

# Exploring *N*-BODIPYs as Privileged Scaffolds to Build Off/On Fluorescent Sensors by PET †

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**Abstract:** A new *N*-boron dipyrromethene (*N*-BODIPY) substituted with a crown ether moiety has been synthesized by reaction of an *F*-BODIPY with a crown-ether-substituted bis(sulfonamide). The workability of this *N*-BODIPY as an off/on sensor for cations by modulation of a photoinduced electron transfer (PET) is explored. The new *N*-BODIPY demonstrates the possibilities of functionalization of these still unexplored but promising dyes.

**Keywords:** BODIPYs; *N*-BODIPYs; fluorescent sensors; off/on sensors; photoinduced electron transfer

## 1. Introduction

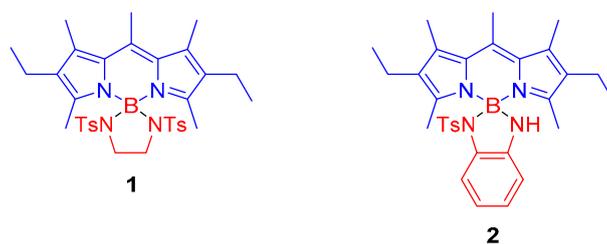
The development of chemosensors for the detection and quantification of analytes (cations, anions, neutral molecules, etc.) is necessary in different fields such as biology, chemistry, pharmacology, materials science, environmental science, etc. Over the traditional tools for the detection of analytes (mass spectrometry, high performance liquid chromatography, atomic absorption spectroscopy, or nuclear magnetic resonance), which require laborious procedures and expensive equipment, fluorescence spectroscopy offers a simpler and more affordable alternative. It is especially important for sensing analytes inside living cells, being minimally disruptive to cells. Together with their high sensitivity and specificity, fluorescent chemosensors have the ability to be used for temporal and spatial sampling for in vivo applications, making it possible to simultaneously visualize the analyte in all regions of a living cell by microscopy imaging [1,2].

A fluorescent chemosensor binds the analyte forming stable chemical systems in which changes in the fluorescent properties of the sensor are triggered. The mechanism of most fluorescent chemosensors is based on fluorescent quenching (off/on sensors), although for the majority of practical problems, enabling the fluorescence by acting with the analyte offers a better solution [1]. One of the photophysical mechanisms behind the analytical detection of analytes by fluorescent chemosensors is photoinduced electron transfer (PET), where binding with the analyte induces (on/off sensor) or inhibits (off/on sensor) a PET in the sensor, quenching or recovering, respectively, its fluorescence [2,3].

In this context, BODIPYs (boron dipyrromethenes; 4-bora-3a,4a-diaza-s-indacenes) offer a good platform to build fluorescent sensors, owing to the excellent photophysical properties of these

outstanding dyes. On the basis of these properties, BODIPY dyes have found wide application in the development of photonic tools (e.g., lasers dyes, chemical sensors, bioimaging probes, photodynamic therapy agents, sunlight harvesting dyes, etc.) [4,5]. Thus, the BODIPY chromophores usually emit a relatively sharp fluorescent peak with high fluorescence quantum yield and a high molar absorption coefficient [4,5]. They also have good solubility, chemical robustness, thermal and photochemical stability, and are one of the few structures that can fluoresce over the entire visible and in the near-IR electromagnetic spectrum, if they are modified accordingly [5–7].

In addition to the functionalization of the dipyrin core, BODIPY dyes can be functionalized at the boron, by substituting the fluorine atoms by *O*-, *C*- or *N*-moieties. This position has usually been chosen to improve interesting physical and chemical properties, such as water solubility for biological applications, or to achieve enhanced photostability for lasing, or to chirally perturb the BODIPY chromophore and enable chiroptical properties [8–11]. In this context, only *C*-BODIPYs [12,13] and *O*-BODIPYs [9–11,13] (i.e., BODIPYs involving B–C or B–O bonds, respectively, instead of B–F bonds) were available, being the elusive *N*-BODIPYs (involving B–N bonds, for example, **1** and **2** in Figure 1) reported recently by our group [14].

