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(Article begins on next page)

1 **Red Light-Emitting Carborane-BODIPY Dyes: Synthesis and Properties of Visible-Light**
2 **Tuned Fluorophores with Enhanced Boron Content**

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14

15 **Abstract.** A small library of 2,6- and 3,5-distyrenyl-substituted carborane-BODIPY dyes was efficiently
16 synthesized by means of a Pd-catalyzed Heck coupling reaction. Styrenyl-carborane derivatives were exploited
17 as molecular tools to insert two carborane clusters into the fluorophore core and to extend the π -conjugation
18 of the final molecule in a single synthetic step. The synthetic approach allows to increase the molecular
19 diversity of this class of fluorescent dyes by the synthesis of symmetric or asymmetric units with enhanced
20 boron content. The structural characterization and photoluminescence (PL) properties of synthesized dyes were
21 evaluated. The developed compounds exhibit a significant bathochromic shift compared to their parent
22 fluorophore scaffolds, and absorption and emission patterns were practically unaffected by the different
23 substituents (Me or Ph) on the C_{cluster} atom (C_c) of the carborane cage or the cluster isomer (*ortho*- or *meta*-
24 carborane). Remarkably, the presence of carborane units at 2,6-positions of the fluorophore produced a
25 significant increase of the emission fluorescent quantum yields, which could be slightly tuned by changing the
26 C_c-substituent and the carborane isomer, as well as introducing ethylene glycol groups at the *meso*-position of

27 the BODIPY. All these features make these dyes promising candidates for further investigations in live-cell
28 imaging and bio-supramolecular assays.

29

30 **Keywords:** carborane • BODIPY • dyads • photoluminescent material • Heck coupling

31

32 **1. Introduction**

33

34 The fascinating chemistry of polyhedral boron-carbon clusters has experienced an exponential and
35 overwhelming growth since their discovery in the 1960s.^[1] Icosahedral carborane derivatives have been the
36 subject of an intense research owing to their unique properties such as high chemical and thermal stability,^[2]
37 delocalized three-dimensional aromaticity,^[3] high hydrophobicity and enriched boron content,^[4] electron-
38 withdrawing character^[5] and high biocompatibility.^[6] The remarkable physico-chemical features of carboranes
39 and their versatility toward functionalization^[7] have been widely exploited in several areas including medicine
40 (as anticancer agents for boron neutron capture therapy (BNCT) and pharmacophores),^[7b, 8] catalysis,^[9]
41 optoelectronic (as non-linear optical materials and liquid crystals),^[10] and nanomaterials.^[11] Additionally, the
42 development of fluorescent materials incorporating carboranes has significantly increased in the last decade,^{[2a,}
43 ^{12]} and their photoluminescent (PL) behavior has been deeply investigated. As a result, the carborane cage
44 linked to certain species (e.g. small fluorophores) directly influences both the PL properties and the thermal
45 stability of the final material,^[13] offering new outstanding opportunities toward the development of luminescent
46 materials, organic field-effect transistors (OFETs), phosphorescent organic light emitting diodes (PHOLEDs),
47 and biomedical tools (mainly bioimaging for diagnosis).^[14] Owing to their unique spectroscopic features
48 BODIPY dyes (4,4-difluoro-4-bora-3a,4a-diaza-s-indacene)^[15] represent a very interesting class of
49 fluorophores for carborane functionalization. Moreover, the countless pre- and post-functionalization synthetic
50 pathways of the BODIPY core allows its easy linkage to the carborane cluster using common synthetic
51 procedures. Several carboranyl-BODIPY dyads with remarkable PL properties for luminescent devices and
52 BNCT purposes have been thus synthesized in the last few years by means of Pd-catalyzed cross coupling
53 reactions or alkyne insertion into decaborane.^[16] In the course of our studies aimed at exploiting the

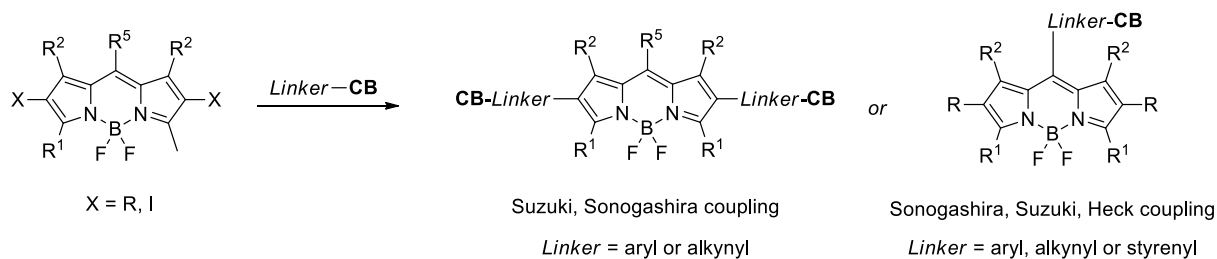
54 photophysical properties of BODIPY dyes for biological applications,^[17] we recently reported the first
55 synthesis of a small family of carborane-(aza)BODIPY dyads by means of a convergent Heck coupling
56 approach, starting from a styrenyl-containing carborane and a brominated (aza)dipyromethene fluorophore.^[18]
57 Although these styrenyl carborane-BODIPY derivatives preserved the photophysical features of the
58 fluorophore, the design of new dyes with optical properties shifted toward the near-infrared region and into
59 the therapeutic window in biological tissues still remains a urgency in view of biomedical applications of these
60 compounds.^[19] Moreover, the need to perform efficient boron rich carriers to find novel potential candidates
61 for BNCT is still on the rise.

