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New BODIPY–triazine based tripod fluorescent systems

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Abstract—A new tripod fluorescent system was developed, which bears a triazine core for combining three different functional groups, such as fluorophore (BODIPY), ligand, and auxiliary group. This concept was confirmed by photophysical properties due to the different auxiliary subunits.

4,4-Difluoro-4-bora-3a,4a-diaza-*s*-indacene (BODIPY) derivatives have proven to be useful fluorophores on account of their high molar absorptivity, fluorescence quantum yields and stability against light and chemical reactions.[1] In this regard, BODIPY dyes have been extensively utilized as biomolecular labels, drug delivery agents, laser dyes, etc.[2] BODIPY derivatives have been also reported as fluorescent chemosensors for metal ions,[3] protons,[4] or NO.[5]

Cyanuric chloride is a very useful template for the synthesis of dendrimers,[6a] macrocycles,[6b] calixarene,[6c] and combinatorial libraries[6d] because it takes advantage of the temperature-dependent stepwise substitution of its three chlorine atoms by different nucleophiles. These substitutions are simple and the yields are routinely high. Even though there is a recent example of mono-substituted triazine–BODIPY, the detailed photophysical properties have not been reported.[7] Herein, we report a new design for a fluorophore–triazine tripod fluorescent system, which can accommodate a combination of three different functional groups, such as fluorophore (BODIPY in this Letter), ligand, and auxiliary group, as shown in Figure 1.

In the case where there is one binding subunit (Fig. 1), the third substituted position on the triazine structure allows the introduction of an auxiliary group with different structures, which might not only modify the chemical and/or physical properties of the products, such as solubility or fine-tune of spectrum but also combine the fluorescent behavior with other research fields such as polymers, nanomaterials, and biochemistry, through functional groups attached to it. In this study, four different BODIPY–triazine tripods bearing different auxiliary subunits were synthesized and their photophysical properties were examined (Fig. 2).

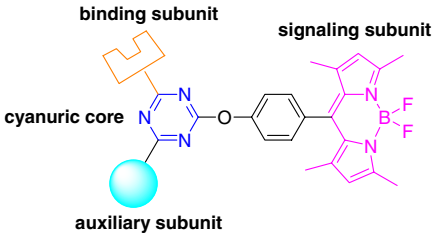

Figure 1. New BODIPY–triazine tripod systems.

As shown in Figure 2, BODIPY–triazine derivatives bearing one binding subunit and an auxiliary subunit (**1**–**4**) were prepared. Generally, an aldehyde containing hydroxyl group should react first with cyanuric chloride due to its relatively poor nucleophilicity, and then with the auxiliary aniline. Di-(2-picolyl)amine (DPA) ligand was introduced in the last stage to form intermediate bearing a triazine core and benzaldehyde, which was used for further condensation (Scheme 1). The detailed

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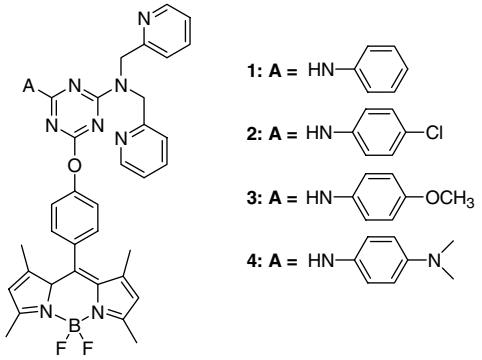


Figure 2. Structures of compounds synthesized.

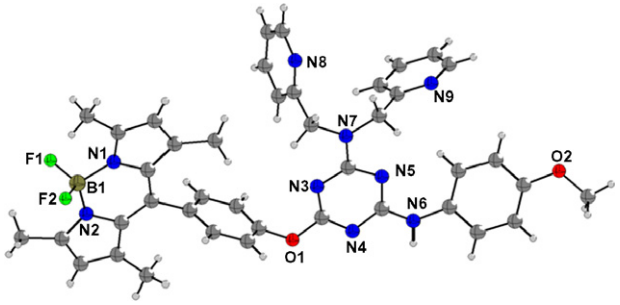


Figure 3. X-ray crystal structure of the compound **3**.

syntheses are explained in the Supplementary data (Schemes S1 and S2). All new compounds **1**–**4** were fully characterized by ^{1}H and ^{13}C NMR and high resolution FAB mass[8] (Supplementary data).

The X-ray crystal structure of compounds **3** (Fig. 3) is also presented. In compound **3**, the pyrrolyl rings and phenyl ring (C14–C19) are planar with an average deviation of 0.0483 Å and 0.0046 Å, respectively. The dihedral angle is 86.9°. The triazine ring and the pyrrolyl rings are almost parallel, with a dihedral angle of 7.4°. Table S1 and Figure S2 show the geometry and intramolecular and intermolecular hydrogen bonds in the crystal structure of compound **3**.

