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The synthesis and properties of naphthopyran– boradiazaindacene conjugates

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ABSTRACT

Three new 3,3-diaryl-3*H*-naphtho[2,1-*b*]pyran–boradiazaindacene conjugates have been synthesised. The naphthopyran–boradiazaindacene conjugates exhibit a weaker photochromic response relative to the simple naphthopyrans with the photomerocyanines fading relatively quickly. Photochromic switching of the naphthopyran unit results in a decrease in the fluorescence intensity for only the most persistent photomerocyanine. A crystal structure shows that the units are essentially orthogonally disposed and that the boradiazaindacene core is extensively delocalised.

1. Introduction

Fluorescent dyes containing the 4,4-difluoro-4-bora-3a,4a-diaza-*s*-indacene core **1**, commonly referred to as BODIPY dyes, have been widely studied [1]. Their impressive fluorescence properties have resulted in a broad range of structural variants designed to tailor absorption/emission wavelength [2], improve two-photon absorption [3], enhance solid state emission [4], sensitivity to analytes [5] and singlet oxygen generation [6], participate in energy transfer systems [7], behave as pH probes [8] and as fluorescence probes for catalyst evaluation in high-throughput screening [9] and serve as sensitizers in dye sensitized solar cell assemblies [10]. There has recently been considerable activity in the fluorescence switching of BODIPY dyes through the use of hydrogen bonded [11] and covalently bonded photochromic systems including diarylethenes **2** [12], spiropyrans **3** [13] and oxazines **4** [14]. Our interests are focussed on photochromic naphthopyrans [15] and we have previously reported the colour modulation of a triarylmethine dye through the photochromic cycling of a naphthopyran [16]. We became curious as to whether a naphthopyran unit could be coupled to a BODIPY dye and subsequently be used to modulate the photophysical properties of such a coupled system. We now report our preliminary results concerning the synthesis, structural characterisation and photochromic response of such BODIPY-naphthopyran conjugates (Scheme 1).

2. Experimental

2.1. Equipment

Unless otherwise stated, reagents were used as supplied by the major chemical catalogue companies. NMR spectra were recorded on a Bruker Avance 400 MHz spectrophotometer (^{1}H NMR 400 MHz, ^{13}C NMR 100 MHz) for sample solutions in $CDCl_3$ with tetramethylsilane as an internal reference. Melting points were either determined in capillary tubes or obtained by differential scanning calorimetry using a TA Instrument DSC 2010. The crystal structure determination was carried out at 150 K on a Bruker-Nonius Apex X8 diffractometer equipped with an Apex II CCD detector and using graphite monochromated Mo-Kα radiation from a FR591 rotating anode generator. The structure was solved by direct methods and refined using SHELXL-97. FT-IR spectra were recorded on a Perkin Elmer Spectrum One spectrophotometer system equipped with a golden gate ATR attachment (neat sample). Fluorescence spectra were recorded in 10 mm path length quartz cuvettes in spectroscopic grade toluene using a Perkin Elmer LS55 fluorescence spectrometer and relative fluorescence quantum yields (Φ_f) were determined using an aqueous acidic, degassed solution of quinine bisulfate (Φ_f = 0.55 in 1 N H_2SO_4) [17]. UV–visible spectra were recorded for spectroscopic grade CH_2Cl_2

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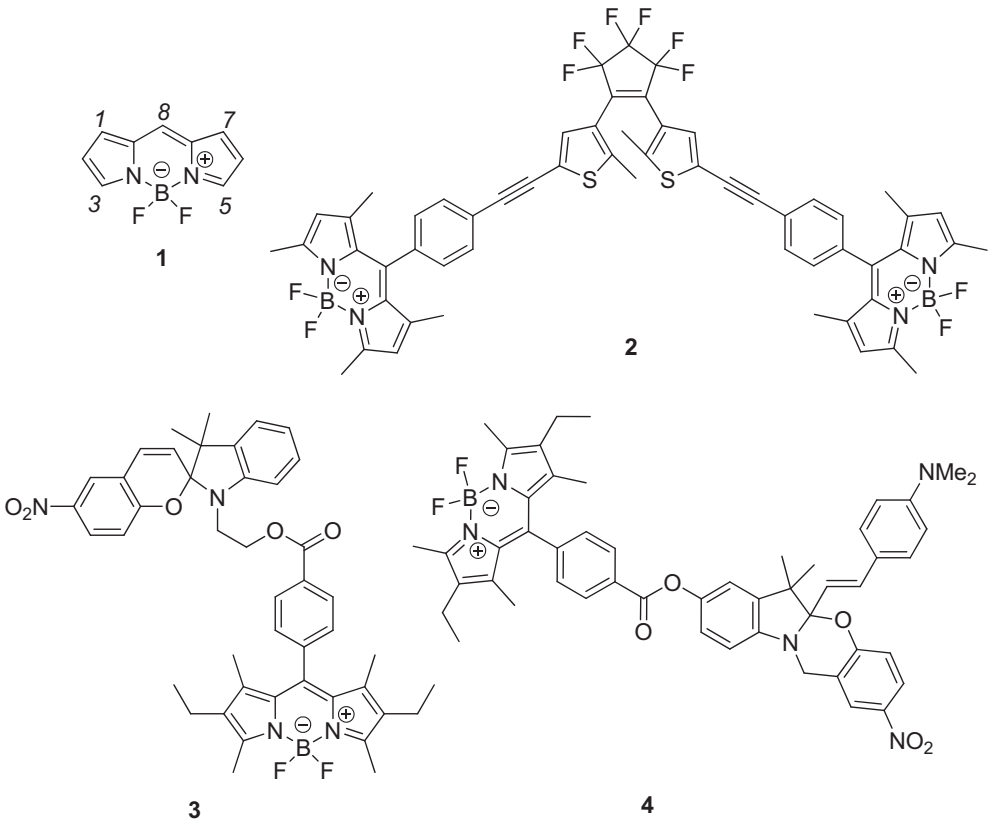