62 To this purpose, we planned to synthesize a new family of styrenyl carborane-BODIPY dyes exhibiting a
63 whole π -conjugate system through the entire backbone of the molecule. In view of the development of bright
64 and stable fluorophores emitting in the red spectral region, the extension of π -conjugation is essential for
65 obtaining a bathochromic shift of both absorbance and emission maxima. The introduction of styrenyl groups
66 on the BODIPY core at the 3,5- and 1,7-positions is one of the most efficient strategies toward a significant
67 redshift of the spectral bands,^[20] while to the best of our knowledge only one example of 2,6-distyrenyl
68 substituted BODIPY dyes has been reported so far.^[21]

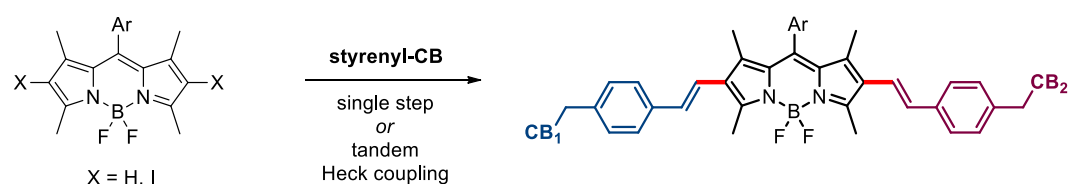
69 On the basis of these considerations and motivated by our ongoing interest in the design of new fluorescent
70 and high boron content carborane-based scaffolds, we herein report the Pd-catalyzed synthesis of a small
71 library of red-light emitting carborane-BODIPY dyads linked at the 2,6-positions and 3,5-positions with a π -
72 conjugated styrene moiety spacer (Figure 1). The rationale of this work focuses on the following key points:
73 a) exploit styrenyl carborane derivatives as molecular tools to insert two boron-carbon cages into the
74 fluorophore and extend the π -conjugation of the final molecule in a single synthetic step, b) enlarge the
75 molecular diversity of the fluorescent dyads by the synthesis of symmetric or asymmetric units and c) enhance
76 the boron content of the dyads. To this purpose, a series of *ortho*- and *meta*- (*o*- and *m*-) substituted styrenyl-
77 carboranes were linked to suitable BODIPY dyes halogenated at the 2,6- and 3,5-positions by means of a Heck
78 coupling approach. The spectroscopic and photophysical properties of these new dyes are also discussed.

Previous works

CB = carborane derivative



This work



■ Red-light emitting carborane-based dyes

■ Synthesis of symmetric and asymmetric units

■ Straightforward cross-coupling reaction

■ Enhanced boron content

79

80 **Figure 1.** Aim of the work.

81

82 2. Experimental section

83

84 2.1 Materials and methods

85 Unless specified, all reagents were used as received without further purifications. $[Pd_2(dba)_3]$, $[Pd(tBu_3P)_2]$ and
86 Cy_2NMe were purchased from Aldrich. All reactions involving air-sensitive reagents were performed under
87 nitrogen in oven-dried glassware using the syringe septum cap technique. Anhydrous CH_2Cl_2 was obtained by
88 distillation over CaH_2 . Anhydrous THF was obtained by distillation over $LiAlH_4$, followed by distillation over
89 Na-benzophenone. Et_3N was distilled over CaH_2 and dry 1,4-dioxane was purchased from Merck-
90 SigmaAldrich and used as received. Reactions were monitored using thin layer chromatography on silica gel
91 coated aluminium plates. Chromatographic separations were performed under pressure on silica gel (40-63
92 μm , 230-400 mesh). R_f values refer to TLC carried out on silica gel plates with UV light (254 nm and/or 366
93 nm) as visualizing agent.

