **1999**, 1723.

[7] Receptors for fluoride ions are of special importance for monitoring fluoride metabolism in nature, the analysis of drinking water, and the detection of chemical warfare agents.[9]

[8] For recent fluoride chemosensors, see a) J. L. Sessler, H. Maeda, T. Mizuno, V. M. Lynch, H. Furuta, *J. Am. Chem. Soc.* **2002**, *124*, 13474; b) S. Aldridge, C. Bresner, I. A. Fallis, S. J. Colesb, M. B. Hursthouseb, *Chem. Commun.* **2002**, 740; c) S. K. Kim, J. Yoon, *Chem. Commun.* **2002**, 770; d) T. Mizuno, W.-H. Wei, L. R. Eller, J. L. Sesslar, *J. Am. Chem. Soc.* **2002**, *124*, 1134; e) T. Gunnlaugsson, A. P. Davis, M. Glynn, *Chem. Commun.* **2001**, 2556; f) K. H. Lee, H.-Y. Lee, D. H. Lee, J.-I. Hong, *Tetrahedron Lett.* **2001**, *42*, 5447; g) H. Furuta, H. Maeda, A. Osuka, *J. Am. Chem. Soc.* **2001**, *123*, 6435; h) M. Takeuchi, T. Shioya, T. M. Swager, *Angew. Chem.* **2001**, *113*, 3476; *Angew. Chem. Int. Ed.* **2001**, *40*, 3372; i) C. R. Cooper, N. Spencer, T. D. James, *Chem. Commun.* **1998**, 1365.

[9] H. Sohn, S. Létant, M. J. Sailor, W. C. Trogler, *J. Am. Chem. Soc.* **2000**, *122*, 5399.

[10] a) S. Yamaguchi, S. Akiyama, K. Tamao, *J. Am. Chem. Soc.* **2000**, *122*, 6335; b) S. Yamaguchi, T. Shirasaka, K. Tamao, *Org. Lett.* **2000**, *2*, 4129; c) S. Yamaguchi, S. Akiyama, K. Tamao, *J. Am. Chem. Soc.* **2001**, *123*, 11372; d) S. Yamaguchi, T. Shirasaka, S. Akiyama, K. Tamao, *J. Am. Chem. Soc.* **2002**, *124*, 8816.

[11] The change in electron-transfer efficiency caused by the binding of the fluoride ion to a boronate ester has already been reported, see H. Shiratori, T. Ohno, K. Nozaki, A. Osuka, *Chem. Commun.* **1999**, 2181.

  

[12] It was confirmed by $^1$H NMR spectroscopy that **1** does not aggregate in THF both in the presence and in the absence of TBAF.
[13] M. J. Crossley, L. A. Johnston, *Chem. Commun.* **2002**, 1122.
[14] The emisson intensity of **1** excited at 294 nm is 13 (at 670 nm) and 16 (at 692 nm) times larger than that of **2** in the absence and in the presence of fluoride ions, respectively, if it is assumed that the energy transfer occurs from the aryl borane moiety to the porphyrin ring.

  