Scheme 1. The 4,4-difluoro-4-bora-3a,4a-diaza-*s*-indacene nucleus **1** and photochromic BODIPY dye systems **2**–**4**.

solutions of the samples (10 mm path length quartz cuvette, PTFE capped, concentration in the range 1.3–2.0 $\times$ 10^{-5} mol dm^{-3}) using a Cary 50 Probe spectrophotometer equipped with a single cell Peltier temperature controlled (20 °C) stirred cell attachment with activating irradiation provided by an Oriel 150 Watt xenon arc lamp source (Newport 66906), xenon ozone free arc lamp (Newport 6255), distilled water liquid filter (Newport 6177), multiple filter holder (Newport 62020), UG11 filter (Newport FSO-UG11), fibre optic coupler (Newport 77799) and liquid light guide (Newport 77557). Spectra (350–750 nm) were recorded at 6 s intervals over a 600 s period. All compounds were homogeneous by TLC [Merck TLC aluminium sheets either silica gel 60 F_{254} (cat. No 105554)] using a range of eluent systems of differing polarity and flash column chromatography was performed on chromatography silica gel (Fluorochem, 40–63 micron particle size distribution). Mass spectra were recorded at the National EPSRC Mass Spectrometry Service Centre, Swansea.

2.2. Preparation of 6-hydroxy-2-naphthaldehyde **5**

n-BuLi (29.4 mL, 47.1 mmol, 1.6 M solution in hexanes) was added dropwise to a cold (−78 °C) stirred solution of 6-bromo-2-naphthol (5 g, 22.4 mmol) in anhydrous THF (80 mL), after 15 min anhydrous 1-formylpiperidine (7.5 mL, 67.2 mmol) was added and the mixture was stirred for 15 min at −78 °C and allowed to gradually warm to room temperature. Water (150 mL) was added and the mixture acidified (~pH 5) with conc. HCl. The aqueous layer was extracted with ethyl acetate (3 $\times$ 50 mL) and the combined organic layers were dried over anhyd. Na_2SO_4 and the solvent removed under vacuum to afford the title compound **5** (3.13 g) 81% yield, mp 177–178 °C (lit. mp 180 °C [18]), δ_H (d_6-DMSO) 7.21 (2H, m, Ar–H), 7.79 (2H, m, Ar–H), 8.02 (1H, d, *J* 8.5 Hz, 4-H), 8.43 (1H, d, *J* 0.6 Hz, 1-H), 10.04 (1H, s, CHO), 10.35 (1H, bs, OH).

2.3. Preparation of 6-[Bis-(3,5-dimethyl-1H-pyrrol-2-yl)methyl]-2-naphthol **7**

6-Hydroxy-2-naphthaldehyde **5** (1.5 g, 8.7 mmol) and 2,4-dimethylpyrrole (1.65 g, 17.4 mmol) were dissolved in CH_2Cl_2 (400 mL) under a nitrogen atmosphere. Trifluoroacetic acid (0.1 mL 0.87 mmol) was added and the solution was stirred at room temperature (rt) for 3 h. The CH_2Cl_2 was removed under vacuum and the crude brown gum was purified by flash chromatography (20:79:1 EtOAc:hexane:triethylamine) to afford the title compound **7** as a pale brown solid (1.68 g) 56%, δ_H 1.84 (6H, s, $(5\text{-}CH_3)_2$), 2.14 (6H, s, $(3\text{-}CH_3)_2$), 5.55 (1H, s, methine), 5.73 (2H, d, *J* 2.6 Hz, pyrrole 4-H), 7.05 (1H, dd, *J* 8.8, 2.5 Hz, Ar–H), 7.10 (1H, d, *J* 2.2 Hz, Ar–H), 7.25 (2H, m, Ar–H), 7.46 (2H, bs, pyrrole NH), 7.60 (1H, d, *J* 8.5 Hz, 4-H), 7.65 (1H, d, *J* 8.8 Hz, 8-H).This sample was used directly for the preparation of 4,4-difluoro-1,3,5,7-tetramethyl-8-(6-hydroxynaphth-2-yl)-4-bora-3a,4a-diaza-s-indacene **6b**.

2.4. Preparation of 4,4-difluoro-1,3,5,7-tetramethyl-8-(6-hydroxynaphth-2-yl)-4-bora-3a,4a-diaza-s-indacene **6b**

Dichlorodicyanoquinone (DDQ) (1.82 g, 8.0 mmol) was added to a stirred solution of 6-[bis-(3,5-dimethyl-1*H*-pyrrol-2-yl)-methyl]-2-naphthol **7** (2.78 g, 8.1 mmol) in CH_2Cl_2 (150 mL). After 15 min at rt triethylamine (30 mL, 280 mmol) and $BF_3.OEt_2$ (30 mL, 237 mmol) were added and the mixture was stirred at RT for 1 h. The reaction mixture was washed with water (600 mL) and aqueous NaOH (200 mL, 2 M aq.). The aqueous solution was back

extracted with CH_2Cl_2 (2 × 50 mL), all of the CH_2Cl_2 extracts were combined, dried over anhyd. Na_2SO_4, filtered and evaporated. The crude compound was purified by silica gel chromatography (10% EtOAc in hexane) to afford the title compound **6b** (0.91 g) 29% yield as a bright orange solid, mp 263.8 °C, ν_{max} 3433.2, 2917.1, 1629.5, 1606.9, 1538.3, 1504.1, 1463.7, 1394.1, 1307.7, 1262.2, 1195.1, 1155.2, 928.4, 903.6, 800.8, 746.4, 608.0, 567.4, 470.6 cm^{-1}, δ_H 1.31 (6H, s, $(CH_3)_2$), 2.57 (6H, s, $(CH_3)_2$), 5.55 (1H, bs, OH), 5.97 (2H, s, pyrrole 4-H), 7.16 (1H, dd, *J* 8.5, 2.5 Hz, 3-H), 7.22 (1H, d, *J* 2.4 Hz, 1-H), 7.31 (1H, dd, *J* 8.5, 2.5 Hz, 7-H), 7.69 (1H, bs, 5-H), 7.77 (1H, d, *J* 8.5 Hz, 4-H), 7.82 (1H, d, *J* 8.5 Hz, 8-H), δ_C 14.62, 93.34, 109.56, 118.68, 121.20, 126.25, 127.16, 127.47, 128.75, 129.97, 130.12, 131.75, 134.42, 141.76, 143.17, 154.24, 155.40, 204.37.Found M + H^+ 391.1791. $C_{23}H_{21}ON_2BF_2$ requires M + H^+ 391.1788.

