Photochemical & Photobiological Sciences

Cite this: Photochem. Photobiol. Sci., 2011, 10, 1030

www.rsc.org/pps

Modulation of the spectroscopic property of Bodipy derivates through tuning the molecular configuration[†]

Yuting Chen,^{*a,b,c*} Liang Wan,^{*b*} Daopeng Zhang,^{*b*} Yongzhong Bian^{*b*} and Jianzhuang Jiang^{**a,b*}

Received 1st January 2011, Accepted 16th February 2011 DOI: 10.1039/c1pp00001b

A series of six Bodipy derivatives, namely

4,4-difluoro-8-(4-amidophenyl)-1,3,5,7-tetramethyl-4-bora-3a,4a-diaza-s-indacene (1), 4,4-difluoro-8-(4-methylphenyl)-1,3,5,7-tetramethyl-4-bora-3a,4a-diaza-s-indacene (2). 4,4-difluoro-8-(4-nitrylphenyl)-1,3,5,7-tetramethyl-4-bora-3a,4a-diaza-s-indacene (3), 4.4-difluoro-8-(4-amidophenyl)-3,5-dimethyl-4-bora-3a,4a-diaza-s-indacene (4), 4,4-difluoro-8-(4-methylphenyl)-3,5-dimethyl-4-bora-3a,4a-diaza-s-indacene (5), and 4,4-difluoro-8-(4-nitrylphenyl)-3,5-dimethyl-4-bora-3a,4a-diaza-s-indacene (6) were structurally characterized by single crystal X-ray diffraction analysis. Two methyl substituents attached at C-1 and C-7 positions of boron-dipyrromethene (Bodipy) moiety in compounds 1-3 were revealed to prevent the free rotation of the benzene moiety, resulting in a molecular configuration with an almost orthogonal dihedral angle between the Bodipy and benzene moieties with the dihedral angle in the range of 81.14–88.56°. This is obviously different from that for 4–6 with a free-rotating benzene moiety relative to the Bodipy core due to the lack of two methyl substituents in the latter series of compounds, leading to an enhanced interaction between the Bodipy and benzene moieties for 4-6 in comparison with 1-3. The resulting larger HOMO-LUMO gap for 1-3 than 4-6 results in a blue-shifted absorption band for 1-3 relative to that for 4-6. Comparative studies over their fluorescence properties also disclose the blue-shifted fluorescence emission band and corresponding higher fluorescence quantum yield for 1-3 relative to those of 4-6, revealing the effect of molecular configuration on the spectroscopic properties of Bodipy derivatives. Comparison of the redox behaviors of these two series of Bodipy compounds provides additional support for this point. In addition, the electron-donating/withdrawing property of the *para* substituent of the benzene moiety was shown to exhibit a slight influence on the electronic absorption and fluorescence emission properties of the Bodipy compounds.

Introduction

Since their first discovery by Treibs and Kreuzer in 1968,¹ 4,4difluoro-4-bora-3a,4a-diaza-s-indacenes (Bodipys) have been an important class of fluorophores with extensive applications in biochemical labeling,² fluorescent sensors,³ sensitizers for solar cells,⁴ and laser dyes,⁵ due to their advantageous photo-spectral properties including high photostability, sharp absorption and emission bands, relatively high absorption coefficient, high fluorescence quantum yields, and the extraordinary feature of excitation/emission wavelengths in the visible region.⁶ In particular, their fluorescent properties can be easily tuned by incorporating different functional groups onto different peripheral positions of the Bodipy core, which meanwhile renders it possible to introduce more recognition sites in Bodipy derivatives for a variety of analytes.⁷

Thus far, a wide variety of Bodipy derivatives with different substituents at peripheral positions of the Bodipy core have been synthesized and have found utilization for different analysis purposes. Akkaya *et al.* revealed that when the methyl group(s) at the C-3 and/or C-5 position(s) of Bodipy core is/are conjugated with electron-rich aromatic aldehyde(s), the extension in the π -electron conjugated system of the Bodipy derivatives results in a pronounced bathochromic shift from UV-visible region to near-infrared (NIR) region in both electronic absorption and fluorescence spectra, leading to the expansion in the photooptical range of Bodipy derivatives.⁸ In a similar manner, fusion of additional aromatic moieties onto the pyrrole rings can also lead to the extension of the π -electron conjugated system for

^aDepartment of Chemistry, Shandong University, Jinan, 250100, China. E-mail: jianzhuang@ustb.edu.cn

^bDepartment of Chemistry, University of Science and Technology Beijing, Beijing, 100083, China

^cDepartment of Chemistry, Dezhou University, Dezhou, 253023, China

[†] Electronic supplementary information (ESI) available: Molecule orbital energy levels for 1–6; electronic absorption and fluorescent spectra properties of compounds 1–6 in different solvents. CCDC reference numbers 798782–798787. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c1pp00001b

the Bodipy compounds and therefore induces a spectroscopic bathochromic shift.9 Nagano and co-workers found that the substituents introduced onto the C-2 and/or C-6 position(s) of the Bodipy core via electrophilic substitution reaction not only modulate the spectroscopic properties of the Bodipy chromophore but also provide water-soluble Bodipy compounds.¹⁰ The same authors also reported that the substituents incorporated at the C-1 and C-7 positions of Bodipy core increase the molecular rigidity and minimize the decrease of fluorescence intensity, resulting in a high fluorescence quantum yield.¹¹ Sunahara et al. disclosed that introduction of different aryl-substituents at the C-8 position of the Bodipy core leads to very slight changes in the electronic absorption and fluorescence emission bands of Bodipy derivatives, with an almost orthogonal configuration between the Bodipy moiety and aryl-group.12 According to Ulrich and Ziessel, replacement of fluorine atoms with aryl,¹³ ethynylaryl,¹⁴ and ethynyl subunits¹⁵ in the Bodiopy compounds results in a dramatic increase in the versatility of Bodipy dyes and opens the way to the preparation of new diad and cascade-type Bodipy dyes. However, systematic study towards revealing the effect of the molecular configuration between the Bodipy and meso-aromatic moieties on the optical properties of Bodipy derivatives through single crystal X-ray diffraction analysis still remains rare despite numerous reports on the effect of C-1/7-substituents preventing free rotation of the meso-aromatic group from the Bodipy moiety.^{7a}