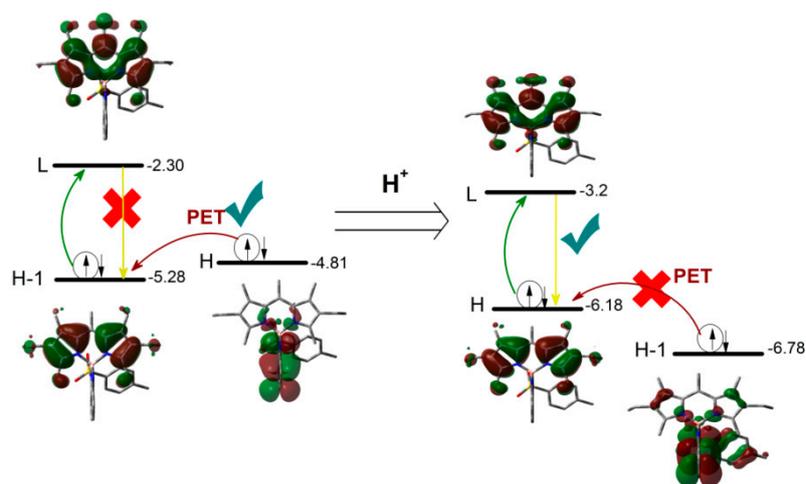


**Figure 1.** Examples of the first *N*-boron dipyrromethenes (*N*-BODIPYs) developed recently by us. Ts, tosylsulfonamide.

*N*-BODIPYs retain the excellent properties of related *F*-BODIPYs and have the advantage, over *O*-BODIPYs, that up to four different moieties, instead of two, can be placed near the BODIPY chromophore, due to the bonding features of the nitrogen atom in comparison with oxygen. This opens up versatile and multiple functionalization possibilities to modulate key properties in BODIPY dyes [14].

As an example of the possibilities of the *N*-BODIPY family, we demonstrated that it is possible to properly introduce certain electron-rich groups (e.g., the *o*-phenylene ring in **2** in Figure 1) triggering an interesting reductive PET that quenches the BODIPY fluorescence. DFT calculations demonstrated that, after the excitation of the BODIPY chromophore, an electron transfer (PET) from the sulfonamide moiety to the semi-vacant orbital of the BODIPY core is thermodynamically feasible (see Figure 2). Such a reductive PET avoids radiative deactivation of the BODIPY, explaining the almost negligible fluorescence response of this *N*-BODIPY ( $\phi$  0.4% in ethyl acetate). The improvement of the fluorescent quantum yield in polar protic solvents, such as 2,2,2-trifluoroethanol ( $\phi$  13.1%), with an ability to interact with the amine lone pairs to reduce its electron-donor character, supports PET as the quenching mechanism. Thus, *o*-phenylene-based *N*-BODIPY **2** acts as a fluorescence off/on sensor for proton, and also for some metal ions such as  $\text{Co}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ , or  $\text{Cr}^{3+}$  [14].

These previous results show that *N*-BODIPYs based on *o*-phenylene could be an excellent platform for the development of off/on sensors. The starting hypothesis is to incorporate, into the *o*-phenylene ring, a functional group that interacts with metal cations, in a way that this interaction decreases the electron-donor character of the nitrogen residue. The nitrogen being less electron donating, the PET would be cancelled or diminished, and therefore the BODIPY chromophore would recover its characteristic fluorescence.



**Figure 2.** (Left) Computationally aided energy diagram (in eV) of the molecular orbitals involved in the absorption and fluorescence electronic transitions, explaining the photoinduced electron transfer (PET) in **2**. (Right) Quenching PET pathway after protonation.

## 2. Materials and Methods

### 2.1. Synthetic Procedures

**General** Common solvents were dried and distilled by standard procedures. All starting materials and reagents were obtained commercially and used without further purifications. Elution flash chromatography was conducted on silica gel (230 to 400 mesh ASTM). Thin layer chromatography (TLC) was performed on silica gel plates (silica gel 60 F254, supported on aluminum). The NMR spectra were recorded at 20 °C, and the residual solvent peaks were used as internal standards. The NMR signals are given in ppm. DEPT-135 NMR experiments were used for the assignment of the type of carbon nucleus (C, CH, CH<sub>2</sub>, and CH<sub>3</sub>). The FTIR spectra were recorded from neat samples using ATR technique. IR bands are given in cm<sup>-1</sup>.