94

95 2.2 Instrumentation

96 ^1H NMR (600 MHz) and $^{13}\text{C}\{^1\text{H}\}$ (150 MHz) NMR spectra were recorded in CDCl_3 on a Jeol ECZR600
97 spectrometer at RT using residual solvent peak as an internal standard. $^{11}\text{B}\{^1\text{H}\}$ (128.38 MHz) NMR spectra
98 were recorded on a Bruker ARX 400 spectrometer in CDCl_3 . Chemical shift values for $^{11}\text{B}\{^1\text{H}\}$ NMR spectra
99 were referenced to external $\text{BF}_3\cdot\text{OEt}_2$, those for ^1H and $^{13}\text{C}\{^1\text{H}\}$ NMR were referenced to $[\text{Si}(\text{CH}_3)_4]$ (TMS).
100 Chemical shifts (δ) are given in parts per million (ppm) and coupling constants (J) in Hertz (Hz). Multiplicities
101 are reported as follows: *s* (singlet), *d* (doublet), *t* (triplet), *q* (quartet), *m* (multiplet). Low-resolution mass
102 spectra were recorded on a Micromass Quattro microTM API (Waters Corporation, Milford, MA, USA) or at
103 an ionizing voltage of 70 eV on a HP 5989B mass selective detector connected to an HP 5890 GC with a
104 methyl silicone capillary column (EI). The MS flow-injection analyses were run on a high resolving power
105 hybrid mass spectrometer (HRMS) Orbitrap Fusion (Thermo Scientific, Rodano, Italy), equipped with an ESI
106 ion source. The samples were analyzed in acetonitrile solution using a syringe pump at a flow rate of 5 $\mu\text{L}/\text{min}$.
107 The tuning parameters adopted for the ESI source were: source voltage 4.0 kV. The heated capillary
108 temperature was maintained at 275 $^\circ\text{C}$. The mass accuracy of the recorded ions (vs. the calculated ones) was
109 ± 2.5 mmu (milli-mass units). Analyses were run using both full MS (150-2000 m/z range) and MS/MS
110 acquisition, at 500000 resolutions (200 m/z).

111

112 ***2.3 Photophysical measurements***

113 The optical properties were evaluated in anhydrous grade THF, MeOH, CH_3CN , CHCl_3 , toluene, dioxane,
114 DMSO purchased from Sigma Aldrich and used without further purifications. Stock solutions in the selected
115 solvent with a concentration between $2.87\cdot 10^{-4}$ M and $3.73\cdot 10^{-4}$ M were prepared for all the compounds tested.
116 UV-Vis spectra were recorded on VARIANT Cary 5 UV-Vis-NIR spectrophotometer. Molar extinction
117 coefficients were determined with solutions of THF with concentrations in the range $0.20\cdot 10^{-5}$ M to $1.5\cdot 10^{-5}$
118 M. Emission spectra have been recorded with a VARIANT Cary Eclipse Fluorescence spectrophotometer. The
119 excitation wavelengths were set just before the respective absorption maxima in each solvent tested to provide
120 adequate excitation energy and maximize the detected signal, excitation and the emission slits are set at 2.5
121 nm. The samples concentration was adjusted to have an absorbance between 0.1 and 1 at the Abs_{max} to evaluate
122 the general photophysical properties in THF (Abs_{max} , Em_{max} , Φ_{F} and Stokes Shift) and the possible
123 solvatochromic features in MeOH, CH_3CN , CHCl_3 , toluene, dioxane, DMSO. All the measurements were

124 carried out in a 1 cm four-sided quartz cuvette from Hellma Analytics. The absorption and steady state emission
125 spectra were corrected for their respective blank. No fluorescent contaminants were detected on excitation in
126 the wavelength region of experimental interest.

127 The Fluorescence quantum yield evaluation was carried out on samples with concentrations adapted to have
128 an absorbance lower than 0.1 in THF at the excitation wavelength (λ_{ex}) using the above-mentioned DMSO
129 stock solutions. The fluorescence quantum yield (ϕ) were evaluated compared on an external standard,
130 Rhodamine 101 (ϕ :1 in MeOH, λ_{ex} 576 nm)^[22] by applying the following equation:

$$131 \quad \phi = \phi_{STD} \frac{I}{I_{STD}} \frac{Abs_{STD}}{Abs} \frac{n^2}{n_{STD}^2} \quad (1)$$

132 where ϕ_{STD} is the fluorescence quantum yield of the standard, I and I_{STD} are the integrated area of the emission
133 band of the sample and the standard respectively. Abs and Abs_{STD} are the absorbance at the excitation
134 wavelength for the sample and the standard, respectively. n and n_{STD} are the solvent refractive index of the
135 sample and the standard solutions, respectively.

136

137 **2.3 Syntheses and characterizations**

138 Iodinated BODIPY dyes **1a**,^[23] **1c**,^[24] **1d**^[25] and styrenyl-containing carboranes^[121] **m-Me-CB**, **o-Ph-CB** and **m-**
139 **Ph-CB** were synthesized according to the procedures reported in literature. Mono-iodinated BODIPY dye **1b**
140 was synthesized starting from the corresponding 4-alkoxy substituted benzaldehyde (see Supporting
141 Information for full synthetic details). Full characterization data, including copies of ¹H and ¹³C NMR spectra
142 (see Supporting Information), have been reported for the newly synthesized compounds. The syntheses of 2,6-
143 disubstituted styrenyl-carborane BODIPY dyes are depicted in Scheme 1 (**2**, **2a**) and Scheme 2 (**3-8**). The
144 synthesis of 3,5-disubstituted styrenyl-carborane BODIPY dye **9** is illustrated in Scheme 3.