In the present work, a series of six Bodipy derivatives, namely 4,4-difluoro-8-(4-amidophenyl)-1,3,5,7-tetramethyl-4bora-3a,4a-diaza-s-indacene (1), 4,4-difluoro-8-(4-methylphenyl)-1,3,5,7-tetramethyl-4-bora-3a,4a-diaza-s-indacene (2), 4,4-difluoro-8-(4-nitrylphenyl)-1,3,5,7-tetramethyl-4-bora-3a,4a-diazas-indacene (3), 4,4-difluoro-8-(4-amidophenyl)-3,5-dimethyl-4bora-3a,4a-diaza-s-indacene (4), 4,4-difluoro-8-(4-methylphenyl)-3,5-dimethyl-4-bora-3a,4a-diaza-s-indacene (5), and 4,4-difluoro-8-(4-nitrylphenyl)-3,5-dimethyl-4-bora-3a,4a-diaza-s-indacene (6), Scheme 1, were structurally characterized by single crystal X-ray diffraction analysis. The compounds 1–3 were revealed to employ an almost orthogonal configuration between the Bodipy and benzene moieties due to the presence of two methyl groups at the C-1 and C-7 positions of Bodipy core, while the counterparts **4–6** without two methyl groups at the Bodipy core take the configuration with a relatively small dihedral angle between the Bodipy and benzene moiety in the single crystal state. This leads to a larger HOMO–LUMO gap for **1–3** than that for **4–6**, resulting in a blue-shifted absorption band for the former series of three compounds than the latter series, which is also responsible for the blue-shifted fluorescence emission band and increased fluorescence quantum yield for **1–3** relative to those of **4–6**. These results clearly reveal the effect of the molecular configuration of Bodipy compounds on their spectroscopic properties.

Result and discussion

Intention and design

Bodipy derivates have attracted increasing attention due to their excellent spectroscopic properties together with the ease of fluorescent modulation by incorporating different functional groups onto different peripheral positions of Bodipy core. Substituents at the C-8 position of Bodipy derivates with an almost orthogonal molecular configuration has been revealed to have little influence on their absorption and fluorescence emission bands. However, there still seems to be no systematic investigation towards understanding the effect of molecular configuration on the electron transfer-originated spectroscopic properties of Bodipy derivates based on the X-ray diffraction analysis. As a consequence, in the present paper two series of Bodipy compounds with different molecular configuration between the Bodipy fluorophore and benzene moiety attached at the C-8 position have been prepared for the purpose of investigating the configurational effect on the electron absorption and fluorescence spectroscopic properties, Scheme 1. In addition, amine, methyl, and nitro groups were introduced onto the para-position of the C-8-attached benzene ring, which renders it possible to further investigate the effect of the electron-donating/withdrawing property of the benzene moiety at



Scheme 1 Synthesis of the Bodipy compounds 1–6.

Table 1	Crystal data	and structure	refinements	of 1-6
---------	--------------	---------------	-------------	--------

Compound	1	2	3	4^{a}	5	6
Formula	$C_{19}H_{20}BF_2N_3$	$C_{20}H_{21}BF_2N_2$	$C_{20}H_{20}BCl_2F_2N_3O_2$	$C_{17}H_{16}BF_2N_3$	$C_{18}H_{17}BF_2N_2$	$C_{17}H_{14}BF_2N_3O_2$
F.W.	339.19	338.20	454.10	311.14	310.15	341.12
Crystal system	Monoclinic	Monoclinic	Triclinic	Monoclinic	Monoclinic	Triclinic
Space group	$P2_1/n$	$P2_1$	$P\overline{1}$	$P2_1/n$	C2/c	$P\overline{1}$
a/Å	10.8454(10)	11.882(3)	8.347(4)	9.935(5)	6.554(3)	6.4804(7)
b/Å	11.8897(11)	8.409(2)	11.611(6)	23.900(5)	26.198(11)	8.3217(9)
c/Å	13.9990(13)	44.412(10)	12.092(6)	13.513(5)	9.732(4)	14.6304
$\alpha/^{\circ}$	90.00	90.00	74.438(9)	90.000(5)	90.00	80.583(2)
$\beta/^{\circ}$	105.262(10)	91.766(4)	83.016(8)	103.184(5)	105.458(8)	84.666(2)
$\gamma/^{\circ}$	90.00	90.00	68.946(8)	90.000(5)	90.00	85.576(2)
$V/Å^3$	1741.5(3)	4435.4(18)	1053.1(9)	3124(2)	1610.4(12)	773.44(15)
Z	4	10	2	8	4	2
$D_{\rm outd}/{\rm g \ cm^{-3}}$	1.294	1.266	1.432	1.323	1.279	1.465
μ/mm^{-1}	0.092	0.088	0.348	0.096	0.091	0.113
F(000)	712	1780	468	1296	648	352
$R, I > 2\theta$	0.0434	0.0754	0.0628	0.0391	0.0445	0.0376
$R_{\rm max} I > 2\theta$	0.0870	0.1882	0.1492	0.0944	0.1031	0.1034
		1 001	0.004	1 009	1 006	0.002

the C-8 position of Bodipy frame on the electron transfer nature of Bodipy fluorophore.