Initially, the fluorescent quantum efficiencies were determined in degassed acetonitrile (Table 1). The fluorescent emission intensity (**1**–**4**) was controlled by introducing different auxiliary groups (Fig. S3). Table 1 shows the relative quantum efficiencies. The quantum efficiency for compound **2** was observed as high as 0.84. On the other hand, there was a substantial quenching effect in compound **4**, which can be attributed to a photo induced electron transfer (PET) process through the *N*,*N*-dimethylamine moiety on the phenyl ring. As shown in Table 1 and the CV data in this section, their relatively small spectral changes (λ_{max}) in the UV and

Table 1. The fluorescence λ_{max} and relative fluorescence quantum efficiencies (QE) in degassed acetonitrile

Compound	**1**	**2**	**3**	**4**
Fluores. (λ_{max}) (nm)	507	507	507	507
QE[a] (%)	80[b]	84	71	24

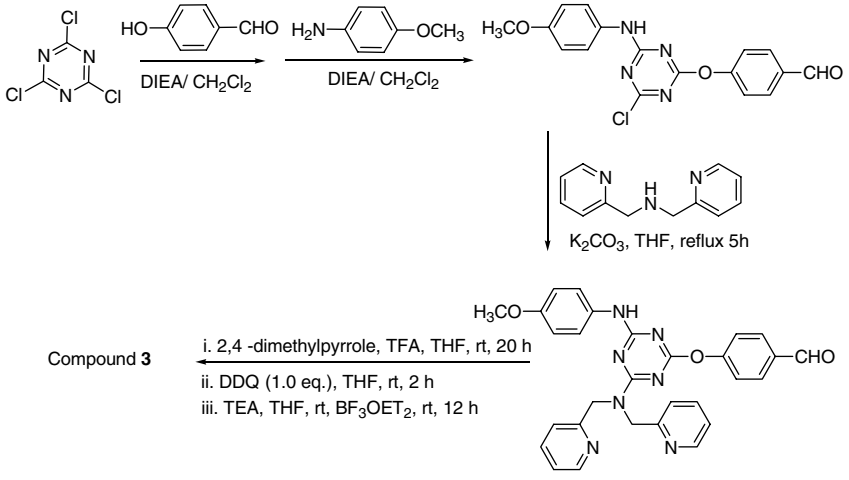
[a] The relative quantum efficiency was determined using that of fluorescein (0.85) in 0.1 M NaOH as a standard.

[b] The relative quantum efficiency was determined in DMSO–acetonitrile (1:9) due to the solubility problem.

fluorescent emissions were probably due to the long distance between the auxiliary groups and BODIPY as well as the angle (~90°) between the triazine and BODIPY moieties, which was also explained by Yu et al.[3g]

As a second point about the auxiliary subunit effect, the fluorescent emission changes in compounds **2** and **4** with Hg^{2+} (10 equiv) were productively compared (Fig. 4): a quenching effect with compound **2**, and an enhancement and a slight red shift with compound **4**. The large chelation enhanced fluorescence (CHEF) effect of compound **4** upon the addition of Hg^{2+} can again be explained by the blocking of the PET mechanism process as shown in the following CV data.

Table 2 summarizes the cyclic voltammetric (CV) data for compounds **2**, **3**, and **4** in either CH_2Cl_2 or CH_3CN



Scheme 1. Synthesis of compound **3**.

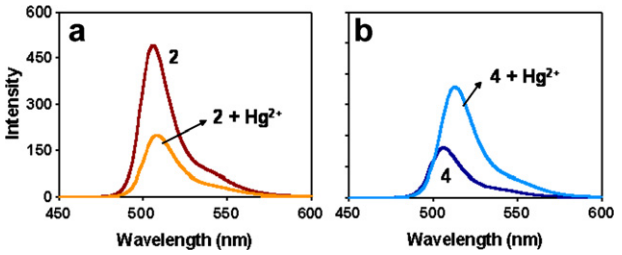


Figure 4. Fluorescent emission changes of **2** (1 μM) and **4** (1 μM) upon the addition of Hg^{2+} (10 equiv) in acetonitrile (excitation at 497 nm).

