ORGANIC
LETTERS

2006
Vol. 8, No. 20
4445−4448

Unusual Fluorescent Monomeric and Dimeric Dialkynyl Dipyrromethene–Borane Complexes

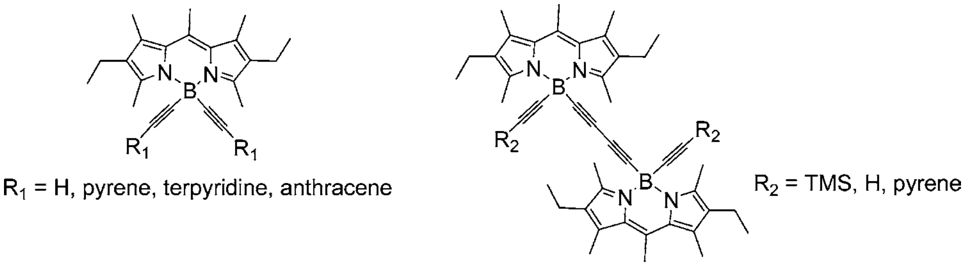
Christine Goze, Gilles Ulrich, and Raymond Ziessel*

Laboratoire de Chimie Moléculaire, Centre National de la Recherche Scientifique (CNRS), Associé au CNRS UMR 7509, Ecole de Chimie, Polymères, Matériaux de Strasbourg (ECPM), 25 rue Becquerel, 67087 Strasbourg, Cedex 02, France

ziessel@chimie.u-strasbg.fr

Received June 29, 2006

ABSTRACT



Novel monomeric and dimeric dialkynyl borondipyrromethene dyes (*E*-Bodipy) have been prepared in two different ways, providing systems in which the boron center is attached to either two similar or two dissimilar acetylenic units incorporating chromophores such as pyrene or anthracene. Both families exhibit interesting fluorescence and redox properties in which almost quantitative intramolecular energy transfer occurs.

Highly luminescent materials have attracted considerable attention over the past decades due to their potential applications in medicinal diagnostics, molecular biology, molecular recognition, and material sciences.[1] A particularly popular class of such dyes is the Bodipy family, in which a dipyrromethene unit chelates a BF_2 center, creating a boradiazaindacene unit.[2] In recognition of the specific presence of fluoro substituents, we designate these molecules herein as *F*-Bodipy species. One of the drawbacks to their use as bioanalytical labels is that, similar to most other known luminophores, they exhibit small Stokes' shifts in their luminescence spectra, a factor that limits the sensitivity of their detection using advanced fluorescence techniques. A promising strategy to enhance the Stokes' shift is to covalently attach an additional chromophore that absorbs at higher energy than the boradiazaindacene center and can thus play the role of an energy donor in a covalently linked tandem system.[3] Substitution of one or both of the fluorine ligands on boron is a particularly efficient means to engineer such dyads.[4] Where the substituents involve an ethynyl (acetylenic), "*E*", linking group, a good conduit for energy transfer, the resulting *E*-Bodipy compounds are very stable.[5] With a high-energy chromophore such as pyrene or anthracene attached to the ethynyl group, these compounds can then be seen as polyfunctional dyes for which a selected excitation wavelength might induce unusually large virtual Stokes' shifts.

---

(1) Forrest, S. R.; Burrows, P.; Thompson, M. E. In *Organic Electroluminscent Materials and Devices*; Miyata, S., Nalwa, H. S., Eds.; Gordon and Breach: Langhorne, PA, 1996. Valeur, B. *Molecular Fluorescence: Principles and Applications*; Wiley-VCH: Weiheim, 2002; pp 351−378. *Fluorescence Spectroscopy in Biology: Advanced Methods and their Applications to Membranes, Proteins, DNA and Cells*; Martin, H., Rudlof, H., Vlatimil, F., Eds.; Springer: Heidelberg, 2005. Lakowicz, J. R. Probe Design and Chemical Sensing. In *Topics in Fluorescence Spectroscopy*; Lacowicz, J. R., Ed.; Plenum: New York, 1994; Vol. 4.

(2) Haughland, R. P. *Handbook of Fluorescent Probes and Research Chemicals*, 6th ed.; Molecular Probes: Eugene, OR, 1996.