X-Ray single crystal structures

Single crystals of 1-3 suitable for X-ray diffraction analysis were obtained by slow diffusion of hexane into the CHCl₂ solution of these compounds, while those of 4-6 obtained from natural solvent evaporation of their CHCl₂ solution. Compounds 1, 2, 5, and 6 are first structurally characterized by X-ray diffraction analysis. However, X-ray diffraction analysis reveals the triclinic crystal system and $P\bar{1}$ space group for single crystals of **3** obtained in the present case, which is different from the monoclinic system and C2/c space group reported previously for the same compound, suggesting a crystal structure of 3 revealed this time isomeric with that reported previously.¹⁶ Both the space group and molecular structure of compound 4 were revealed to be just the same as those determined previously.¹⁷ There are five and two molecules with slightly different configurations per unit cell for 2 and 4, respectively. In contrast, only one molecule exists per unit cell for the remaining four compounds 1, 3, 5, and 6. The crystal data of the whole series of compounds 1–6 are listed in Table 1.

In these compounds, the central six-membered ring is essentially coplanar with two fused pyrrole rings, Fig. 1, with the very small maximum deviation from the least-squares mean plane of the C_9BN_2 frame being 0.052 Å for 1, 0.0404 Å for 2 (actually the average of 0.033, 0.036, 0.042, 0.043, and 0.048 Å in five molecules per unit cell), 0.077 Å for 3, 0.036 Å for 4 (the average of 0.032 and 0.04 Å in two molecules), 0.022 Å for 5, and 0.022 Å for 6, respectively, Fig. 1, indicating the slightly less planar degree of C_9BN_2 frame for 1–3 with two methyl substituents at the C-1 and C-7 positions in comparison with that for 4–6 without the two methyl substituents on the Bodipy core. The bond lengths within the C_9BN_2 backbone, without any clear distinction between single and double bonds for 1–6, reveals the strongly delocalized π -system nature of the C_9BN_2 frame in these six compounds. However, this π -electron delocalization is interrupted between the

two B–N single bonds, in coincidence with the result reported for other Bodipys.¹⁸

It is worth noting that the presence and absence of the two methyl groups at C-1 and C-7 positions of Bodipy core lead to remarkably different molecular configurations in single crystal state, principally in the dihedral angle between the benzene moiety and Bodipy frame, between 1-3 and 4-6. As shown in Fig. 1, the dihedral angle between the benzene and Bodipy moiety is 88.56 in 1, 81.14° in 2 (the average of 80.52, 80.62, 80.74, 82.13 and 82.20° in five molecules), and 82.93° in 3, indicating an almost perpendicular configuration between the benzene and Bodipy moiety. However, the corresponding dihedral angles decrease to 46.99° in **4** (the average of 48.25 and 45.73° in two molecules), 64.69° in 5, and 58.63° in 6, which are significantly smaller than those in 1-3 since the two methyl substituents at C-1 and C-7 positions of Bodiy core in 1-3 prevent the benzene group from free rotation around the Bodipy moiety. This rotation of the benzene group with respect to the Bodipy moiety has an obvious influence on the electron transfer nature within the Bodipy compounds, which in turn is responsible for their different optical properties as detailed below.

DFT calculations

Density functional theory (DFT) calculation was carried out using PBE1PBE/6-31+G(d,p) based on the crystal structures of two series of Bodipy derivatives. Since PBE1PBE displays excellent performance in energy calculation of various molecules,¹⁹ the calculation result obtained at this level in the present case is precise enough for the discussion. All calculations were carried out using the Gaussian 03 program²⁰ on an IBM P690 system housed at Shandong Province High Performance Computing Center.

The calculated energies of the highest occupied molecular orbitals (HOMOs) and the lowest occupied molecular orbitals (LUMOs) of these compounds are listed in Table 2. As can be seen, after introducing two methyl substituents onto the C-1 and C-7 positions, both the HOMO and LUMO energies of **1–3** become

		-	-					
Compounds	HOMO/eV	LUMO/eV	LUMO-HOMO/eV	$\lambda_{Ab}(max)/nm$	$\lambda_{\rm em}({\rm max})/{\rm nm}$	$arPsi_{ m f}$	$E_{\rm ox}/{ m V}$	$E_{\rm red}/{ m V}$
1	-2.33	-5.69	3.36	500	513	0.491	0.934	-1.64
2	-2.34	-5.71	3.37	500	513	0.600	0.993	-1.531
3	-2.93	-6.15	3.22	506	527	0.009	1.061	-1.394
4	-2.57	-5.85	3.28	507	523	0.198	1.080	-1.540
5	-2.64	-5.93	3.29	510	526	0.292	1.090	-1.490
5	-3.22	-6.32	3.10	518	555	0.002	1.132	-1.344
	1	¢	2	3	8			
		ę.	-9 C		T. G			
		~ 17	· ~ Ĩ	20	~ 1 2-			
		-000	• • • • • • • •		-			
		~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	a 8	de	ale de des			
		( <del>0</del> ) ^{88.5}	56°	$\theta$ 81.14°	82.39°			
		/			1			
	4		5	6				
		1 m			<b>.</b>			
		$\sum$			XX			
		2 Le	21	2	2 Lis			
			• •	)- ·				
		af Y h		Jo .	af 8 do			
		•	-		and an D			
				1	1			
		· /	0	5.1.55 ⁹	- 58 63°			
		θ,46.99	)°	θ 64.69°	θ			
					1			
		<b>*</b>						

Table 2 Calculated energy data, the recorded spectroscopic and electrochemical data of 1-6 in CH₂Cl₂

Fig. 1 Molecular structures of 1–6 in top-view (top) and side-view (bottom), respectively, with the atoms except for the ones of Bodipy and benzene moieties omitted for clarity in side-view (bottom).