2.5. General method for the preparation of 4,4-difluoro-1,3,5,7-tetramethyl-8-(3′,3′-bis-(diaryl)-3′H-naphtho[2,1-b]pyran-8′-yl)-4-bora-3a,4a-diaza-s-indacenes ***9***

4-TsOH (0.05 g) was added in a single portion to a warm (ca. 50 °C) stirred solution of the 4,4-difluoro-1,3,5,7-tetramethyl-8-(6-hydroxynaphth-2-yl)-4-bora-3a,4a-diaza-*s*-indacene **6b** (0.15 g, 0.38 mmol) and the 1,1-diarylprop-2-yn-1-ol (0.38 mmol) in toluene (25 mL). The resulting suspension was heated under reflux until no propynol remained by TLC (ca. 1.5 h). The solution was cooled to RT and washed with water (3 × 20 mL). The combined aqueous layers were extracted with toluene (2 × 20 mL). The toluene extracts were combined with the original toluene layer and dried over Na_2SO_4. Evaporation of the toluene afforded the crude product that was purified by elution from silica. The following compounds were obtained by this protocol:

2.5.1. 4,4-Difluoro-1,3,5,7-tetramethyl-8-(3′,3′-bis-(4-methoxyphenyl)-3′H-naphtho[2,1-b]pyran-8′-yl)-4-bora-3a,4a-diaza-s-indacene ***9a***

Compound **9a** from **6b** and 1,1-bis(4-methoxyphenyl)prop-2-yn-1ol **8a** after elution from silica with 30% EtOAc in hexane as orange microcrystals (51.6 mg) 21% yield, mp 290.8 °C, λ_{max} 488 nm, ε 58400 M^{-1} cm^{-1} (CH_2Cl_2), λ_{abs} 507 nm, λ_{em} 513 nm, Φ_f 0.43 (PhMe), ν_{max} 2960.8, 2923.3, 1602.8, 1544.8, 1508.3, 1305.6, 1248.2, 1184.8, 1154.7, 1016.3, 972.4, 795.9, 764.1, 709.8, 581.9, 475.2 cm^{-1}, δ_H 1.31 (6H, s, $(CH_3)_2$), 2.56 (6H, s, $(CH_3)_2$), 3.79 (6H, s, $(OMe)_2$), 5.96 (2H, s, pyrrole-H), 6.25 (1H, d, *J* = 10 Hz, 2′-H), 6.87 (4H, m, Ar—H), 7.22 (1H, d, *J* = 8.8 Hz, 5′-H), 7.29 (1H, d, *J* = 10.0 Hz, 1′-H), 7.33 (1H, dd, *J* = 8.5, 1.5 Hz, 9′-Hp), 7.38 (4H, m, Ar—H), 7.63 (1H, d, *J* = 1.5 Hz, 7′-H), 7.65 (1H, d, *J* = 8.8 Hz, 6′-H), 8.07 (1H, d, *J* = 8.5 Hz, 10′-H), δ_C 14.61, 14.81, 55.26, 82.48, 113.44, 113.59, 118.46, 119.18, 121.17, 122.46, 126.23, 127.88, 128.14, 128.33, 129.19, 129.66, 129.83, 129.94, 137.26, 141.68, 143.21, 151.30, 155.38, 158.96. Found M^+ 639.2737. $C_{40}H_{35}O_3N_2BF_2$ requires M^+ 639.2740.

Other compounds prepared via this method:

2.5.2. 4,4-Difluoro-1,3,5,7-tetramethyl-8-[3′-(2-fluorophenyl)-3′-(4-pyrrolidinophenyl)-3′H-naphtho[2,1-b]pyran-8′-yl]-4-bora-3a,4a-diaza-s-indacene ***9b***