145

146 *General procedure (A) for the Heck coupling reactions.* A round-bottomed flask equipped with a condenser
147 was charged with 3 mL of dry 1,4-dioxane, and the solvent was degassed with nitrogen for 15 minutes. The
148 appropriate styrenyl-containing carborane (2.1 equiv.) and iodinated BODIPY derivatives **1a-b** or **1d** (1 equiv.)
149 were added, followed by Pd₂(dba)₃ (3 mol%), Pd(P(*t*-Bu)₃)₂ (6 mol%) and Cy₂NMe (4.8 equiv.). The reaction
150 mixture was heated at reflux overnight. After complete conversion of the starting material (as monitored by

151 TLC analysis), the mixture was filtered over celite, washed with THF and concentrated to dryness. The crude
152 residue was purified by flash column chromatography on silica gel.

153

154 *General procedure (B) for the Heck coupling reactions.* A round-bottomed flask equipped with a condenser
155 was charged with 3 mL of dry 1,4-dioxane, and the solvent was degassed with nitrogen for 15 minutes. The
156 appropriate styrenyl-containing carborane (1 equiv.) and the styrenyl-carborane BODIPY derivative **6** (1.1
157 equiv.) were added, followed by Pd₂(dba)₃ (5 mol%), Pd(P(*t*-Bu)₃)₂ (5 mol%) and Cy₂NMe (1.34 equiv.). The
158 reaction mixture was heated at reflux overnight. After complete conversion of the starting material (as
159 monitored by TLC analysis), the mixture was filtered over celite, washed with THF and concentrated to
160 dryness. The crude residue was purified by flash column chromatography on silica gel.

161

162 **Synthesis and characterization of compound 2.** General procedure (A) starting from **1a** and *m*-Me-CB.
163 Purification by flash column chromatography on silica gel (PE/DCM 6/4 v/v) gave **2** as a bright blue solid.
164 (43%, R_f = 0.5 PE/DCM 6/4 v/v). ¹H NMR (600 MHz, CDCl₃): δ 7.54-7.52 (m, 3H), 7.37 (d, *J* = 8.2 Hz, 4H),
165 7.34-7.33 (m, 2H), 7.07 (d, *J* = 8.2 Hz, 4H), 6.87 (d, *J* = 16.5 Hz, 2H), 6.63 (d, *J* = 16.5 Hz, 2H), 3.18 (s, 4H),
166 2.74 (s, 6H), 1.64 (s, 6H), 1.47 (s, 6H). ¹³C{¹H} NMR (150 MHz, CDCl₃) δ: 155.4, 141.6, 138.9, 137.1, 136.4,
167 135.4, 131.6, 131.0, 130.4, 129.4, 129.3, 129.0, 128.4, 128.2, 126.2, 120.0, 70.9, 42.8, 24.7, 14.2, 13.1. ¹¹B{¹H}
168 NMR (128.38 MHz, CDCl₃) δ: 0.99 (s, 1B, BF₂) -6.17 (s, 2B), -7.88 (s, 2B), -10.50 (br s, 12B), -13.04 (s, 4B).
169 ESI-HRMS [M+Na]⁺: *m/z* 891.6674; C₄₃H₅₉B₂₁F₂N₂Na⁺ requires 891.6638.

170

171 **Synthesis and characterization of compound 2a.** Isolated by flash column chromatography on silica gel
172 (PE/DCM 6/4 v/v) from crude reaction mixture of **2** (6%, R_f = 0.6 PE/DCM 6:4 v/v). ¹H NMR (600 MHz,
173 CDCl₃): δ 7.50-7.49 (m, 3H), 7.38 (d, *J* = 8.2 Hz, 2H), 7.35-7.33 (m, 2H), 7.23 (d, *J* = 8.3 Hz, 2H), 7.07 (d, *J*
174 = 8.2 Hz, 2H), 7.02 (d, *J* = 8.3 Hz, 2H), 6.88 (d, *J* = 16.5 Hz, 1H), 6.63 (d, *J* = 16.5, 1H), 5.84 (s, 1H), 5.10 (s,
175 1H), 3.18 (s, 2H), 3.16 (s, 2H), 2.73 (s, 3H), 2.37 (s, 3H), 1.64 (s, 3H), 1.63 (s, 3H), 1.48 (s, 3H), 1.22 (s, 3H).
176 ¹³C {¹H} NMR (150 MHz, CDCl₃): δ 155.2, 155.0, 140.7, 140.5, 139.4, 138.8, 136.7, 136.3, 135.3, 131.5,
177 130.8, 130.3, 130.1, 129.3, 129.2, 128.7, 128.2, 126.5, 126.2, 120.1, 117.6, 80.4, 70.8, 42.7, 42.6, 29.8, 24.6,

178 14.1, 13.5, 13.0, 12.9. $^{11}\text{B}\{^1\text{H}\}$ NMR (128.38 MHz, CDCl_3) δ : 1.01 (s, 1B, BF_2), -6.24 (s, 2B), -7.91 (s, 2B), -
179 10.50 (br s, 12B), -13.04 (s, 4B). ESI-HRMS $[\text{M}+\text{Na}]^+$: m/z 891.6618; $\text{C}_{43}\text{H}_{59}\text{B}_{21}\text{F}_2\text{N}_2\text{Na}^+$ requires 891.6638.