higher in comparison with those of corresponding counterpart in 4–6, namely 1 > 4, 2 > 5, and 3 > 6. However, the LUMO level for 1–3 increases to a larger extent than the HOMO level, resulting in an enlarged HOMO–LUMO gap of 1–3 in comparison with 4–6 (Fig. S1, ESI†). On the basis of a previous study, the molecular structure for the six Bodipy compounds 1–6 could be divided into two parts, namely the Bodipy fluorophore and the benzene moiety connected through C–C single bond in a twisted form.²¹ The HOMO for all these compounds is localized in the Bodipy moiety regardless of the substituent at the C-8 position. However, the LUMO of 1–6 exhibits significant dependence on the molecular configuration of the Bodipy compounds. When the benzene and Bodipy moieties are perpendicular to each other, the LUMO is localized on the Bodipy frame. In contrast, when the benzene moiety is coplanar with the Bodipy moiety in the compounds, the LUMO becomes extensively delocalized into the benzene moiety.²² As a consequence, the change in the molecular configuration, *i.e.* the dihedral angle between benzene and Bodipy moieties, leads to different LUMO energy level and corresponding HOMO– LUMO energy gap between 1–3 and 4–6, Fig. 2. This in turn is responsible for the different electron absorption spectroscopic features between these two series of Bodipy compounds as detailed



Fig. 2 Orbital maps of LUMOs and HOMOs of 1-6.

below due to the nearly pure HOMO–LUMO electron transition nature of  $S_0$ – $S_1$  transition in these Bodipy compounds.²³

#### **Electronic absorption properties**

The electronic absorption spectra of 1-6 were recorded in a variety of solvents with different polarity including toluene,  $CH_2Cl_2$ , THF,  $CH_3CN$ , DMF, and MeOH, and the data are compiled in Tables 2 and S1 (ESI[†]). As shown in Fig. 3, these six compounds show typical electronic absorption features of Bodipy derivates, namely narrow spectral bands with two absorption maxima. The electronic absorption maxima at *ca*. 500 nm can be attributed to a strong  $S_0$ – $S_1$  transition, while the second maximum or shoulder at the high energy side to the 0–1 vibrational transition. Along with the decrease in the solvent polarity from MeOH to toluene, their absorption maxima take slight shift (*ca*. 6 nm) to the lower energy



Fig. 3 The electronic absorption (A and B) and fluorescence spectra (C and D) of Bodipy compounds 1–6 at the concentration of  $1 \times 10^{-5}$  M in CH₂Cl₂ and CH₃CN, respectively, with the excitation wavelength of 450 nm.

direction (Fig. S2, ESI[†]), indicating the relatively small change in the dipole moment between the ground and excited states of these compounds. The result is in line with the behavior of other Bodipy derivates reported previously.²⁴

It is worth noting that the main absorption band for 1-3 is obviously blue-shifted in comparison with that for 4-6 due to the bigger HOMO-LUMO gap of the former series of three compounds, Table 2. Nevertheless, along with the change of the para-substituent at the C-8 attached benzene moiety from NH₂, CH₃, to NO₂ group, the main absorption band in their electronic absorption spectra takes a slight red-shift, ca. 5 nm, from NH₂substituted 1 to NO₂-substituted 3. However, along with the same order, the main absorption band takes a more significant degree of red-shift, ca. 11 nm, from NH₂-substituted 4 to NO₂substituted 6. As mentioned in the DFT calculation section, the LUMO energy level is primarily located on the Bodipy core in 1-3 with almost perpendicular configurations between the Bodipy core and the benzene moiety, indicating the little effect of benzene moiety on the electronic absorption band of 1-3 involving the  $S_0-S_1$  transition. In contrast, the LUMO energy level in 4-6 with smaller dihedral angles between the Bodipy core and the benzene moiety is partly delocalized into benzene moiety, resulting in the dependence of electronic absorption band involving the  $S_{0}$ - $S_1$  transition on the benzene moiety in 4-6. As a consequence, the change in the electron-donating/withdrawing ability of parasubstituent of benzene moiety from NH₂ to NO₂ via CH₃ induces a much more significant effect on the main electronic absorption band for the series of 4-6 in comparison with 1-3, Fig. 3, revealing the enhanced interaction between the Bodipy core and the benzene moiety for 4-6.

#### Fluorescence properties

To systematically investigate the effect of the molecular configuration and the electron-donating/withdrawing ability of benzene moiety on the electron transfer-originated fluorescence properties of Bodipy derivatives, the steady-state fluorescence emission spectra of 1-6 were measured in the same six kinds of solvents as done for their electronic absorption spectra and the data are summarized in Tables 2 and S1 (ESI[†]). The fluorescence emission spectra of 1-6 display a clearly Stokes-shifted band relative to their main electronic absorption band with the Stokes-shift of ca. 13 nm for NH₂- or CH₃-substituted 1 and 2, ca. 20 nm for NO₂substituted 3, ca. 17 nm for NH2- or CH3-substituted 4 and 5, and 37 nm for NO₂-substituted **6**, Fig. 3. Obviously, the fluorescence emission band for 1-3 takes a relatively less extent of Stokesshift in comparison with corresponding counterpart in 4-6. This is attributed to the nearly orthogonal configuration between the Bodipy core and the benzene moiety associated with two methyl substituents at the C-1 and C-7 positions of the Bodipy core in the former series of three compounds, which prevents the free rotation of a benzene moiety along the single C–C bond connecting the benzene and Bodipy moieties. In contrast, in the latter series of three compounds 4-6, the free rotation of the benzene ring relative to the Bodipy moiety due to the absence of two corresponding methyl groups renders it possible to induce an enhanced interaction between the benzene and Bodipy moieties. As a consequence, a relatively larger Stokes-shift in the fluorescence emission band was observed for 4-6 than corresponding counterparts 1-3 due

to the larger transfiguration between the excited state and ground state for the Bodipy compounds  $4-6.^{25}$  This is clearly evidenced by the smaller degree of red-shift in the fluorescence emission band along with the change of the *para*-substituent at the benzene moiety from NH₂, CH₃, to NO₂ group for 1, 2, and 3, *ca.* 12 nm, in comparison with that for 4, 5, and 6 along with the same order, *ca.* 33 nm. Moreover, the fluorescence quantum yields of 1–3 are significantly higher than those of the corresponding counterparts 4–6, further confirming the enhanced interaction between the benzene and Bodipy moieties in the latter series of compounds 4–6 due to the free rotation of benzene moiety, which in turn leads to a larger extent of excited energy loss from the excited Bodipy moiety *via* non-irradiative decay for 4–6 than 1–3.²⁶