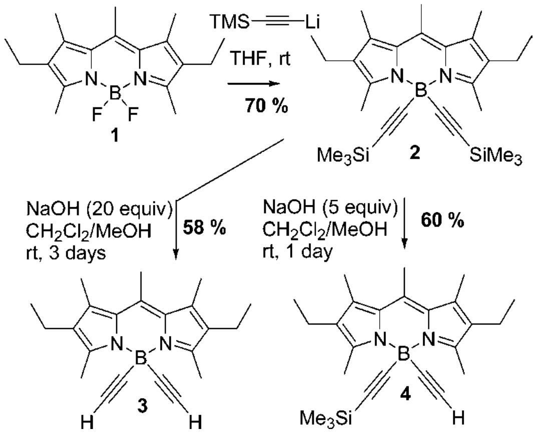
(3) Ziessel, R.; Goze, C.; Ulrich, G.; Césario, M.; Retailleau, P.; Harriman, A.; Roston, J. P. *Chem.−Eur. J.* **2005**, *11*, 7366−7378. Burghart, A.; Thoresen, L. H.; Chen, J.; Burgess, K.; Bergström, F.; Johansson, L. B. A. *Chem. Commun.* **2000**, 2203−2204. Wan, C.-W.; Burghart, A.; Chen, J.; Bergström, F.; Johansson, L. B. A.; Woldford, M. F.; Kim, T. G.; Topp, M. R.; Hochstrasser, R. M.; Burgess, K. *Chem.−Eur. J.* **2003**, *9*, 4430−4441.

10.1021/ol061601j CCC: $33.50

Our initial work showed that appropriately functionalized ethynes could be readily introduced as substituents at boron in a Bodipy core. However, in several cases, the ethyne derivatives were not readily available and in some others the lithio derivative of the alkyne did not react efficiently with the *F*-Bodipy to give the desired derivative. Thus, we turned to a two-step procedure involving the preliminary formation of the simple bis(ethynyl) Bodipy to use its terminal ethynyl CH centers for subsequent cross-coupling reactions with halogeno chromophores.

The starting *F*-Bodipy **1** was selected because of its simplicity, accessibility, stability, and interesting photophysical properties.[6] The target synthon **3** was prepared in two steps. First, the introduction of two trimethylsilylacetylene units using 2 equiv of the corresponding organolithium derivative led, apparently in a single step, to the *E*-Bodipy **2** in good yield (Scheme 1). No monosubstituted intermediate could be detected by thin-layer chromatography during the reaction. Removal of the trimethylsilyl groups using excess NaOH afforded **3** as the major product. Interestingly, deprotection of the triethylsilyl analogue failed under all conditions tried. Using a limited quantity of NaOH and a shorter reaction time, we could also obtain the monoprotected *E*-Bodipy **4** from **2**.

Scheme 1



Compounds **2**−**4** were fully characterized by NMR, UV, infrared spectroscopy, mass spectroscopy, and elemental analysis. The ^{11}B NMR spectra show strong shielding of the boron atom ($\delta = -11.10$ ppm for **2**, -11.05 ppm for **3**, and -11.08 ppm for **4**) with respect to **1** ($\delta \approx +3.82$ ppm) indicating the boron centers to be located in the shielding zone of the triple bond. Interestingly, the chemical shift of the acetylenic protons is unusual in **3** ($\delta = 2.17$ ppm), compared to that in simple systems. The crystallographically determined molecular structure of **3** is shown in Figure 1. The boron center adopts a distorted tetrahedral geometry, differing significantly from that in *F*-Bodipy compounds. The B−C bonds in **3** are similar to those in the pyramidal tris-(3,3-dimethyl-1-butynyl)pyridinoborane ($d_{\mathrm{B-C}} = 1.592$−1.593 Å).[7] The boron center sits in the dipyrromethene mean plane, with no distortion of the indacene core such as that seen with a more congested *E*-Bodipy.[5] No elongation of the C≡C triple bond is observed, which confirms the absence of back-donation due to the absence of an empty orbital on the tetrahedral boron center.