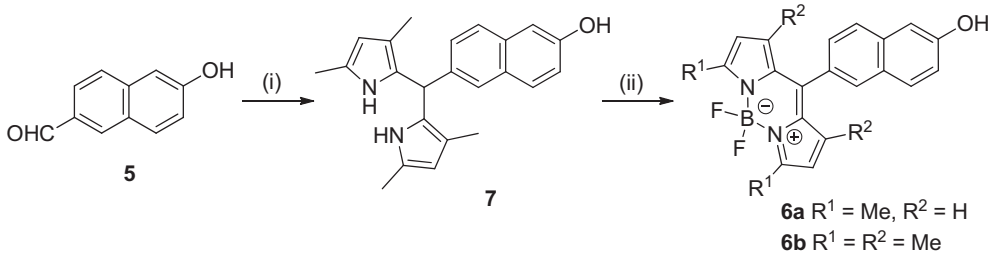
Compound **9b** from **6b** and 1-(2-fluorophenyl)-1-(4-pyrrolidinophenyl)prop-2-yn-1-ol **8b** after elution from silica with 30% EtOAc in hexane as orange microcrystals (71.8 mg) 28%, mp 255.4 °C, λ_{max} 488 nm, ε 80400 M^{-1} cm^{-1} (CH_2Cl_2), λ_{max} post-irradiation 580 nm with $t_{½}$ = 8 s (CH_2Cl_2), λ_{abs} 507 nm, λ_{em} 514 nm, Φ_f 0.44 (PhMe), ν_{max} 2962.9, 1609.6, 1540.2, 1510.5, 1470.6, 1363.5, 1305.2, 1188.3, 1153.7, 1078.4, 1051.2, 974.9, 809.6, 752.2, 476.4 cm^{-1}, δ_H 1.31 (3H, s, CH_3), 1.32 (3H, s, CH_3), 1.96 (4H, m, $N(CH_2)_2$), 2.56 (6H, s, $(CH_3)_2$), 3.26 (4H, m, $N(CH_2)_2$), 5.96 (1H, s, pyrrole-H), 5.97 (1H, s, pyrrole-H), 6.47 (1H, dd, *J* = 10.0, 4.2 Hz, 2′-H) 6.50 (2H, m, Ar—H), 7.03 (1H, m, Ar—H), 7.15 (1H, m, Ar—H), 7.28 (6H, m, Ar—H, 5′-H, 9′-H), 7.63 (1H, d, *J* = 1.5 Hz, 7′-H), 7.66 (1H, d, *J* = 8.8 Hz, 6′-H), 7.71 (1H, m, Ar—H), 8.07 (1H, d, *J* = 8.5 Hz, 10′-H), δ_C 14.61, 14.81, 25.49, 47.47, 81.48, 110.95, 113.41, 116.49, 118.62, 119.10, 121.15, 122.50, 123.73, 126.15, 126.70, 127.84, 127.99, 128.03, 128.08, 129.22, 129.36, 129.66, 129.78, 129.83, 129.94, 131.74, 132.04, 141.73, 143.24, 147.48, 151.11, 155.35. Found M + H^+ 668.3058. $C_{42}H_{37}ON_3BF_3$ requires M + H^+ 668.3055.

2.5.3. 4,4-Difluoro-1,3,5,7-tetramethyl-8-[3′-(2-bromophenyl)-3′-(4-pyrrolidinophenyl)-3′H-naphtho[2,1-b]pyran-8′-yl]-4-bora-3a,4a-diaza-s-indacene ***9c***

Compound **9c** from **6b** and 1-(2-bromophenyl)-1-(4-pyrrolidinophenyl)prop-2-yn-1-ol **8c** after elution from silica with 35% EtOAc in hexane as orange microcrystals (120.4 mg) 43%, mp 227.5 °C, λ_{max} 488 nm, ε 82100 M^{-1} cm^{-1} (CH_2Cl_2), λ_{max} post-irradiation 582 nm with $t_{½}$ = 112 s (CH_2Cl_2), λ_{abs} 507 nm, λ_{em} 514 nm, Φ_f 0.39 (PhMe), ν_{max} 2959.8, 1607.8, 1539.9, 1507.9, 1462.1, 1364.3, 1306.1, 1187.6, 1153.6, 972.6, 810.0, 795.8, 752.1, 578.3, 476.2 cm^{-1},δ_H 1.313 (3H, s, CH_3), 1.317 (3H, s, CH_3), 1.98 (4H, m, $N(CH_2)_2$), 2.56 (6H, s, $(CH_3)_2$), 3.30 (4H, m, $N(CH_2)_2$), 5.97 (2H, s, pyrrole-H), 6.52 (2H, m, Ar—H), 6.66 (1H, d, *J* = 10.0 Hz, 2′-H), 7.14 (1H, m, Ar—H), 7.30 (6H, m, Ar—H, 5′-H, 9′-H), 7.59 (1H, dd, *J* = 7.6, 1.2 Hz, Ar—H), 7.63 (1H, d, *J* = 1.6 Hz, 7′-H), 7.65 (1H, d, *J* = 8.8 Hz, 6′-H), 7.79 (1H, dd, *J* = 8.0, 1.6 Hz, Ar—H), 8.07 (1H, d, *J* = 8.7 Hz, 10′-H), δ_C 14.61, 14.82, 25.49, 47.46, 83.77, 110.96, 113.60, 119.10, 119.24, 121.15, 121.29, 122.54, 125.82, 126.17, 126.90, 127.86, 128.71, 129.05, 129.18, 129.40, 129.47, 129.67, 129.78, 129.90, 131.73, 135.23, 141.75, 143.01, 143.23, 147.36, 151.25, 155.35. Found M + H^+ 727.2285. $C_{42}H_{37}ON_3BBrF_2$ requires M + H^+ 727.2290.

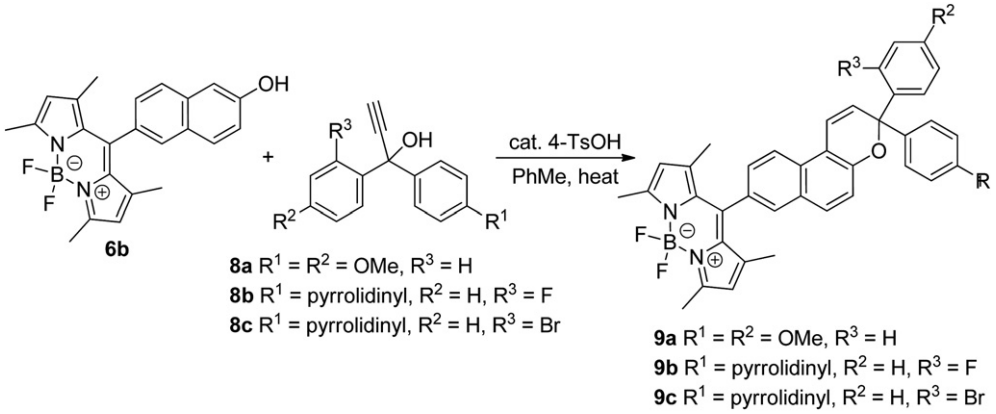
3. Discussion

Photochromic naphthopyrans are most conveniently accessed from the acid-catalysed condensation between a naphthol and



Reagents: (i) 2,4-dimethylpyrrole, cat. TFA, CH_2Cl_2, rt; (ii) DDQ, CH_2Cl_2, rt then Et_3N, $BF_3.OEt_2$, rt

Scheme 2. Synthesis of 8-(6-hydroxynaphthalen-2-yl)-1,3,5,7-tetramethyl-BODIPY dye **6b**.