It is also noteworthy that the electron-donating/withdrawing property of the *para*-substituent of the benzene moiety has an obvious effect on the fluorescence properties of 1-6. As can be seen in Fig. 3 and Tables 2 and S1 (ESI⁺), the shift between the two corresponding counterparts with the same para-substituent of benzene moiety but different molecular conformation ranges from ca. 10 nm for NH₂-substituted 1 vs. 4, ca. 12 nm for CH₃substituted 2 vs. 5, to ca. 28 nm for NO₂-substituted 3 vs. 6. More remarkably, the fluorescence quantum yield of the Bodipy compounds is closely related to the electron-donating/withdrawing properties of the benzene moiety in 1-6 due to their modulation on the MO energy level as mentioned above, which in turn exhibits influence on the electron transfer between the benzene and Bodipy moieties. As listed in Tables 2 and S1,† along with the change in the para-substituent of benzene moiety from the electron-donating group of NH₂ and CH₃ for 1 and 2 to electron-withdrawing group of NO₂ for 3, the fluorescence quantum yield largely decreases from 1 and 2 to 3 in apolar solvent such as toluene and  $CH_2Cl_2$ . However, in polar solvents like methanol, DMF, acetonitrile, and THF, the fluorescence quantum yield of 1 was markedly decreased ca. 30-fold. In contrast, the corresponding fluorescence quantum yield for 2 or 3 displayed a slight decrease comparable to that in apolar solvent. This is also true for the series of compounds 4-6. According to our calculation results, when the strong electronwithdrawing NO₂ group is introduced onto the para-position of the benzene moiety in 3 and 6, the LUMO energy of the electrondeficient benzene moiety gets decreased, being close to the LUMO of Bodipy fluorophore. This induces an electron transfer from the excited Bodipy moiety to the benzene moiety in these two compounds, resulting in the fluorescence quenching of the Bodipy fluorophore.²⁷ In contrast, when the electron-donating CH₃ group is introduced onto the *para*-position of the benzene moiety in 2 and 5, the LUMO energy level of the benzene moiety is increased, becoming further higher than that of Bodipy fluorophore, which in turn inhibits the electron transfer from the LUMO of the excited Bodipy fluorophore to the LUMO of the benzene moiety and therefore switches on the fluorescence of Bodipy moiety for 2 and 5 in these six solvents, Tables 2 and S1 (ESI[†]).

This should also be true for the Bodipy compounds 1 and 4 with a much stronger electron-donating group of  $NH_2$  incorporated onto the *para*-position of the benzene moiety. However, as mentioned above, the fluorescence properties of 1 and 4 are revealed to be intensively dependent on the polarity of the solvents. When 1 and 4 were dissolved into the apolar solvents like toluene and  $CH_2Cl_2$ , intensive fluorescence was observed for these two compounds, similar to 2 and 5. In contrast, when 1 and 4 were dissolved in polar solvents, including THF,  $CH_3CN$ , DMF, and MeOH, the intermolecular interaction between the  $NH_2$  group and solvent molecules, in particular hydrogen bond interactions, induced the photo-induced electron transfer between the excited Bodipy moiety and the benzene moiety, as shown in 3 and 6, resulting in fluorescence quenching from the Bodipy moiety for 1 and 4.¹⁶

#### **Electrochemistry properties**

The redox behaviors of **1–6** were studied by cyclic voltammetry in CH₂Cl₂ and the electrochemical data are listed in Table 2, Fig. 4 and Fig. S4.† Within the electrochemical window of CH₂Cl₂, all these compounds exhibited one irreversible one-electron oxidation and one quasi-reversible one-electron reduction, which are attributed to removal from or addition of one electron to the frontier molecular orbitals of **1–6**. Comparison of the redox behavior between the two counterparts with the same *para*substituent of benzene moiety but different dihedral angle between Bodipy moiety and benzene moiety, namely **1** *vs.* **4** (–1.640 V *vs.* -1.540 V), **2** *vs.* **5** (–1.531 V *vs.* –1.490 V) and **3** *vs.* **6** (–1.394 V *vs.* –1.344 V) reveals that compounds **1–3** with almost orthogonal configuration are harder to get one electron to be reduced than the corresponding counterparts **4–6** with lower dihedral angles between Bodipy moiety and benzene moiety, indicating the effect of the molecular configuration on the redox properties of Bodipy compounds. Nevertheless, as can be expected, along with the change of the *para*-substituent from the electron-donating NH₂ and CH₃ group to the electron-withdrawing NO₂ group, the quasireversible reduction potential increases in the order of 1 < 2 < 3, which is also true for the latter series of 4 < 5 < 6, Table 2, indicating that the electron-withdrawing NO₂ group increases the redox potential, which is beneficial to the photo-induced electron transfer between the excited Bodipy and nitrophenyl moieties.