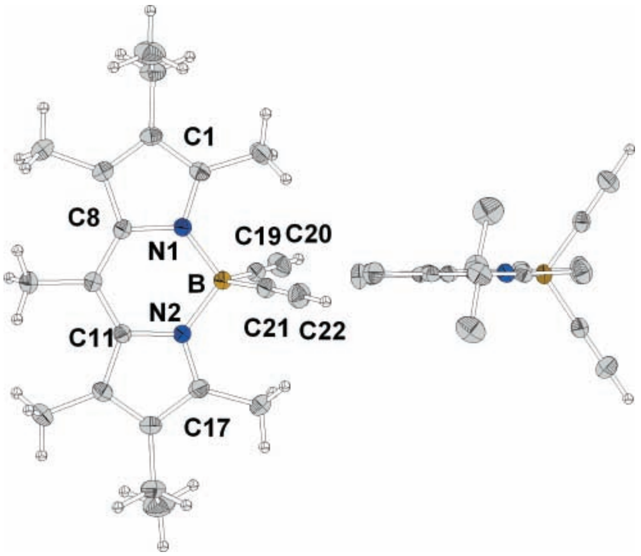
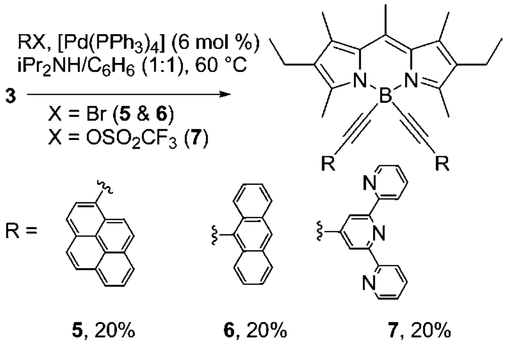


Figure 1. X-ray data for compound **3**. Selected bonds and angles: BN$_2$ = 1.553 Å (4), BN$_1$ = 1.561 Å (3), BC$_{21}$ = 1.595 Å (4), BC$_{19}$ = 1.592 Å (3), C$_{21}$C$_{22}$ = 1.189 Å (3), C$_{19}$C$_{20}$ = 1.192 Å (3), N$_1$BN$_2$ = 106.3°, C$_{19}$BC$_{22}$ = 111.5°, C$_{21}$BN$_2$ = 109.7°, C$_{19}$BN$_1$ = 109.3°. (a) View perpendicular to the Bodipy main axis. (b) View along the indacene plane. All hydrogen atoms except for the acetylenic function were removed for the sake of clarity.

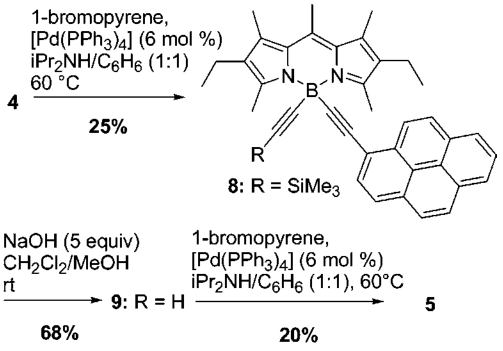
Successful attachment of various chromophores to the ethynyl groups was achieved by Pd(0)-catalyzed cross-coupling reactions with aromatic derivatives such as 1-bromopyrene, 1-bromoanthracene, or [{(4′-trifluoromethyl)-sulfonyl}oxy]-2,2′:6′,2”-terpyridine (Scheme 2).

Scheme 2



The cross-coupling reaction of the monoprotected compound **4** with 1-bromopyrene afforded **8** in 25% yield. The remaining trimethylsilyl unit could then be removed, and a second cross-coupling reaction with 1-bromopyrene gave **5** (Scheme 3).

Scheme 3



Switching the catalyst from Pd(0) to a mixture of Pd(II) and CuI under aerobic conditions led exclusively to the acetylenic homocoupled products **10** and **13** (Scheme 4). The absence of Pd(II) salts considerably reduced the isolated yields. As previously found for **2**, the deprotection reaction of the butadiyne **10** is very slow, and after 6 days, a mixture of monodeprotected **11** (43%) and dideprotected **12** (37%) compounds could be isolated. No obvious decomposition of the compounds was observed under these harsh conditions. Oxidative homocoupling of **9** afforded the bridged bis(pyrene) compound **13** in good yield.