**Synthesis of 3b.** Under argon atmosphere, BCl<sub>3</sub> (1.0 M in CH<sub>2</sub>Cl<sub>2</sub>, 0.3 mL, 0.30 mmol) was dropwise added over a solution of commercial 2,6-diethyl-1,3,5,7,8-pentamethyl-*F*-BODIPY (PM567; 50 mg, 0.16 mmol) in dry CH<sub>2</sub>Cl<sub>2</sub> (8 mL). The reaction mixture was stirred for 1 h (disappearance of starting BODIPY was monitored by TLC). Then, triethylamine (127 mg, 1.26 mmol) was added, followed by **11b** (306 mg, 0.47 mmol) and the resulting mixture stirred for 2 h (the reaction progress was monitored by TLC). The reaction mixture was filtered through celite and washed with CH<sub>2</sub>Cl<sub>2</sub> and the solvent was evaporated under reduced pressure. The reaction crude was purified by flash chromatography (silica gel, EtOAc/MeOH 99:1). **3b**: 65 mg (45%). Red solid. *R*<sub>f</sub> = 0.23 (EtOAc/MeOH 99:1). <sup>1</sup>H NMR (CDCl<sub>3</sub>, 700 MHz) δ 7.05 (s, 2H); 4.16 (m, 4H); 3.92 (m, 4H); 3.77 (m, 8H); 2.72 (m, 4H); 2.68 (s, 3H); 2.38 (q, *J* = 7.5 Hz, 4H); 2.37 (s, 6H); 2.04 (s, 6H); 1.69 (m, 4H); 1.63 (s, 7H); 1.25 (m, 12H); 1.21 to 1.15 (m, 12H); 0.98 (t, *J* = 7.5 Hz, 6H); and 0.85 (t, *J* = 7.2 Hz, 6H) ppm. <sup>13</sup>C NMR (CDCl<sub>3</sub>, 176 MHz) δ 151.8 (C); 144.3 (C); 140.6 (C); 137.7 (C); 133.4 (C); 133.3 (C); 127.5 (C); 102.0 (CH); 71.0 (CH<sub>2</sub>); 70.8 (CH<sub>2</sub>); 70.3 (CH<sub>2</sub>); 70.0 (CH<sub>2</sub>); 53.1 (CH<sub>2</sub>); 31.8 (CH<sub>2</sub>); 29.8 (CH<sub>2</sub>); 29.11 (CH<sub>2</sub>); 29.09 (CH<sub>2</sub>); 28.6 (CH<sub>2</sub>); 22.8 (CH<sub>2</sub>); 22.7 (CH<sub>2</sub>); 17.8 (CH<sub>3</sub>); 17.4 (CH<sub>2</sub>); 15.2 (CH<sub>3</sub>); 15.1 (CH<sub>3</sub>); 14.2 (CH<sub>3</sub>); and 13.0 (CH<sub>3</sub>) ppm. <sup>11</sup>B NMR (CDCl<sub>3</sub>, 160 MHz) δ 0.92 (s) ppm. FTIR ν 2922, 1718, 1561, 1464, 1196, and 985 cm<sup>-1</sup>.

### 2.2. Photophysical Properties

Diluted dye solutions (around 2 × 10<sup>-6</sup> M) were prepared by adding the corresponding solvent (spectroscopic grade) to the residue from the adequate amount of a concentrated stock solution in acetone, after vacuum evaporation of this solvent. The cation sensing experiments were conducted by adding controlled and small amounts (to ensure the water-ethanol miscibility) of concentrated aqueous solutions of the cations to diluted ethanolic solutions of the dye. UV-Vis absorption and

steady-state fluorescence were recorded on a Varian model CARY 4E spectrophotometer and an Edinburgh Instruments spectrofluorometer (model FLSP920, Edinburgh Instruments: Edinburgh, UK), respectively, using 1 cm path length quartz cuvettes. The emission spectra were corrected from the monochromator wavelength dependence, the lamp profile, and the photomultiplier sensitivity. Fluorescence quantum yields ( $\phi$ ) were calculated upon excitation at 500 nm using commercial PM567 ( $\phi^r = 0.84$  in ethanol) as the reference. The values were corrected by the refractive index of the solvent.

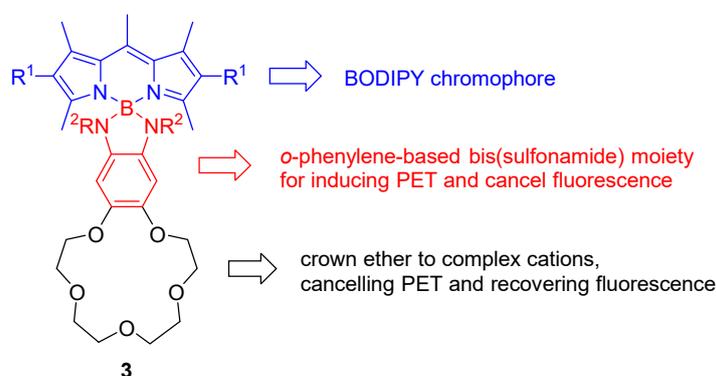
### 2.3. Computational Methods

Ground state geometries were optimized at the density functional theory (DFT) level using the B3LYP hybrid method and the double valence basis set adding a polarization function (6 to 31 g\*). The energy minimization was conducted without any geometrical restriction and the geometries were considered as energy minimum when the corresponding frequency analysis did not give any negative value. The theoretical calculations were carried out using the Gaussian 16 implemented in the computational cluster provided by the SGIker resources of the UPV/EHU.