# Conclusion

Briefly summarizing above, a series of six Bodipy derivatives have been structurally characterized by single crystal X-ray diffraction analysis. The compounds 1–3 with two methyl groups at the C-1 and C-7 positions of Bodipy core were revealed to employ the relatively rigid molecular configuration with an almost orthogonal dihedral angle between the Bodipy and benzene moieties. In contrast, compounds 4–6 without two methyl substituents take the configuration with a free-rotating benzene moiety relative to the Bodipy core, leading to an enhanced interaction between these two moieties in 4–6 in comparison with in 1–3. The resulting larger HOMO–LUMO gap for 1–3 than for 4–6 leads to blue-shifted



Fig. 4 Cyclic voltammetry of  $NH_2$ -substituted 1 and 4 as well as  $NO_2$ -substituted 3 and 6 in  $CH_2Cl_2$  containing 0.1 M [ $NBu_4$ ][ $ClO_4$ ] at the scan rate of 20 mV s⁻¹.

the spectroscopic properties of Bodipy derivatives. This effect gets additional support from the redox behavior of these two series of Bodipy compounds. The present result appears to represent the first systematic study towards understanding the effect of the molecular configuration on the optical properties, which should be helpful for designing and preparing novel Bodipy derivatives with potential applications in chemical and biological fields. Experimental General chemicals

Column chromatography was carried out on silica gel (Merck,

absorption and fluorescence emission bands, and in particular

higher fluorescence quantum yield for the former series of three

compounds, revealing the effect of molecular configuration on

Kieselgel 60, 70-230 mesh) with the indicated eluents. All other reagents and solvents were used as received. Dichloromethane was freshly distilled from CaH₂ under nitrogen. The compounds 1, 2, 3, 4, and 6 were prepared according to the published procedures.¹⁶⁻¹⁷

# General instruments

¹H NMR spectra were recorded on a Bruker DPX 400 spectrometer (400 MHz) in CDCl₃ using the residual solvent resonance of CDCl₃ at 7.26 ppm relative to SiMe₄ (0.00 ppm). MALDI-TOF mass spectra were taken on a Bruker BIFLEX III ultra-high resolution Fourier transform ion cyclotron resonance (FT-ICR) mass spectrometer with alpha-cyano-4-hydroxycinnamic acid as matrix. Elemental analyses were performed on an Elementar Vavio El III. Electronic absorption spectra were recorded on a Hitachi U-4100 spectrophotometer. Steady-state fluorescence spectroscopic studies were performed on an F 4500 (Hitachi). The slit width was 2.5 nm for emission. The photon multiplier voltage was 700 V. The relative quantum efficiencies of fluorescence of Bodipy derivatives were obtained by comparing the area under the corrected emission spectrum of the test sample with that of a solution of 4,4-difluoro-8-(4-methylphenyl)-1,3,5,7-tetramethyl-4bora-3a,4a-diaza-s-indacene in CH₂Cl₂ with excitation wavelength of 450 nm, which has a quantum efficiency of 0.60 according to the literature.16

Electrochemical measurements were carried out with a BAS CV-50W voltammetric analyzer. The cell comprised inlets for a glassy carbon disk working electrode of 2.0 mm in diameter and a silverwire counter electrode. The reference electrode was Ag/Ag⁺ {a solution of 0.01 M AgNO3 and 0.1 M [NBu4][ClO4] in acetonitrile}, which was connected to the solution by a Luggin capillary whose tip was placed close to the working electrode. Results were corrected for junction potentials by being referenced internally to the ferrocenium/ferrocene (Fe⁺/Fe) couple  $[E_{1/2}(Fe^+/Fe) = +0.50]$ V vs. SCE]. Potentials in this paper are referenced to the SCE. Typically, a 0.1 M solution of [NBu₄][ClO₄] in CH₂Cl₂ containing 0.5 M of sample was purged with nitrogen for 10 min, and then the voltammograms were recorded at ambient temperature. The scan rate was 20 mV s⁻¹.

# X-Ray crystallographic analysis

Crystal data and details of data collection and structure refinement are given in Table 1. Data were collected on a Bruker SMART CCD diffractometer with a Mo-K $\alpha$  sealed tube ( $\lambda = 0.71073$ Å) at 293 K, using a  $\omega$  scan mode with an increment of 0.3°. Final unit cell parameters were obtained by global refinements of reflections obtained from integration of all the frame data. The collected frames were integrated using the preliminary cellorientation matrix. The SMART software was used for collecting frames of data, indexing reflections, and determination of lattice constants; SAINT-PLUS for integration of intensity of reflections and scaling; SADABS for absorption correction; and SHELXL for space group and structure determination, refinements, graphics, and structure reporting. CCDC reference numbers 798782-798787 for six Bodipy compounds 1-6. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c1pp00001b

# Synthesis 4,4-difluoro-8-(4-methylphenyl)-3,5-dimethyl-4-bora-3a,4a-diaza-s- indacene (5)

To the mixture of 4-methylbenzaldehyde (120 mg, 1 mmol) and 2methylpyrrole (160 mg, 2.00 mmol) dissolved in CH₂Cl₂ (100 mL), one drop of TFA was added. The resulting mixture was then stirred at room temperature under N2 atmosphere. When thin-layer chromatography (TLC) monitoring (silica, CH₂Cl₂) indicated the complete consumption of the aldehyde, a solution of DDQ (227 mg, 1 mmol) in CH₂Cl₂ (40 mL) was added and the reaction mixture was further stirred for another 15 min. After the addition of N,N-diisopropylethylamine (DIEA) (2 mL) into the mixture for 5 min, the BF₃-OEt₂ (2.0 mL) was added into the reaction mixture and stirring was continued for another 50 min. The resulting mixture was evaporated, and the residue was chromatographed on a silica gel column using  $CH_2Cl_2$ /hexane (1:2) as eluent. Repeated chromatography followed by recrystallization from CH₂Cl₂ and MeOH gave the target compound 5 as black-green crystals, 84 mg (27%). ¹H NMR (CDCl₃, 400 MHz):  $\delta$  7.375 (d, 2H, J = 7.2 Hz), 7.267 (d, 2H, J = 14.6 Hz), 6.716 (d, 2H, J = 2.4 Hz), 6.245 (d, 2H, J =J = 3.2 Hz), 2.637 (s, 6H), 2.429 (s, 3H); MS (MALDI-TOF): an isotopic cluster peaking at m/z 310.15, [Calcd. For M⁺ 310.14]; Anal. calcd for C₁₈H₁₇BF₂N₃: C, 69.71; H, 5.52; N, 9.03%. Found: C, 69.05; H, 4.82; N, 9.74.