180

181 **Synthesis and characterization of compound 3.** General procedure (A) starting from **1a** and **m-Ph-CB**.

182 Purification by flash column chromatography on silica gel (PE/DCM 6/4 v/v) gave **3** as a bright blue solid

183 (57%, $R_f = 0.4$ PE/DCM 6/4 v/v). ^1H NMR (600 MHz, CDCl_3): δ 7.49-7.40 (m, 4H), 7.33-7.24 (m, 11H), 7.15

184 (d, $J = 7.9$ Hz, 4H), 7.02 (d, $J = 7.9$ Hz, 4H), 6.80 (d, $J = 16.5$ Hz, 2H), 6.55 (d, $J = 16.5$ Hz, 2H), 3.18 (s, 4H),

185 2.66 (s, 6H), 1.40 (s, 6H). $^{13}\text{C}\{^1\text{H}\}$ NMR (150 MHz, CDCl_3): δ 155.3, 141.5, 138.8, 137.0, 136.2, 135.3, 131.5,

186 130.8, 130.3, 129.3, 129.2, 128.9, 128.6, 128.3, 127.8, 126.2, 120.0, 78.2, 76.3, 42.9, 14.1, 13.0. $^{11}\text{B}\{^1\text{H}\}$ NMR

187 (128.38 MHz, CDCl_3) δ : 0.95 (s, 1B, BF_2), -5.90 (s, 4B), -10.66 (br s, 12B), -13.51 (s, 4B). ESI-HRMS

188 $[\text{M}+\text{Na}]^+$: m/z 1015.6956; $\text{C}_{53}\text{H}_{63}\text{B}_{21}\text{F}_2\text{N}_2\text{Na}^+$ requires 1015.6951.

189

190 **Synthesis and characterization of compound 4.** General procedure (A) starting from **1b** and **m-Ph-CB**.

191 Purification by flash column chromatography on silica gel (DCM) gave **4** as a bright blue solid (52%, $R_f =$

192 0.55 DCM). ^1H NMR (600 MHz, CDCl_3): δ 7.38 (d, $J = 8.2$ Hz, 4H), 7.35 (d, $J = 8.6$ Hz, 4H), 7.26-7.18 (m,

193 8H), 7.10 (d, $J = 8.1$ Hz, 4H), 7.06 (d, $J = 8.7$ Hz, 2H), 6.88 (d, $J = 16.5$ Hz, 2H), 6.62 (d, $J = 16.5$ Hz, 2H),

194 4.23-4.20 (m, 2H), 3.95-3.92 (m, 2H), 3.79-3.76 (m, 2H), 3.75-3.70 (m, 2H), 3.70-3.66 (m, 2H), 3.62-3.58 (m,

195 2H), 3.47 (t, $J = 6.8$ Hz, 2H), 3.26 (s, 4H), 2.72 (s, 6H), 1.58-1.54 (m, 2H), 1.52 (s, 6H), 1.40-1.33 (m, 2H),

196 0.91 (t, $J = 7.4$ Hz, 3H). $^{13}\text{C}\{^1\text{H}\}$ NMR (150 MHz, CDCl_3): δ 155.2, 139.0, 137.2, 136.3, 135.4, 132.0, 130.9,

197 130.4, 129.6, 129.4, 128.9, 128.7, 128.4, 127.9, 127.6, 127.2, 126.3, 120.2, 115.5, 78.3, 76.4, 71.4, 71.1, 70.9,

198 70.8, 70.2, 69.9, 67.7, 43.0, 31.8, 29.8, 19.4, 14.1, 13.4. $^{11}\text{B}\{^1\text{H}\}$ NMR (128.38 MHz, CDCl_3) δ : 0.93 (s, 1B,

199 BF_2), -5.92 (s, 4B), -10.64 (br s, 12B), -13.48 (s, 4B). ESI-HRMS $[\text{M}+\text{Na}]^+$: m/z 1219.8335; $\text{C}_{63}\text{H}_{83}\text{B}_{21}\text{F}_2\text{N}_2$

200 O_4Na^+ requires 1219.8318

201

202 **Synthesis and characterization of compound 5.** A round-bottomed flask equipped with a reflux condenser

203 was charged with 3 mL of dry 1,4-dioxane, and the solvent was degassed with nitrogen for 15 minutes. The

204 carborane **m-Me-CB** (1 equiv.) and mono-iodinated BODIPY derivative **1c** (1.1 equiv.) were added, followed

205 by $\text{Pd}_2(\text{dba})_3$ (1.2 mol%), $\text{Pd}(\text{P}(t\text{-Bu})_3)_2$ (1.6 mol%) and Cy_2NMe (1.34 equiv.). The reaction mixture was