Scheme 3. Synthesis of naphthopyran substituted BODIPY dyes **9a**–**c**.

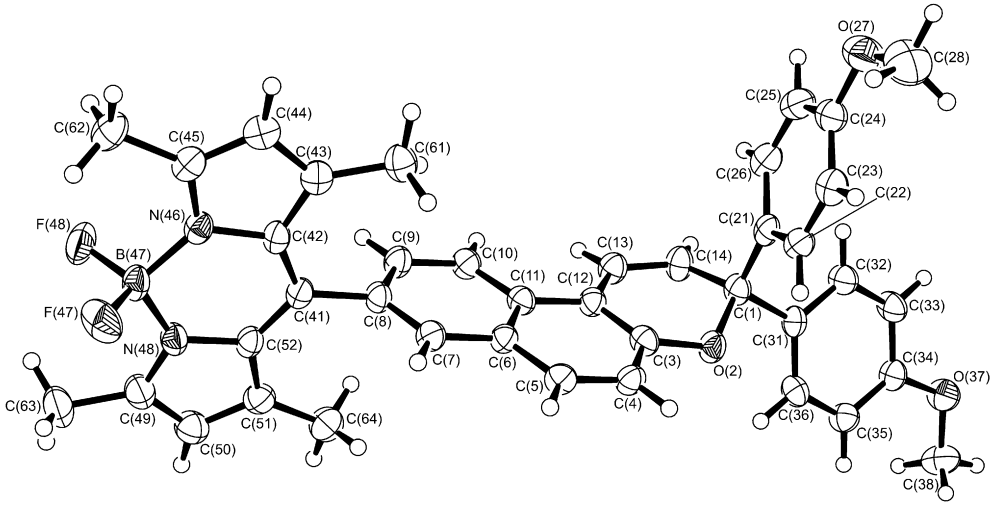


Fig. 1. X-ray crystal structure of **9a** (50% probability thermal ellipsoids).

a 1,1-diarylprop-2-yn-1-ol [19,20]. The BODIPY unit is invariably obtained from the reaction between an excess of a substituted pyrrole and an aromatic aldehyde in the presence of a catalytic amount of trifluoroacetic acid, oxidation of the intermediate dipyrromethane unit affording a typically unstable dipyrromethene which is directly transformed into the BODIPY dye upon treatment with a tertiary amine and $BF_3 \cdot OEt_2$ [1].

Considering the two key functional group requirements (a naphthol and an aromatic aldehyde) a convenient starting material for our initial exploration was 6-hydroxy-2-naphthaldehyde **5**, in which the hydroxyl group is conjugated to the aldehyde function. 6-Hydroxy-2-naphthaldehyde was readily synthesised in 81% yield by the low temperature dilithiation of 6-bromo-2-naphthol with *n*-butyllithium and quenching the resulting dianion with anhydrous *N*-formylpiperidine. Examination of the literature revealed that an 8-(6-hydroxynaphthalen-2-yl)-3,5-dimethyl-BODIPY dye **6a** had been previously reported and its pH sensing properties explored [8]. Encouraged by this fact, but also aware of the reactive nature of unsubstituted pyrrole ring carbon atoms we elected to prepare the tetramethyl substituted analogue **6b** commencing from 2,4-dimethylpyrrole (Scheme 2).

Condensation of **5** with 2,4-dimethylpyrrole catalysed by trifluoroacetic acid gave 6-[bis-(3,5-dimethyl-1*H*-pyrrol-2-yl)-methyl]naphthalen-2ol **7** in 56% yield. The ^{1}H NMR spectrum of **7** displayed signals for the pyrrole NH at δ 7.46, pyrrole ring protons at δ 5.73 and a singlet at δ 5.55 assigned to the methine proton. Oxidation of **7** was achieved with DDQ and the resulting crude product was reacted directly with an excess of triethylamine and $BF_3.OEt_2$ in dichloromethane to afford **6b** in 29% yield. The structure of **6b** was confirmed by the presence of key ^{1}H NMR signals for the

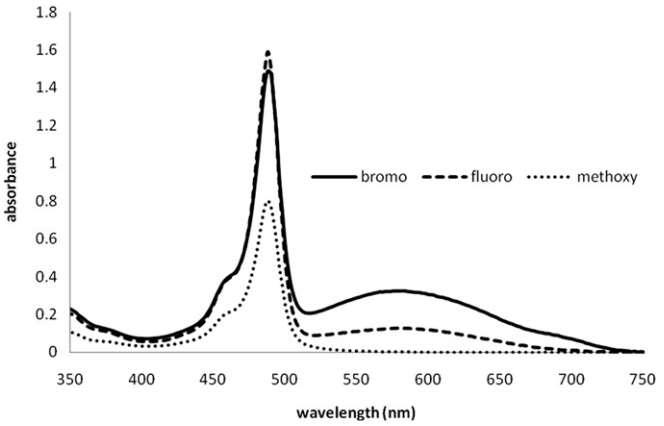
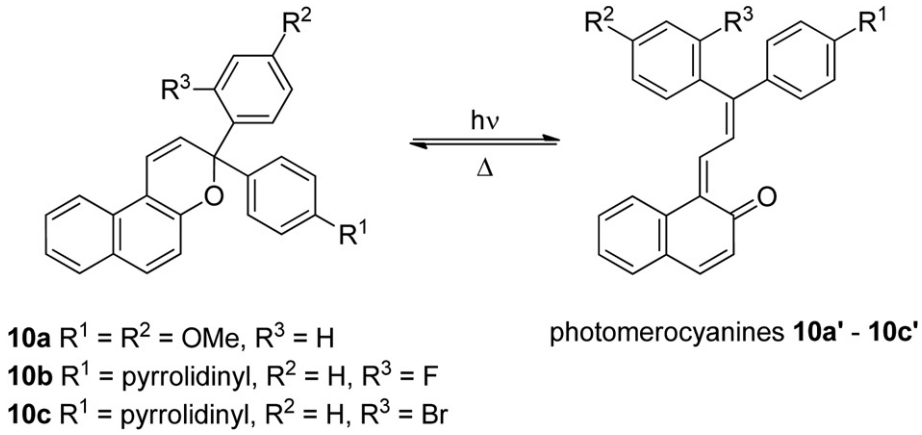