# Acknowledgements

Financial support from the Natural Science Foundation of China, Ministry of Education of China, and Fundamental Research Funds for the Central universities, Beijing Municipal Commission of Education, and University of Science and Technology Beijing is gratefully acknowledged.

#### References

- 1 A. Treibs and F. H. Kreuzer, Difluorboryl-komplexe von di- and tripyrrylmethenen, Justus Liebigs Ann. Chem., 1968, 718, 208-223.
- 2 (a) J. Karolin, L. B. A. Johansson, L. Strandberg and T. Ny, Fluorescence and absorption spectroscopic properties of dipyrrometheneboron difluoride (BODIPY) derivatives in liquids, lipid membranes, and proteins, J. Am. Chem. Soc., 1994, 116, 7801-7803; (b) E. J. Merino and K. M. Weeks, Facile conversion of aptamers into sensors using a 2'-ribose-linked fluorophore, J. Am. Chem. Soc., 2005, 127, 12766-12767; (c) B. R. Sculimbrene and B. Imperiali, Lanthanide-binding tags as luminescent probes for studying protein interactions, J. Am. Chem. Soc., 2006, 128, 7346-7352.
- 3 (a) J. L. Bricks, A. Kovalchuk, C. Trieflinger, M. Nofz, M. Buschel, A. I. Tolmachev, J. Daub and K. Rurack, On the development of sensor

molecules that display Fe^{III}-amplified fluorescence, *J. Am. Chem. Soc.*, 2005, **127**, 13522–13529; (*b*) D. W. Domaille, L. Zeng and C. J. Chang, Visualizing ascorbate-triggered release of labile copper within living cells using a ratiometric fluorescent sensor, *J. Am. Chem. Soc.*, 2010, **132**, 1194–1195; (*c*) K. Rurack, M. Kollmannsberger and J. Daub, Molecular switching in the near infrared (NIR) with a functionalized boron-dipyrromethene dye, *Angew. Chem., Int. Ed.*, 2001, **40**, 385–387.

- 4 (a) K. Rurack, M. Kollmannsberger, U. Resch-Genger and J. Daub, A selective and sensitive fluoroionophore for Hg^{II}, Ag^I, and Cu^{II} with virtually decoupled fluorophore and receptor units, J. Am. Chem. Soc., 2000, **122**, 968–969; (b) Y. Gabe, Y. Urano, K. Kikuchi, H. Kojima and T. Nagano, Highly sensitive fluorescence probes for nitric oxide based on boron dipyrromethene chromophore-rational design of potentially useful bioimaging fluorescence probe, J. Am. Chem. Soc., 2004, **126**, 3357–3367; (c) K. Yamada, Y. Nomura, D. Citterio, N. Iwasawa and K. Suzuki, Highly sodium-selective fluoroionophore based on conformational restriction of oligoethyleneglycol-bridged biaryl Boron-dipyrromethene, J. Am. Chem. Soc., 2005, **127**, 6956–6957; (d) M. Baruah, W. Qin, R. A. L. Vallee, D. Beljonne, T. Rohand, W. Dehaen and N. Boens, A highly potassium-selective ratiometric fluorescent indicator based on BODIPY azacrown ether excitable with visible light, Org. Lett., 2005, **7**, 4377–4379.
- 5 T. L. Arbeloa, F. L. Arbeloa, I. L. Arbeloa, I. Garcia-Moreno, A. Costela, R. Sastre and F. Amat-Guerri, Correlations between photophysics and lasing properties of dipyrromethene-BF₂ dyes in solution, *Chem. Phys. Lett.*, 1999, **299**, 315–321.
- 6 (a) G. Ulrich, R. Ziessel and A. Harriman, The chemistry of fluorescent bodipy dyes: versatility unsurpassed, *Angew. Chem., Int. Ed.*, 2008, 47, 1184–1201; (b) J. Q. Feng, B. L. Liang, D. L. Wang, L. Xue and X. Y. Li, Novel fluorescent dyes with fused perylene tetracarboxlic diimide and BODIPY analogue structures, *Org. Lett.*, 2008, 10, 4437–4440; (c) J. Wang and X. Qian, Two regioisomeric and exclusively selective Hg(II) sensor molecules composed of a naphthalimide fluorophore and an *o*-phenylenediamine derived triamide receptor, *Chem. Commun.*, 2006, 109–111.
- 7 (a) A. Loudet and K. Burgess, BODIPY dyes and their derivatives: syntheses and spectroscopic properties, *Chem. Rev.*, 2007, **107**, 4891– 4932; (b) K. Tanaka, T. Miura, N. Umezawa, Y. Urano, K. Kikuchi, T. Higuchi and T. Nagano, Rational design of fluorescein-based fluorescence probes: Mechanism-based design of a maximum fluorescence probe for singlet oxygen, *J. Am. Chem. Soc.*, 2001, **123**, 2530– 2536.
- 8 S. Ozlem and E. U. Akkaya, Thinking outside the silicon box: Molecular AND logic as an additional layer of selectivity in singlet oxygen generation for photodynamic therapy, *J. Am. Chem. Soc.*, 2009, 131, 48–49.
- 9 Z. Shen, H. Rohr, K. Rurack, H. Uno, M. Spieles, B. Schulz, G. Reck and N. Ono, Boron-diindomethene (BDI) dyes and their tetrahydrobicyclo precursors-en route to a new class of highly emissive fluorophores for the red spectral range, *Chem.-Eur. J.*, 2004, **10**, 4853– 4871.
- 10 T. Yogo, Y. Urano, Y. Ishitsuka, F. Maniwa and T. Nagano, Highly efficient and photostable photosensitizer based on BODIPY chromophore, J. Am. Chem. Soc., 2005, 127, 12162–12163.
- 11 K. Yamada, T. Toyota, K. Takakura, M. Ishimaru and T. Sugawara, Preparation of BODIPY probes for multicolor fluorescence imaging studies of membrane dynamics, *New J. Chem.*, 2001, 25, 667–669.
- 12 H. Sunahara, Y. Urano, H. Kojima and T. Nagano, Design and synthesis of a library of BODIPY-based environmental polarity sensors utilizing photoinduced electron-transfer-controlled fluorescence ON/OFF switching, J. Am. Chem. Soc., 2007, 129, 5597–5604.
- 13 C. Goze, G. Ulrich, L. J. Mallon, B. D. Allen, A. Harriman and R. Ziessel, Synthesis and photophysical properties of borondipyrromethene dyes bearing aryl substituents at the boron center, *J. Am. Chem. Soc.*, 2006, **128**, 10231–10239.