206 heated at reflux overnight. After complete conversion of the starting material (as monitored by TLC analysis),
207 the mixture was filtered over celite, washed with THF and concentrated to dryness. The crude residue was
208 purified by flash column chromatography on silica gel (PE/DCM 7/3 v/v) to give **5** as a bright purple solid
209 (72%, $R_f = 0.4$ PE/DCM 7/3 v/v). ^1H NMR (600 MHz, CDCl_3): δ 7.53-7.46 (m, 3H), 7.36 (d, $J = 8.1$ Hz, 2H),
210 7.31-7.27 (m, 2H), 7.05 (d, $J = 8.2$ Hz, 2H), 6.86 (d, $J = 16.5$ Hz, 1H), 6.60 (d, $J = 16.5$ Hz, 1H), 6.00 (s, 1H),
211 3.16 (s, 2H), 2.71 (s, 3H), 2.57 (s, 3H), 1.46 (s, 3H), 1.37 (s, 3H). $^{13}\text{C}\{^1\text{H}\}$ NMR (150 MHz, CDCl_3): δ 156.1,
212 154.8, 143.6, 141.8, 138.7, 137.1, 136.4, 135.2, 131.9, 131.2, 130.7, 130.3, 129.3, 129.2, 128.6, 128.2, 126.2,
213 121.7, 120.1, 76.8, 70.8, 42.8, 24.6, 14.8, 14.6, 14.1, 13.0.

214

215 **Synthesis and characterization of compound 6.** To a stirred solution of **5** (0.13 mmol) in dry DCM (30 mL)
216 under a positive N_2 atmosphere was added *N*-iodosuccinimide (NIS, 0.26 mmol, 2 eq.), and the reaction
217 mixture was stirred at RT overnight. The mixture was then washed with water, dried over Na_2SO_4 and purified
218 by flash column chromatography on silica gel (PE/DCM 75/25 v/v) to give **6** as purple solid (84%, $R_f = 0.55$
219 PE/DCM 75/25 v/v). ^1H NMR (600MHz, CDCl_3): δ 7.48-7.43 (m, 3H), 7.30 (d, $J = 8.3$ Hz, 2H), 7.24-7.20
220 (m, 2H), 6.99 (d, $J = 8.1$ Hz, 2H), 6.77 (d, $J = 16.5$ Hz, 1H), 6.55 (d, $J = 16.5$ Hz, 1H), 3.10 (s, 2H), 2.65 (s,
221 3H), 2.58 (s, 3H), 1.56 (s, 3H), 1.34 (s, 3H), 1.31 (s, 3H). $^{13}\text{C}\{^1\text{H}\}$ NMR (150 MHz, CDCl_3): δ 157.2, 155.0,
222 143.6, 141.4, 140.3, 136.8, 136.6, 135.1, 131.5, 131.3, 130.3, 129.7, 129.4, 128.1, 126.2, 119.6, 84.8, 76.6,
223 70.8, 42.7, 29.8, 24.6, 16.9, 16.0, 14.3, 13.1.

224

225 **Synthesis and characterization of compound 7.** General procedure (**B**) starting from **6** and *o*-Ph-CB.
226 Purification by flash column chromatography on silica gel (PE/DCM 6/4 v/v) gave **7** as a bright blue solid
227 (55%, $R_f = 0.35$ PE/DCM 75/25 v/v). ^1H NMR (600 MHz, CDCl_3): δ 7.72 (d, $J = 7.7$ Hz, 2H), 7.57-7.50 (m,
228 4H), 7.49-7.43 (m, 2H), 7.38 (d, $J = 8.1$ Hz, 2H), 7.34-7.32 (m, 2H), 7.29 (d, $J = 8.1$ Hz, 2H), 7.07 (d, $J = 8.0$
229 Hz, 2H), 6.87 (d, $J = 16.3$ Hz, 1H), 6.85 (d, $J = 16.3$ Hz, 1H), 6.78 (d, $J = 8.1$ Hz, 2H), 6.62 (d, $J = 16.5$ Hz,
230 1H), 6.58 (d, $J = 16.5$ Hz, 1H), 3.18 (s, 2H), 3.07 (s, 2H), 2.73 (s, 3H), 2.72 (s, 3H), 1.64 (s, 3H), 1.47 (s, 3H),
231 1.46 (s, 3H). $^{13}\text{C}\{^1\text{H}\}$ NMR (150 MHz, CDCl_3): δ 155.4, 155.3, 141.6, 138.9, 137.4, 137.1, 136.4, 135.4, 134.5,
232 131.6, 131.6, 131.0, 130.9, 130.7, 130.5, 130.4, 129.4, 129.3, 129.2, 129.0, 128.9, 128.4, 126.2, 126.1, 120.3,
233 120.0, 83.8, 82.1, 70.8, 42.8, 40.8, 32.1, 24.7, 22.8, 14.2, 13.1. $^{11}\text{B}\{^1\text{H}\}$ NMR (128.38 MHz, CDCl_3) δ : 1.08

234 (s, 1B, BF₂), -3.17 (s, 2B), -6.22 (s, 1B), -7.98 (s, 1B), -10.24 (br s, 14B), -12.93 (s, 2B). ESI-HRMS [M+Na]⁺:
235 *m/z* 953.6817; C₄₈H₆₁B₂₁F₂N₂Na⁺ requires 953.6794 .