Fig. 2. Absorption spectra of **9a**–**c** recorded immediately after cessation of UV irradiation.



Scheme 4. Model photochromic compounds **10a**–**c**.

pyrrole ring protons at δ 5.97, the pyrrole methyl group signals at δ 1.26 and δ 2.57 and a broadened hydroxyl signal at δ 5.08. The mass spectrum of **6b** displayed the expected molecular ion $[M + H]^+$ of m/z 391.1791 with a base peak at m/z 371.1739 assigned to $[M\text{-}F]^+$.

Heating **6b** with 1,1-bis(4-methoxyphenyl)prop-2-yn-1ol **8a** which was available from our other studies [21] in PhMe containing a catalytic amount of 4-TsOH gave 4,4-difluoro-1,3,5,7-tetramethyl-8-(3′,3′-bis-(4-methoxyphenyl)-3′*H*-naphtho[2,1-*b*]pyran-8′-yl)-4-bora-3a,4a-diaza-*s*-indacene **9a** as orange-red crystals in 21% yield (Scheme 3). The structure of this product was clearly indicated by ^{1}H NMR spectroscopy which showed the typical 2-H pyran ring doublet at δ 6.25 (J = 10 Hz) [17] and a signal for the equivalent pyrrole ring protons at δ 5.96 and completely established by an X-ray crystal structure (Fig. 1) [22]. The bond lengths and angles of the BODIPY unit of **9a** compare favourably with those of previously reported boraindacene fluorophores [23] and indicate a highly delocalised cyanine dye like system with little distinction between single and double bonds. Steric interactions between the proximal methyl groups (C-1 and C-7) and the naphthalene moiety result in a near orthogonal arrangement of the boraindacene and naphthopyran units with an angle between planes of 85°.

The absorption spectrum of **9a** in CH_2Cl_2 solution showed no evidence of photochromism upon UV irradiation, with the sample exhibiting the expected intense absorption of the BODIPY unit at 488 nm (Fig. 2).

It should be noted that λ_{max} for the simple 3,3-bis(4-methoxyphenyl) substituted naphthopyran **10a** appears at 475 nm (PhMe solution) and is relatively short-lived [half-life ($t_{½}$) = 3 s] [24]. It may be that the photochromic response of this new BODIPY substituted naphthopyran **9a** results in a weak band at ca. 475 nm which fades rapidly and is thus masked by the intense absorption associated with the BODIPY unit (Scheme 4).

Photochromic response – structure relationships are well-documented for the 3*H*-naphtho[2,1-*b*]naphthopyran isomers [19,20,25–27]. We thus decided to simultaneously bathochromically shift λ_{max} and decrease the rate of fade of the subsequent BODIPY substituted naphthopyran. These features were conveniently accomplished using propynol **8b** wherein the pyrrolidine unit is responsible for a bathochromic shift in λ_{max} and the fluorine atom leads to a decrease in the rate of fade through steric interactions which hinder the rate of ring-closure of the photomerocyanine [28]. The new naphthopyran **9b** was obtained in 28% yield by the previously described method for **9a** and displayed a characteristic dd (J = 10.0, 4.2 Hz) for 2-H at δ 6.47 in its ^{1}H NMR spectrum through coupling with 1-H and the F atom of the *o*-fluorophenyl unit [28,29]. The absorption spectrum of **9b** displayed a weak photochromic response with λ_{max} of 580 nm and a $t_{½}$ of ca. 8 s (Figs. 2 and 3). The comparable data for the naphthopyran **10b** are λ_{max} = 554 nm and $t_{½}$ = 40 s [28]. The difference in λ_{max} suggests that the BODIPY unit at C-8 behaves as an electron releasing

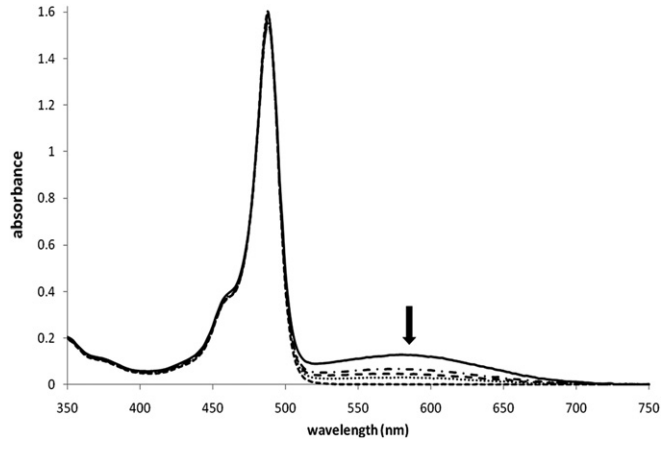


Fig. 3. Absorption spectra of **9b** illustrating fade of photomerocyanine **9b**′ over time after cessation of UV irradiation to a steady state.