- 14 C. Goze, G. Ulrich and R. Ziessel, Tetrahedral boron chemistry for the preparation of highly efficient "cascatelle" devices, J. Org. Chem., 2007, 72, 313–322.
- 15 C. Goze, G. Ulrich and R. Ziessel, Unusual fluorescent monomeric and dimeric dialkynyl dipyrromethene-borane complexes, *Org. Lett.*, 2006, 8, 4445–4448.
- 16 A. Cui, X. Peng, J. Fan, X. Chen, Y. Wu and B. Guo, Synthesis, spectral properties and photostability of novel boron-dipyrromethene dyes, J. Photochem. Photobiol., A, 2007, 186, 85–92.
- 17 J. Shin, B. O. Patrick and D. Dolphin, Self-assembly via intermolecular hydrogen-bonding between o-/m-/p-NH₂ and BF₂ groups on dipyrromethenes, *Tetrahedron Lett.*, 2008, 49, 5515–5518.
- 18 M. Broring, R. Kruger, S. Link, C. Kleeberg, S. Kohler, X. Xie, B. Ventura and L. Flamigni, Bis(BF₂)-2,2'-bidipyrrins (BisBODIPYs): highly fluorescent BODIPY dimers with large stokes shifts, *Chem.-Eur. J.*, 2008, 14, 2976–2983.
- 19 (a) Y. Zhao and D. G. Truhlar, Benchmark databases for nonbonded interactions and their use to test density functional theory, J. Chem. Theory Comput., 2005, 1, 415–432; (b) Y. Zhao and D. G. Truhlar, Design of density functionals that are broadly accurate for thermochemistry, thermochemical kinetics, and nonbonded interactions, J. Phys. Chem. A, 2005, 109, 5656–5657.
- 20 M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, J. A. Montgomery, Jr., T. Vreven, K. N. Kudin, J. C. Burant, J. M. Millam, S. S. Iyengar, J. Tomasi, V. Barone, B. Mennucci, M. Cossi, G. Scalmani, N. Rega, G. A. Petersson, H. Nakatsuji, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, M. Klene, X. Li, J. E. Knox, H. P. Hratchian, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. Ochterski, P. Y. Ayala, K. Morokuma, G. A. Voth, P. Salvador, J. J. Dannenberg, V. G. Zakrzewski, S. Dapprich, A. D. Daniels, M. C. Strain, O. Farkas, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. V. Ortiz, Q. Cui, A. G. Baboul, S. Clifford, J. Cioslowski, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, M. Challacombe, P. M. W. Gill, B. G. Johnson, W. Chen, M. W. Wong, C. Gonzalez and J. A. Pople, GAUSSIAN 03 (Revision B.05), Gaussian, Inc., Wallingford, CT, 2004.
- 21 Y. Urano, M. Kamiya, T. Kanda, T. Ueno, K. Hirose and T. Nagano, Evolution of fluorescein as a platform for finely tunable fluorescence probes, J. Am. Chem. Soc., 2005, 127, 4888–4894.
- 22 H. L. Kee, C. Kirmaier, L. Yu, P. Thamyongkit, W. J. Youngblood, M. E. Calder, L. Ramos, B. C. Noll, D. F. Bocian, W. R. Scheidt, R. R. Birge, J. S. Lindsey and D. Holten, Structural control of the photodynamics of boron-dipyrrin complexes, *J. Phys. Chem. B*, 2005, 109, 20433–20443.
- 23 J. Banuelos Prieto, F. Lopez Arbeloa, V. Martinez Martinez, T. Arbeloa Lopez, F. Amat-Guerri, M. Liras and I. Lopez Arbeloa, Photophysical properties of a new 8-phenyl analogue of the laser dye PM567 in different solvents: internal conversion mechanisms, *Chem. Phys. Lett.*, 2004, **385**, 29–35.
- 24 Y. H. Yu, A. B. Descalzo, Z. Shen, H. Rohr, Q. Liu, Y. W. Wang, M. Spieles, Y. Z. Li, R. K. Urack and X. Z. You, Monoand di(dimethylamino)styryl-substituted borondipyrromethene and borondiindomethene dyes with intense near-infrared fluorescence, *Chem.-Asian J.*, 2006, **1**, 176–187.
- 25 J. Waluk, Ground- and excited-state tautomerism in porphycenes, Acc. Chem. Res., 2006, 39, 945–952.
- 26 W. Qin, M. Baruah, M. Van der Auweraer, F. C. De Schryver and N. Boens, Photophysical properties of borondipyrromethene analogues in solution, *J. Phys. Chem. A*, 2005, **109**, 7371–7384.
- 27 T. Ueno, Y. Urano, H. Kojima and T. Nagano, Mechanism-based molecular design of highly selective fluorescence probes for nitrative stress, J. Am. Chem. Soc., 2006, 128, 10640–10641.