## 3. Results and Discussion

### 3.1. Synthetic Development

As a proof of concept, we designed molecule **3**, shown in Figure 3. This *N*-BODIPY fulfills the following features considered in the initial hypothesis for the development of off/on sensors: (1) BODIPY chromophore; (2) *o*-phenylene diamino moiety attached to the boron, which should cancel the fluorescence of the BODIPY by PET; (3) a crown ether attached to the phenylene ring for cation recognition (e.g., sodium cations) [15]; (4) possibility of inactivating the PET when the crown ether binds cations, owing to the diminished electron donor capability of the crown ether-substituted phenylene ring; and (5) synthetic accessibility through the methodology developed by us for *N*-BODIPYs, leading to low-cost sensors [14].

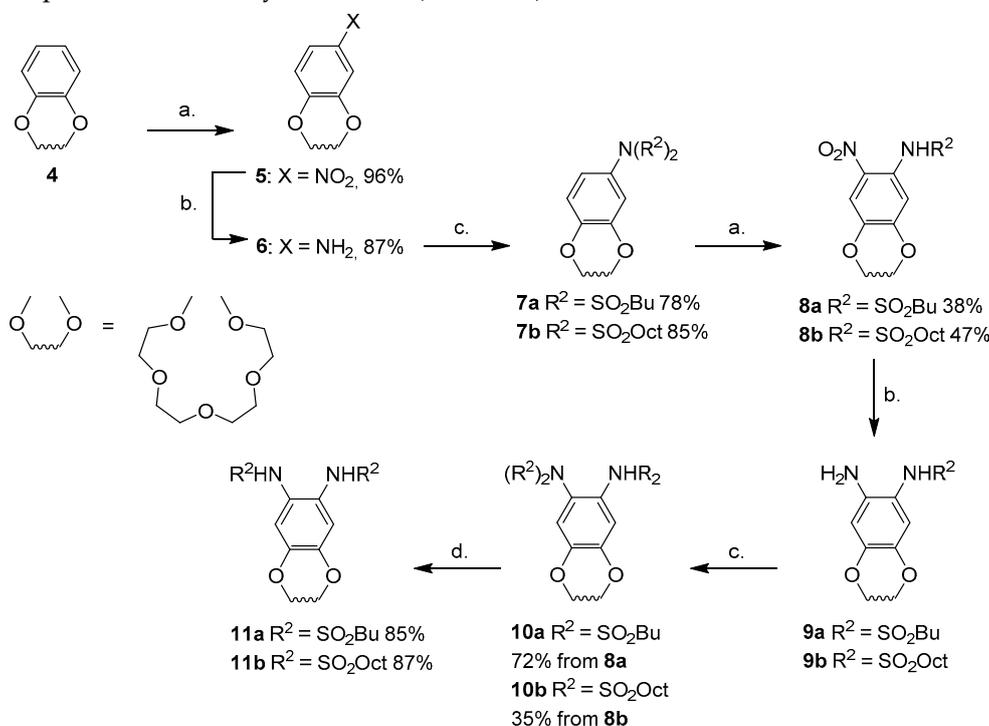


**Figure 3.** Design of off/on sensors based on *N*-BODIPY. R<sup>1</sup>, alkyl and R<sup>2</sup>, alkanesulfonyl.

As we established earlier [14], *N*-BODIPYs can be prepared from *F*-BODIPYs and sulfonamides by nucleophilic substitution of fluorine. The use of sulfonamides as nitrogen moieties is important for the stability of the final *N*-BODIPY [14]. Thus, as starting materials for the synthesis of **3**, 2,6-diethyl-4,4-difluoro-1,3,5,7,8-pentamethylBODIPY (known as PM567) was chosen as the starting *F*-BODIPY because of its electron richness (needed to stabilize the *N*-BODIPY [14]) and its commercial availability. As the nitrogen moiety, we chose bis(sulfonamide) **11a** (see Scheme 1), which includes a benzo-15-crown-5 and butyl substituents to get the solubility necessary for the BODIPY-sulfonamide coupling reaction.