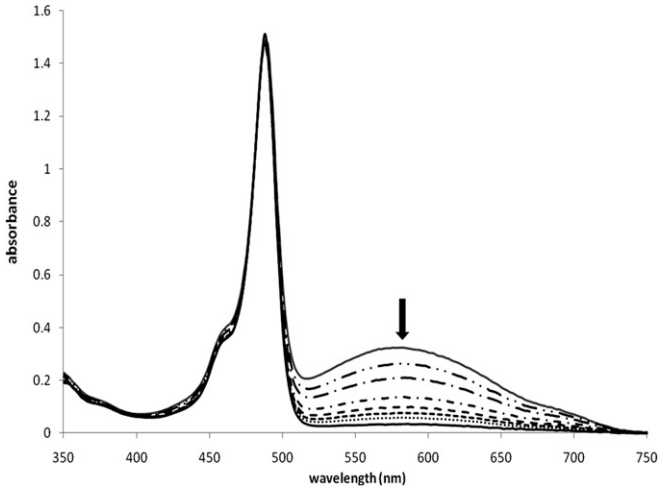
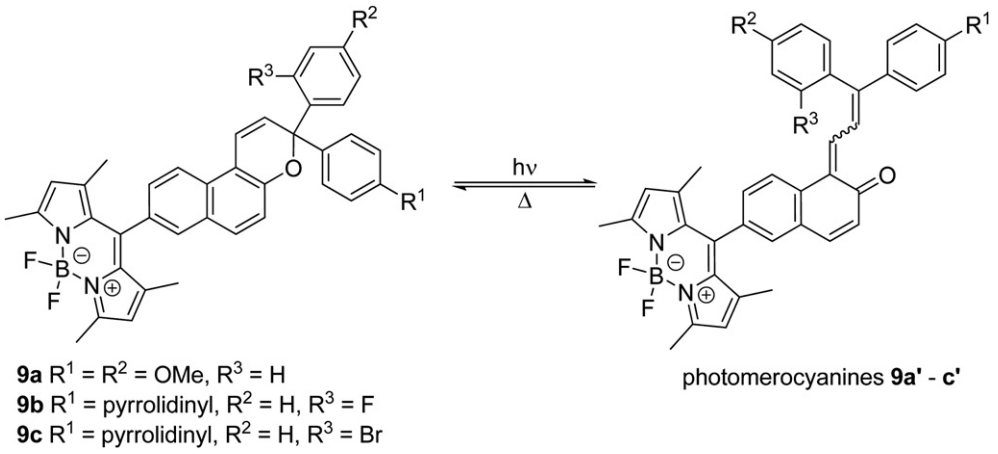


Fig. 4. Absorption spectra of **9c** illustrating fade of photomerocyanine over time.



9a $R^1 = R^2 = OMe$, $R^3 = H$
9b R^1 = pyrrolidinyl, $R^2 = H$, $R^3 = F$
9c R^1 = pyrrolidinyl, $R^2 = H$, $R^3 = Br$

Scheme 5. Photochromic response of BODIPY substituted naphthopyrans **9a**–**c**.

substituent comparable in its effect to a C-8 methoxy group [24,25]. The shorter half-life associated with photomerocyanine **9b**′ infers that this species is less stable than that derived from **10b**.

In a third attempt to further enhance the photochromic response propynol **8c** was employed. The bromine atom in **8c** significantly hinders the ring-closure of the photomerocyanine such that the photomerocyanine **10c**′ derived from **10c** has λ_{max} 554 nm and $t_{½}$ of 1024 s [28]. Heating **8c** with **6b** gave **9c** in 43% yield. The ^{1}H NMR spectrum of **9c** displayed a doublet at δ 6.66 ($J = 10.0$ Hz) which confirmed the formation of the pyran unit. The persistence of the photomerocyanine **9c**′ [$\lambda_{max} = 582$ nm $t_{½} = 112$ s (Figs. 2 and 4)] is ca. fourteen fold greater than that observed for **9b**′, derived from **9b** upon UV irradiation, which confirms the success of our structural modification. However, the half-life of **9c**′ is again significantly lower than that of **10c**′, indicating the relative instability of the BODIPY substituted photomerocyanine **9c**′. It should be noted that during the photochromic measurements of **9a**–**c** the intensity of the sharp absorption band at 488 nm characteristic of the BODIPY unit remained essentially unchanged, a feature that is consistent with observations made by Neckers et al., concerning the influence of photochromic cycling of the P-type photochromic dithienylethene–BODIPY system **2** [12] (Scheme 5).

The reason for the extremely weak photochromic response of **9a**–**c** relative to **10a**–**c** may stem from the fact that it has been established that the initial event in the photochromic process is absorption of photons generating an excited singlet state from which ring-opening of the pyran ring ensues [30]. Fluorescence emission is also derived from a singlet excited state and it may be that the most efficient (or rapid) energy dissipation process occurs via fluorescence rather than the required electrocyclic bond reorganisation leading to the photomerocyanine and hence photochromism. Detailed fast spectroscopic studies are required to establish this feature but are outside the scope of this preliminary synthetic chemistry investigation.