Table 2. Cyclic voltammetric data for **2**, **3**, and **4**[a]

Compound	E_{ox} (E_{pa}/E_{pc})	E_{red} (E_{pa}/E_{pc})
2[b]	1.22/—[d]	−1.20/−1.26
3[b]	1.05(s)/—[d], 1.22/—[d]	−1.20/−1.26
4[b]	0.62/0.48, 1.21/—[d]	−1.20/−1.26
4[c]	0.58/0.48, 1.23/—[d]	−1.12/−1.18
4 + $Hg(ClO_4)_2$[c]	0.81/0.59, 1.08(s)/—[d], 1.20/—[d]	−1.13/−1.17
$Hg(ClO_4)_2$[c]	0.75/0.55	

[a] Potentials are shown in V versus SCE and s means shoulder peak.
[b] CVs were recorded in CH_2Cl_2 solution at a scan rate of 0.2 V/s.
[c] CVs were recorded in CH_3CN solution due to solubility of $Hg(ClO_4)_2$ at a scan rate of 0.1 V/s.
[d] Cathodic peak was hard to be observed at this experimental scan rate.

containing 0.1 M tetrabutylammonium hexafluorophosphate with a scan rate of 0.2 V/s or 0.1 V/s. The CVs for compounds **2**–**4** have common features, that is, a less reversible oxidation wave at 1.2 V and a more reversible reduction wave at −1.2 V, due to a redox reaction of BODIPY. The potential differences between these two oxidation and reduction waves for the above three compounds are 2.4 V within a 0.02 V range, which are related to the differences between the HOMO and LUMO energy levels of BODIPY.[9] This suggests that the emission wavelength of the fluorophore is affected insignificantly by the auxiliary subunit,[10] as shown in Table 1.

The anodic shoulder peak of the CV of compound **3** at 1.03 V and the redox wave of the CV of compound **4** at 0.53 V appears to be caused by the methoxyphenyl and *N*,*N*′-dimethylaminophenyl moieties, respectively (Fig. 5a and b). Relatively large differences in the CV shape were found in compound **4**, which also showed a CHEF with Hg^{2+} (Fig. 4). In the presence of Hg^{2+} (>1 equiv), the redox wave of compound **4** at 0.53 V disappeared virtually, and a new anodic shoulder peak at 1.08 V was produced with a single peak due to excess $Hg(ClO_4)_2$ (Fig. 5b and c). The positive shift of *N*,*N*′-diaminophenylene redox potential can be interpreted in terms of either of the following two ways: One possibility is electron donation of *N*,*N*′-dimethylamine to the DPA binding subunit in chelating with Hg^{2+} and the other possibility is *N*,*N*′-dimethylaminophenyl moiety of **4** serves as an additional chelation site with Hg^{2+}. The electrondensity of *N*,*N*′-dimethylaminophenyl moiety becomes lower upon chelation, which shifts the oxidation potential to the higher positive potential. This can be an evidence for the CHEF effect for compound

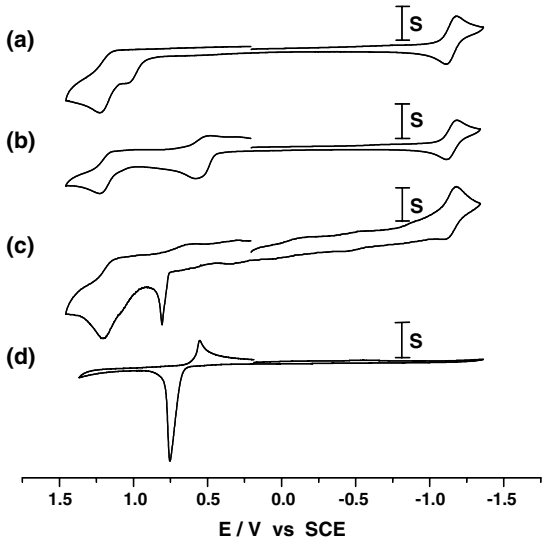


Figure 5. Cyclic voltammograms of 1 mM **3** (a), **4** (b), **4** containing $Hg(ClO_4)_2$ (c), and $Hg(ClO_4)_2$ (d) at a platinum disk electrode with negative scan direction; in CH_3CN containing 0.1 M $TBAPF_6$; $v = 0.1$ V/s. The scale bar represents 5 (a–c) and 20 μA (d), respectively.

4 regarding the blocking of PET mechanism process. The current of 55 μA in the presence of Hg^{2+} reduced to 17 and 6 μA upon the addition of compounds **2** and **3**, respectively, which means the Hg^{2+} is bound to the DPA binding unit. However, unlike the case of compound **4**, there was not any significant change for the redox peak of BODIPY.

In conclusion, we report a new tripod fluorescent system, which bears a triazine core for combining three different functional groups, such as fluorophore, ligand, and auxiliary group. This concept was confirmed by photophysical properties due to the different auxiliary subunits. We believe that the flexibility, potential variety and high quantum efficiency of this tripod system can present various applications in the fields of tagging materials of biological systems, fluorescent chemosensors, organo EL materials and nanomaterials. Further research related to this new tripod system, such as building a library of tripod system, application to biomarkers and sensors, is currently under investigation.

Acknowledgments

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2007.11.063.