Bis(sulfonamide) **11a** is not commercially available and it was prepared by the synthetic route shown in Scheme 1, based on the one developed by Krause for the synthesis of 15,16-diaminobenzo-15-crown-5 [16]. Thus, amino derivative **6** was obtained by standard nitration, followed by reduction of the nitro group, of commercial benzo-15-crown-5 (**4**) [16]. Then, **6** was subjected to sulfonylation

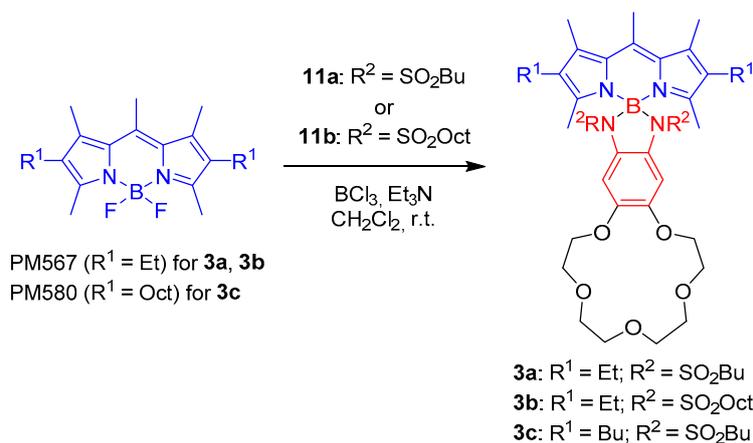
with butanesulfonyl chloride, but the sulfonimide **7a**, instead of the expected sulfonamide was obtained. Sulfonimide **7a** was used directly for the next *o*-nitration, losing one butanesulfonyl chain in the reaction medium, to our satisfaction. Subsequent reduction of the nitro group of **8a** and sulfonylation of the newly formed amino group in **9a** led to a new sulfonimide **10a**, that could be finally transformed in the target bis(sulfonamide) **11a** by treatment with tetrabutylammonium fluoride (TBAF) [17]. Thus, bis(sulfonamide) **11a** was prepared from benzo-15-crown-5 (**4**) in seven reaction steps with an overall yield of 15% (Scheme 1).



**Scheme 1.** Synthetic route to *o*-phenylene-based bis(sulfonamide)s functionalized with crown ether. Reagents and conditions: (a) HNO<sub>3</sub>, AcOH, CHCl<sub>3</sub>, 0 °C; (b) H<sub>2</sub>, H-Cube®, Pd(C) 10%, EtOAc, r.t.; (c) butanesulfonyl chloride for **7a** and **10a** / octanesulfonyl chloride for **7b** and **10b**, Et<sub>3</sub>N, CH<sub>2</sub>Cl<sub>2</sub>, 0 °C; and (d) TBAF, THF, reflux. Oct, octyl and TBAF, tetrabutylammonium fluoride.

Finally, the reaction of PM567 with bis(sulfonamide) **11a** using the conditions described by us for the preparation of *N*-BODIPYs (activation of the nucleophilic substitution of fluorine through the use of BCl<sub>3</sub>/Et<sub>3</sub>N in methylene chloride at room temperature, see Scheme 2 [14]), led to **3a**. Unfortunately, **3a** was obtained unpurified with remains of **11a**, since the separation of both compounds could not be performed, either by elution chromatography, or by recrystallization, due to their similar polarity and solubility.

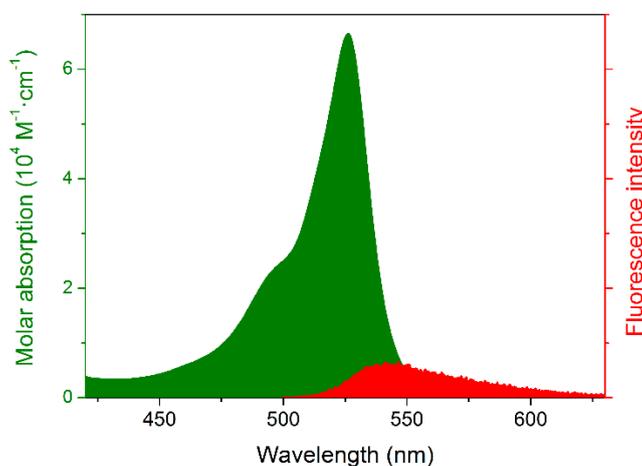
In order to overcome the purification problems, other *N*-BODIPYs functionalized with 15-crown-5 were synthesized, introducing variations in the alkyl substituents of both the BODIPY core and the bis(sulfonamide) moiety (see **3b** and **3c** in Scheme 2). To this end, 2,6-dibutyl-4,4-difluoro-1,3,5,7,8-pentamethylBODIPY (known as PM580) or octyl-substituted bis(sulfonamide) **11b** were used as starting materials. Unknown **11b** was obtained following a synthetic route analogous to that developed for **11a** (see Scheme 1). *N*-BODIPY **3c** could not be separated from its corresponding bis(sulfonamide) **11a**. On the contrary, the reaction of PM580 and **11b** led to octanosulfonamide-derived *N*-BODIPY **3b**, after successful separation from the starting bis(sulfonamide) **11b**, in a satisfactory 45% yield.