The fluorescence spectra of the three new BODIPY substituted naphthopyrans **9a**–**c** were next examined. All three compounds **9a**–**c** displayed good fluorescence with narrow Stokes' shifts typical of the BODIPY fluorophore [1]. Excitation and emission spectra were recorded for each compound before (unirradiated) and immediately post-UV irradiation; the normalised absorption and emission spectra are presented in Figs. 5–7. Unlike the significant changes in fluorescence emission intensity that were noted for the photochromic cycling of the dithienylethene–BODIPY system **2** [12], no such dramatic differences were noted for the series **9a**–**c**. For **9a**, which displayed no evidence of a photochromic response under the applied irradiation conditions, there was only

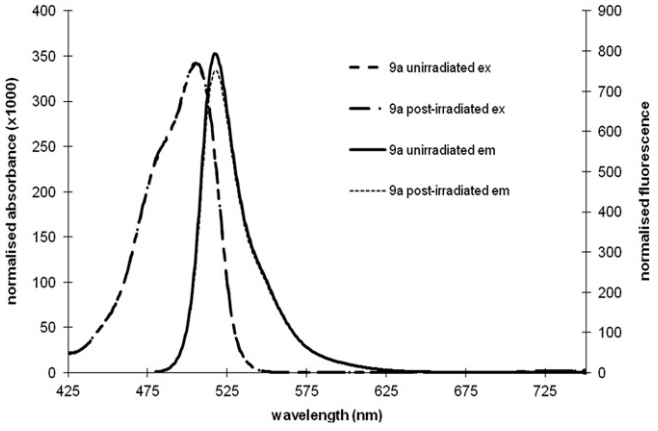


Fig. 5. Excitation and emission fluorescence spectra of **9a** in PhMe.

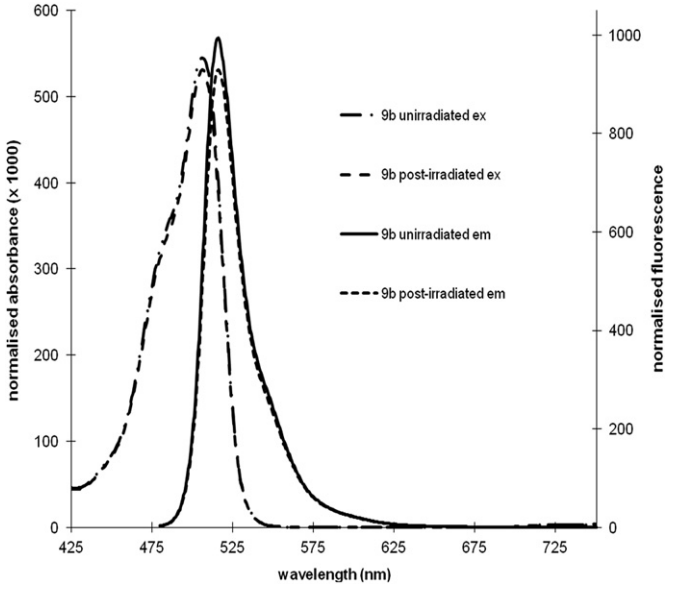


Fig. 6. Excitation and emission fluorescence spectra of **9b** in PhMe.

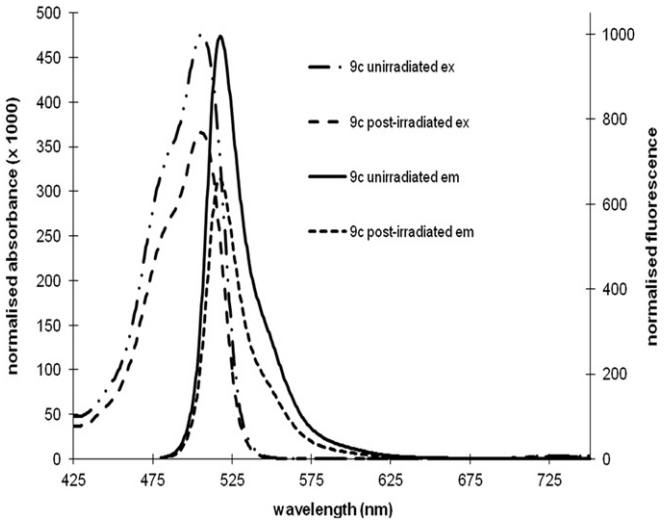


Fig. 7. Excitation and emission fluorescence spectra of **9c** in PhMe.

a very slight decrease in the emission spectrum intensity at the emission maximum recorded immediately after cessation of UV irradiation. For **9b**, which displays a weak photochromic response, there were minor decreases in the intensity of both the excitation and emission spectra maxima recorded pre- and post-irradiation. The greatest differences in intensity of both excitation and emission maxima were noted for the most photochromic compound examined **9c** (Fig. 7), where a ca. 35% decrease in emission intensity was noted.

Interestingly, there was no change in the wavelength of the emission maxima upon examination of the solution of **9c** immediately after the termination of irradiation, indicating that despite the conjugation between the pyran oxygen atom and the *meso*-position of the BODIPY unit, photochromic cycling between the pyran (ether type) and photomerocyanine (C═O type) has no apparent influence on the position of the emission maximum. Boens et al., have described the influence of the change in ionisation of a similarly disposed OH group in **6a** upon fluorescence (emission or lambda) and the molecule serves as an efficient pH probe [8]. It may be the situation for **9c** that there is still not a significantly high population of the photomerocyanine **9c′** under the applied irradiation conditions to induce an appreciable change in the fluorescence spectrum.

Our efforts to explore such BODIPY-naphthopyran conjugates are ongoing with (i) the preparation of naphthopyrans containing more sterically demanding C-3 *geminal* aryl substituents in order to increase the population of the photomerocyanine, and (ii) to examine the relocation of the BODIPY unit onto the *para*-position of one of the C-3 *geminal* aryl rings.

4. Conclusion

A series of photochromic naphthopyran–BODIPY conjugates have been synthesised. A crystal structure reveals that the BODIPY unit is almost orthogonally disposed towards the naphthalene ring system of the naphthopyran. The presence of the BODIPY unit located at the 8-position of the naphthopyran results in a less persistent photomerocyanine with a bathochromically shifted λ_{max} relative to the parent naphthopyran. This feature may be a consequence of the electron rich nature of the BODIPY unit combined with rapid fluorescence resulting from an initially formed excited singlet state rather than a presumably slower electrocyclic bond reorganisation leading to photochromism. Photoinduced ring-opening of the naphthopyran unit resulted in a decrease in the fluorescence intensity which was most significant for the naphthopyran with the most persistent photomerocyanine.

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