236

237 **Synthesis and characterization of compound 8.** General procedure (B) starting from **6** and *m*-Ph-CB.

238 Purification by flash column chromatography on silica gel (PE/DCM 7/3 v/v) gave **8** as a bright blue solid.

239 (35%, R_f = 0.21 PE/DCM 7/3 v/v). ¹H NMR (600 MHz, CDCl₃): δ 7.53 (m, 3H), 7.38-7.33 (m, 9H), 7.23-7.21

240 (m, 2H), 7.10-7.06 (m, 4H), 6.87 (d, *J* = 16.5 Hz, 2H), 6.62 (d, *J* = 16.5 Hz, 2H), 3.26 (s, 2H), 3.18 (s, 2H),

241 2.74 (s, 6H), 1.64 (s, 3H), 1.47 (s, 6H). ¹³C{¹H} NMR (150 MHz, CDCl₃): δ 155.4, 141.6, 138.9, 137.1, 137.1,

242 136.4, 136.3, 135.4, 132.0, 131.0, 130.9, 130.4, 129.4, 129.3, 129.0, 128.7, 128.4, 127.9, 126.3, 126.2, 121.0,

243 120.0, 78.3, 76.8, 76.3, 70.9, 43.0, 42.8, 24.7, 14.2, 13.1. ¹¹B{¹H} NMR (128.38 MHz, CDCl₃) δ: 1.01 (br s,

244 1B, BF₂), -6.05 (s, 3B), -7.85 (s, 1B), -10.46 (s, 12B), -13.01 (s, 4B). ESI-HRMS [M+Na]⁺: *m/z* 953.6824;

245 C₄₈H₆₁B₂₁F₂N₂Na⁺ requires 953.6794 .

246

247 **Synthesis and characterization of compound 9.** General procedure (A) starting from **1d** and *m*-Ph-CB.

248 Purification by flash column chromatography on silica gel (PE/DCM 7/3 v/v) gave **9** as a bright blue solid.

249 (30%, R_f = 0.33 PE/DCM 7/3 v/v). ¹H NMR (600 MHz, CDCl₃): δ 7.79 (d, *J* = 16.3 Hz, 2H), 7.62 (d, *J* = 8.1

250 Hz, 4H), 7.56-7.50 (m, 6H), 7.37-7.36 (m, 4H), 7.32 (d, *J* = 16.3 Hz, 2H), 7.25-7.21 (m, 5H), 7.19 (d, *J* = 8.1

251 Hz, 4H), 6.93 (d, *J* = 4.5 Hz, 2H), 6.82 (d, *J* = 4.4 Hz, 2H), 3.30 (s, 4H). ¹³C{¹H} NMR (150 MHz, CDCl₃): δ

252 154.8, 139.8, 138.0, 136.4, 136.2, 135.9, 135.3, 134.4, 130.6, 130.5, 130.0, 129.9, 128.7, 128.4, 127.9, 129.9,

253 119.7, 116.5, 78.4, 76.1, 43.1. ESI-MS [M+H]⁺: *m/z* 939.16.

254

255 **3. Results and discussion**

256

257 **3.1 Synthesis and characterization of dyes**

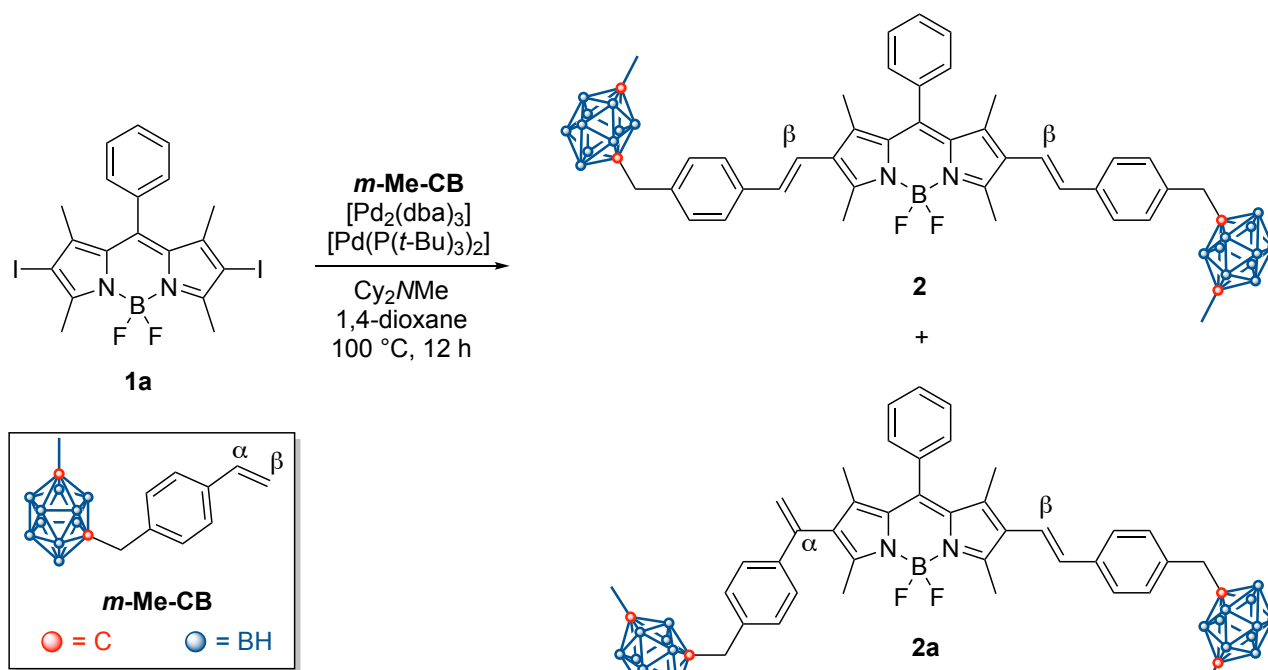
258 The presence of halogen atoms, either directly on the BODIPY core or attached to an aryl ring, facilitates