All these new *E*-Bodipy compounds exhibit intense absorption around 515 nm, with extinction coefficients of ~65 000 M^{-1} cm^{-1}, assigned to a spin-allowed $S_0 \rightarrow S_1$ transition centered on the Bodipy core. The second weak and broad $S_0 \rightarrow S_2$ ($\pi-\pi^*$) transition located at ca. 380 nm was also clearly evident (Supporting Information, Figure S1). The structured absorption peaks appearing in the high-energy region around 380−220 nm are assigned to spin-allowed $\pi-\pi^*$ transitions centered on the additional aromatic nucleus, and in particular, the sharp band at about 375 nm is due to the pyrene subunit (Figure 2). The presence of two Bodipy moieties resulted in the doubling of the $S_0 \rightarrow S_1$ transition (e.g., for **12** in Supporting Information, Figure S1).

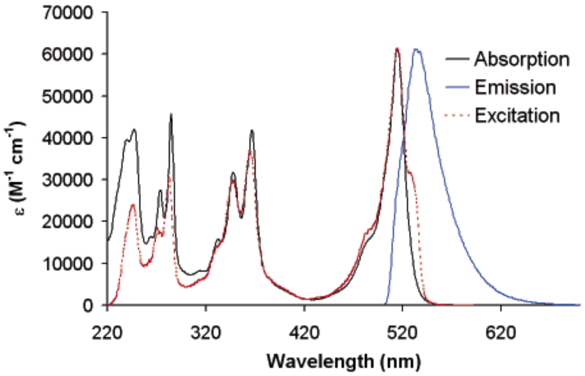
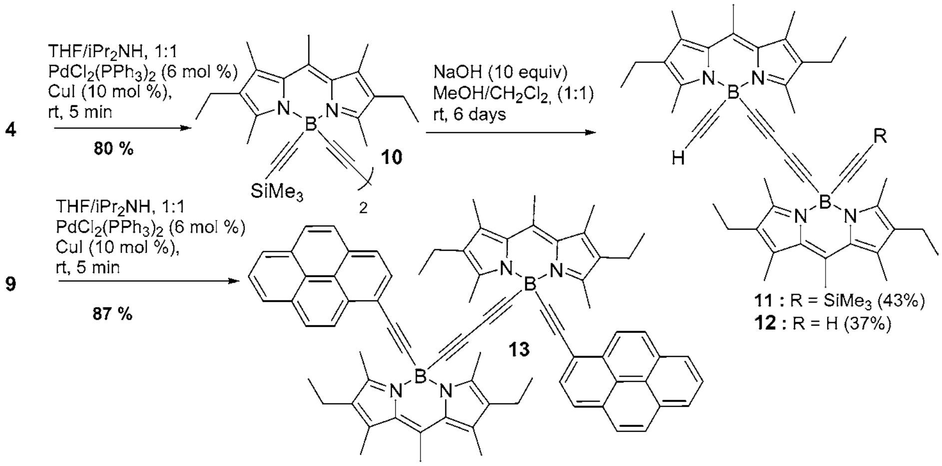


Figure 2. Absorption (10^{-6} M), emission, and excitation (10^{-8} M) spectra of **9** in CH_2Cl_2, at room temperature.

Very strong fluorescence, with quantum yields reaching 92−98% for **3** and **12**, was measured using Rhodamine 6G as a reference and is in keeping with that of *F*-Bodipy analogues.[3,5,6] For **9**, irradiation in the pyrene-absorption region at 370 nm resulted in the absence of pyrene emission at the expense of the Bodipy emission. The quantum yield of 80% is consistent with almost quantitative (94%) intramolecular energy transfer from the pyrene residue to the Bodipy. In keeping with this assumption is the perfect match between the excitation spectra and the absorption spectra (Figure 2). Furthermore, the Stokes' shifts increase from 600 cm^{-1} in *F*-Bodipys to >7000 cm^{-1} for the novel *E*-Bodipys bearing a supplementary chromophore. The absence of any significant dynamic quenching of the luminescence by molecular oxygen excludes the presence of an emissive triplet excited state.