**Scheme 2.** Preparation of *N*-BODIPYs functionalized with crown ether through  $\text{BCl}_3$ -activated substitution of fluorine. Oct: octyl.

### 3.2. Photophysical and Cation Sensing Properties

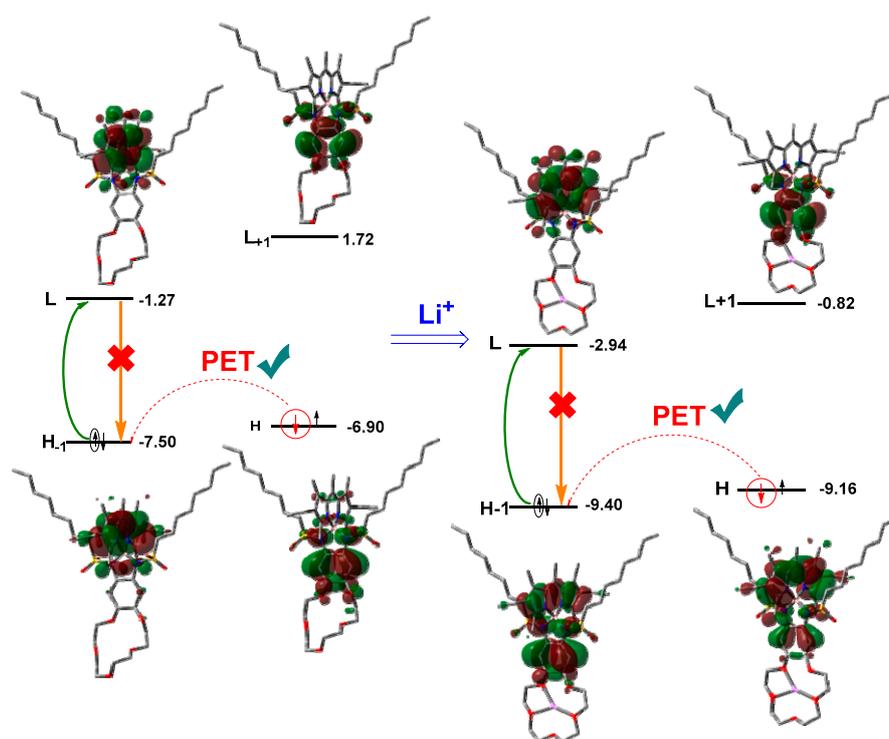
The spectral signatures of compound **3b** fully resemble those of its corresponding *F*-BODIPY precursor, the commercially available PM567 [4]. Thus, the main visible absorption band of *N*-BODIPY **3b** is located at 525 nm and the fluorescence band appears energetically close, at around 545 nm, leading to a small Stokes shift (around  $700 \text{ cm}^{-1}$ ) almost invariable regardless of the physicochemical properties of the solvent, the typical features of BODIPYs (Figure 4). In other words, the attached functionality at the boron atom, replacing the fluorine atoms, has little impact in the position of the spectral bands. Indeed, the boron bridge does not take part in the chromophoric  $\pi$ -system, which is spanned just through the dipyrin backbone. However, whereas the absorption probability is high (up to  $67,000 \text{ M}^{-1} \text{ cm}^{-1}$ ), the emission is very weak, with a fluorescence quantum yield of just 0.5% (Figure 4). Such fluorescence is so low that the corresponding fluorescence decay curve could not be measured with our photon counter with a resolution of tens of picoseconds. In view of the previous results attained for *N*-BODIPY **2** (see Figures 1 and 2), such fluorescence quenching is attributed to an efficient reductive PET process. In fact, the electron donor ability of the moiety resulting from the phenyl fused to the spiranic ring involving the amines was able to induce PET (Figure 2), and therefore further addition of an electron donor crown ether to such phenyl reinforces the viability of the PET. Indeed, the recorded fluorescence efficiencies for compound **3b** are even lower than those of *N*-BODIPY **2** (see Figure 2) [14].