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7. Röhr, H.; Trieflinger, C.; Rurack, K.; Daub, J. *Chem. Eur. J.* **2006**, *12*, 689. During our data processing, the Daub group reported a BODIPY structure containing a mono-substituted triazine structure via a condensation reaction between a BODIPY dye bearing a thiol group and cyanuric chloride. Indeed, we first adopted the same methodology in our studies (hydroxyl in the case instead of thiol), but only the abovementioned mono-substituted derivative was obtained successfully through that type of direct condensation involving in the most reactive chlorine atom of cyanuric chloride. Subsequent substitutions of the second and third chlorine atoms on the triazine core from the mono-substituted structure by nucleophiles (ligands used in this report) were failed when fluorophore exists. So we turned to search for other more reliable ways (as reported herein) to fulfill the desired structure diversity.
8. *Compound* **1**: as red solid (135.8 mg, 0.192 mmol, 32.0%): mp 235–236 °C. ^{1}H NMR ($CDCl_3$): δ 1.33 (s, 6H), 2.54 (s, 6H), 4.85 (s, 2H), 4.98 (s, 2H), 5.94 (s, 2H), 7.01 (m, 1H), 7.13–7.27 (m, 10H), 7.45 (m, 2H), 7.57 (m, 2H), 8.48 (d, 1H, $J = 3.6$ Hz), 8.54 (d, 1H, $J = 3.6$ Hz). ^{13}C NMR ($CDCl_3$): δ 14.4, 14.5, 52.1, 120.3, 121.2, 121.4, 121.6, 122.2, 122.3, 122.8, 123.3, 128.7, 131.4, 131.6, 136.5, 136.6, 138.2, 140.8, 143.0, 149.3, 149.4, 152.8, 155.5, 166.2, 167.5, 171.4. HRMS (FAB) *m*/*z* 708.3194 $(M+H)^+$, calcd for $C_{40}H_{37}BF_2N_9O$: 708.3189; *Compound* **2**: as red solid (117 mg, 0.15 mmol, 26%): mp 98 °C. ^{1}H NMR ($CDCl_3$): δ 1.33 (s, 6H), 2.55 (s, 6H), 4.85 (s, 2H), 4.97 (s, 2H), 5.95 (s, 2H), 7.16–7.37 (m, 12H), 7.58 (m, 2H), 8.57 (dd, 2H, $J = 20.6$, 4.2 Hz). ^{13}C NMR ($CDCl_3$): δ 14.4, 14.5, 52.2, 121.3, 121.7, 122.4, 122.8, 128.3, 128.7, 128.8, 131.4, 131.8, 136.6, 136.8, 143.0, 149.4, 152.7, 155.6, 157.0. HRMS (FAB) *m*/*z* 742.2766 $(M+H)^+$, calcd for $C_{40}H_{36}BClF_2N_9O$: 742.2800; *Compound* **3**: as red solid (106 mg, 0.144 mmol, 24.0%) mp: 138–140 °C. ^{1}H NMR ($CDCl_3$): δ 1.32 (s, 6H), 2.54 (s, 6H), 3.75 (s, 3H), 4.83 (s, 2H), 4.94 (s, 2H), 5.94 (s, 2H), 6.73 (m, 2H), 7.12–7.40 (m, 10H), 7.56 (m, 2H), 8.47 (d, 1H, $J = 3.8$ Hz), 8.54 (d, 1H, $J = 3.8$ Hz). ^{13}C NMR ($CDCl_3$): δ 14.4, 14.5, 52.0, 55.4, 113.8, 121.2, 121.4, 121.6, 122.1, 122.3, 122.4, 122.8, 131.2, 131.4, 131.5, 136.4, 140.8, 143.0, 149.2, 152.8, 155.5, 155.9, 157.2. HRMS (FAB) *m*/*z* 738.3291 $(M+H)^+$, calcd for $C_{41}H_{39}BF_2N_9O_2$ 738.3295; *Compound* **4**: as red solid (112.6 mg, 0.15 mmol, 25%): mp 146–148 °C. ^{1}H NMR ($CDCl_3$): δ 1.32 (s, 6H), 2.54 (s, 6H), 2.88 (s, 6H), 4.83 (s, 2H), 4.96 (s, 2H), 5.86 (s, 2H), 6.60 (m, 2H), 7.01–7.27 (m, 10H), 7.56 (m, 2H), 8.48 (d, 1H, $J = 3.8$ Hz), 8.54 (d, 1H, $J = 4.1$ Hz). ^{13}C NMR ($CDCl_3$): δ 14.4, 14.5, 40.9, 51.9, 112.9, 121.2, 121.5, 122.1, 122.4, 122.8, 128.6, 131.4, 136.4, 140.9, 143.0, 147.5, 149.2, 152.8, 155.4, 157.4. HRMS (FAB) *m*/*z* 750.3528 $(M+H)^+$, calcd for $C_{42}H_{41}BF_2N_{10}O$: 750.3533.
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