Additionally, these molecules exhibit interesting redox properties as illustrated in Figure 3. In all cases, reversible oxidation and reduction processes are found around ≈+0.9 and ≈−1.4 V and are assigned to the formation of the Bodipy radical cation (Bodipy$^{+\bullet}$) and radical anion (Bodipy$^{-\bullet}$), respectively. Remarkably, replacing the fluoro by ethynyl

Scheme 4



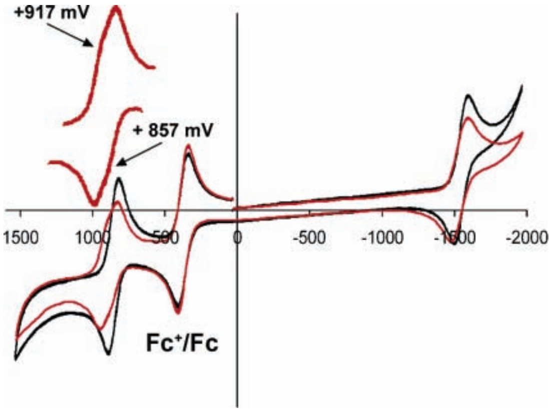


Figure 3. Cyclic voltammetry of **3** (black line) and **12** (red line), in CH_2Cl_2 at 20 °C using 0.1 M $^n Bu_4PF_6$ as supporting electrolyte at a scan rate of 200 mV/s. Ferrocene (Fc) was used as an internal standard (half-wave potential = 0.38 V (ΔE_p = 60 mV vs SCE)). For **12**, the cathodic side is enlarged in the inset and the arrows indicate the position of the second overlapping redox process.

fragments facilitates the oxidation by about 100 mV and shifts the reduction by about 230 mV to more anodic potentials. Interestingly, for **12** bearing two Bodipy residues, the oxidation wave involves the overlap of two successive redox processes due to the oxidation of each Bodipy center. The difference of 30 ± 5 mV is in keeping with a weakly electronically coupled system, with a calculated comproportionation constant of 3.3 ± 0.4.[8] As would be expected from the incorporation of additional polyaromatic rings and the fact that the various parts of the whole framework are only weakly electronically coupled, other redox waves are observed (e.g., for **6**, two dielectronic systems at +1.29 and −1.83 V are assigned to the radical cation and anion of anthracene). The superposition of the waves indicates that the two anthracene subunits are electronically independent.

In short, we have established a synthetic route for substitution of the fluoro ligands in difluoroboradiazaindacene derivatives by protected alkyne fragments. Although there are some difficulties in deprotection, the method is useful for the subsequent preparation of bridged *E*-Bodipy dimers, in which some electronic interactions are evidenced by cyclic voltammetry. Cross-coupling reactions readily produce arylethynyl Bodipy derivatives in which very efficient intramolecular energy transfer gives rise to large virtual Stoke shifts. Interestingly, the other optical and redox properties of the parent *F*-Bodipy compounds are retained. This work opens the door for the engineering of a vast range of new molecules, some being dendritic, in which the basic properties of different chromophoric components are retained but in which spatial proximity of these components is sufficient to provide information transfer when electronically or optically addressed.

Supporting Information Available: Figure S1, experimental procedures, and characterization of all the compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

OL061601J

---

(4) Nishimoto, T.; Misawa, T.; Ogiso, A.; Tsukahara, H.; Takuma, K.; Imai, G.; Kogure, H. Japanese Patent JP 13322744, 1998. Nishimoto, T.; Misawa, T.; Sugimoto, K.; Tsukahara, H.; Tsuda, T.; Umehara, H.; Takuma, H. Japanese Patent JP 10287819, 1997. Murase, S.; Otsu-Shi, S.; Tominaga, T.; Kohama, A. European Patent EP 1253 151 A1, 2002.

(5) Ulrich, G.; Goze, C.; Guardigli, M.; Roda, A.; Ziessel, R. *Angew. Chem., Int. Ed.* **2005**, 44, 3694−3698.

(6) Burghart, A.; Kim, H.; Welch, M. B.; Thoresen, L. H.; Reibenspies, J.; Burgess, K. *J. Org. Chem.* **1999**, *64*, 7813−7819.

(7) Bayer, M. J.; Pritzkow, H.; Siebert, W. *Eur. J. Inorg. Chem.* **2002**, 2069−2072.

(8) Richardson, D. E.; Taube, H. *Inorg. Chem.* **1981**, *20*, 1278−1285.