**Figure 4.** Absorption and fluorescence spectra of compound **3b** in diluted solutions (2 mM) of ethyl acetate.

Against this background, we tested the ability of compound **3b** to act as an off/on switch for the sensing of cations. The initial hypothesis was that the attached crown ether should be a receptor with improved affinity for cations. Once the cation is chelated, the electron donor ability of the crown ether should decrease, and also the probability of the PET, recovering the fluorescent signal of the BODIPY. Therefore, in the absence of cation the compound **3b** is not fluorescent (off state), but once the cation is caught by the receptor, the quenching PET would be suppressed, yielding a bright emission from the BODIPY (on state), as detailed in Figure 2, but with higher specificity owing to the crown ether ability to host those cations whose size fit that of the crown ether. Therefore, we tested the sensing ability of compound **3b** against a wide battery of cations with different size and charge (monovalent:  $H^+$ ,  $Li^+$ ,  $Na^+$ , and  $K^+$ ; divalent:  $Ca^{2+}$ ,  $Mg^{2+}$ ,  $Ni^{2+}$ ,  $Zn^{2+}$ ,  $Co^{2+}$ , and  $Fe^{2+}$ ; and trivalent:  $Fe^{3+}$  and  $Cr^{3+}$ ). However, none of these were able to increase the fluorescence signal even using a large excess of cation (up to 20 equivalent per dye molecule) in the media. This behavior was rather astonishing since some of the tested cations have a good affinity with the crown ether receptor and it is well-known that they are easily chelated by the crown ether. However, such recognition is not translated in a change in the fluorescence response. Therefore, compound **3b** is not a suitable off/on switch for cations, since the fluorescent quenching of the PET remains unaltered in the absence or in the presence of cation.

In order to try to unravel the reason for the no sensing of compound **3b**, we carried out a computational simulation of the dye alone and once chelated with  $Li^+$ , a cation with good affinity with the appended crown ether in the *N*-BODIPY (Figure 5). As expected, in the absence of cation, the added functionalization at the boron atom is able to promote a PET process, as depicted previously in Figure 2. In fact, the HOMO is placed at the boron substituents and its energy falls between the energy gap responsible for the absorption of the BODIPY (electron hop from the HOMO-1 to the LUMO). With this energetical distribution of the molecular orbitals upon excitation, the transfer of an electron from the boron functionalization to the BODIPY is thermodynamically feasible (0.6 eV in Figure 5). However, a closer inspection of the molecular orbitals reveals that the HOMO is



**Figure 5.** Calculated distribution of the molecular orbitals (energies in eV) from the optimized ground state geometry (B3LYP/6-31g\*) of compound **3b** in absence of cation (**left**) and with  $Li^+$  chelated at the crown ether (**right**).

placed almost exclusively in the phenylated spiranic ring, and it is not extended to the crown ether (Figure 5). Thus, the electron donor moieties responsible for the PET are the nitrogens reinforced by the phenyl fused to the spiranic ring at the boron center. Upon binding of  $\text{Li}^+$  in the crown ether, the highest occupied orbital of the boron functionalization is still placed between those involved in the electronic transition of the chromophore, suggesting that the PET is still going on, albeit the cation is chelated with the crown ether receptor (Figure 5). Surely it is true that the binding of the cation reduces the electron donor ability of the crown ether and likely of the whole moiety grafted at the boron (indeed the energy gap for the PET decreases down to 0.25 eV in Figure 5), however it is not enough to suppress the PET (the energy of the highest occupied orbital of the boron substituent decreases below that of the BODIPY) and recover the fluorescence emission, as it occurs in Figure 2. In other words, the electron donor ability of the amines involved in the phenylated spiranic ring is able itself to induce PET regardless of the cation recognition by the crown ether, and thus hampering the use of compound **3b** as a chemosensor switch.

#### 4. Conclusions

A new *N*-BODIPY substituted with a crown ether moiety has been synthesized, demonstrating the possibilities of functionalization of these still unexplored but promising dyes. Unfortunately, the designed *N*-BODIPY, featuring a crown ether as receptor unit for cations, did not succeed as off/on switching. Likely the cation is chelated by the crown ether, but this event is not traduced in a change in the PET probability. The fluorescence response must remain unaltered upon binding of the cation because the moiety to which the crown ether is appended, is able itself to induce the PET. In this regard theoretical calculations are a suitable tool to find out what is going on and help in the design of new successful chemosensors for the detection of cations.

**Author Contributions:** Conceptualization, B.L.M. and S.d.l.M.; methodology, J.B. and B.L.M.; software, J.B.; validation, F.M. and C.R.; investigation, C.R., C.S., and E.A.Z.; writing—original draft preparation, C.R., C.S., B.L.M., and J.B.; writing—review and editing, B.L.M., J.B., and S.d.l.M.; supervision, B.L.M., J.B., and S.d.l.M.; funding acquisition, J.B. and S.d.l.M.

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**Conflicts of Interest:** The authors declare no conflict of interest.

#### References

1. Antina, E.V.; Bumagina, N.A.; V'yugin, A.I.; Solomonov, A.V. Fluorescent indicators of metal ions based on dipyrromethene platform. *Dye. Pigment.* **2017**, *136*, 368–381.
2. Wu, D.; Sedgwick, A.C.; Gunnlaugsson, T.; Akkaya, E.U.; Yoon, J.; James, T.D. Fluorescent chemosensors: The past, present and future. *Chem. Soc. Rev.* **2017**, *46*, 7105–7123.
3. Daly, B.; Ling, J.; de Silva, A.P. Current developments in fluorescent PET (photoinduced electron transfer) sensors and switches. *Chem. Soc. Rev.* **2015**, *44*, 4203–4211.
4. Bañuelos, J. BODIPY dye, the most versatile fluorophore ever? *Chem. Rec.* **2016**, *16*, 335–348.
5. Ulrich, G.; Ziesel, R.; Harriman, A. The chemistry of fluorescent BODIPY dyes: Versatility unsurpassed. *Angew. Chem. Int. Ed.* **2008**, *47*, 1184–1201.
6. Belmonte-Vázquez, J.L.; Avellanal-Zaballa, E.; Enríquez-Palacios, E.; Cerdán, L.; Esnal, I.; Bañuelos, J.; Villegas-Gómez, C.; López Arbeloa, I.; Peña-Cabrera, E. Synthetic approach to readily accessible benzofuran-fused borondipyrromethenes as red-emitting laser dyes. *J. Org. Chem.* **2019**, *84*, 2523–2541.
7. Clarke, R.G.; Hall, M.J. Recent developments in the synthesis of the BODIPY dyes. In *Advances in Heterocyclic Chemistry*; Hall, M.J., Ed.; Academic Press: Cambridge, MA, USA, 2019; Volume 128, pp. 181–261.
8. Blázquez-Moraleja, A.; Álvarez-Fernández, D.; Prieto Montero, R.; García-Moreno, I.; Martínez-Martínez, V.; Bañuelos, J.; Sáenz-de-Santa-María, I.; Chiara, M.D.; Chiara, J.L. A general modular approach for the solubility tagging of BODIPY dyes. *Dye. Pigment.* **2019**, *170*, 107545.

9. Durán-Sampedro, G.; Agarrabeitia, A.R.; Cerdán, L.; Pérez-Ojeda, M.E.; Costela, A.; García-Moreno, I.; Esnal, I.; Bañuelos, J.; Arbeloa, I.L.; Ortiz, M.J. Carboxylates versus Fluorines: Boosting the Emission Properties of Commercial BODIPYs in Liquid and Solid Media. *Adv. Funct. Mat.* **2013**, *23*, 4195–4205.
10. Sánchez-Carnerero, E.M.; Moreno, F.; Maroto, B.L.; Agarrabeitia, A.R.; Ortiz, M.J.; Vo, B.G.; Muller, G.; Moya, S.D.L. Circularly polarized luminescence by visible-light absorption in a chiral O-BODIPY dye: Unprecedented design of CPL organic molecules from achiral chromophores. *J. Am. Chem. Soc.* **2014**, *136*, 3346–3349.
11. Jiménez, J.; Cerdán, L.; Moreno, F.; Maroto, B.L.; García-Moreno, I.; Lunkley, J.L.; Muller, G.; De La Moya, S. Chiral organic dyes endowed with circularly polarized laser emission. *J. Phys. Chem. C* **2017**, *121*, 5287–5292.
12. Ziessel, R.; Ulrich, G.; Haefele, A.; Harriman, A. An artificial light-harvesting array constructed from multiple BODIPY dyes. *J. Am. Chem. Soc.* **2013**, *135*, 11330–11344.
13. Bodio, E.; Goze, C., Investigation of B-F substitution on BODIPY and aza-BODIPY dyes: Development of B-O and B-C BODIPYs. *Dye. Pigment.* **2019**, *160*, 700–710.
14. Ray, C.; Díaz-Casado, L.; Avellanal-Zaballa, E.; Bañuelos, J.; Cerdán, L.; García-Moreno, I.; Moreno, F.; Maroto, B.L.; López-Arbeloa, Í.; de la Moya, S. N-BODIPYs come into play: Smart dyes for photonic materials. *Chem. Eur. J.* **2017**, *23*, 9383–9390.
15. Móczár, I.; Huszthy, P. Optically active crown ether-based fluorescent sensor molecules: A mini-review. *Chirality* **2019**, *31*, 97–109.
16. Kruse, R.; Breitmaier, E. Doppel-ionopor mit dihydrotetraazal[1 4]annulen- und kronenether-funktion. *Chem. Ber.* **1981**, *114*, 832–836.
17. Yasuhara, A.; Kameda, M.; Sakamoto, T. Selective monodesulfonylation of N,N-disulfonylarylamines with tetrabutylammonium fluoride. *Chem. Pharm. Bull.* **1999**, *47*, 809–812.



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