259 further extension of the π-conjugation and to build sophisticated structures by means of metal-catalyzed

260 coupling reactions.^[26] Based on our previously reported results on the functionalization of the (aza)BODIPY

261 core with styrenyl-containing carborane derivatives,^[18] we started our preliminary investigation by testing the

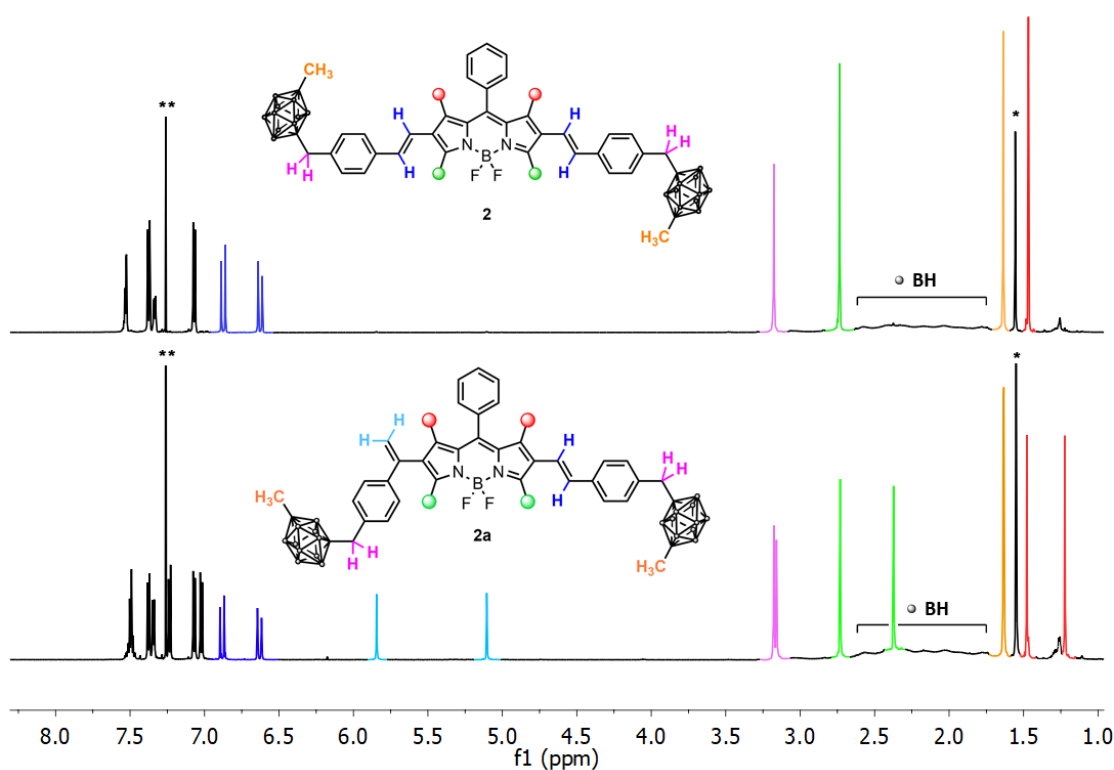
262 Heck coupling procedure on the 2,6-diiodo-BODIPY derivative **1a** and the methyl substituted styrenyl *m*-
 263 carborane *m*-Me-CB (Scheme 1). The 2,6-diiodo-1,3,5,7-tetramethylBODIPY dye **1a**, synthesized by
 264 condensation of 2,4-dimethylpyrrole with benzaldehyde followed by mild iodination with I₂/HIO₃,^[27] exhibits
 265 an absorption maxima at 534 nm and a negligible fluorescence quantum yield due to the high heavy atom-
 266 induced intersystem crossing (ISC) at the excited state.^[28] The styrenyl-carborane *m*-Me-CB has been easily
 267 synthesized by electrophilic trapping of the parent lithium-*closo*-carborane cluster with 4-vinylbenzyl chloride
 268 as previously reported.^[12]



269
 270 **Scheme 1.** Model Heck coupling reaction for the synthesis of 2,6-bis(styrenylcarborane)-BODIPY dyes.

271
 272 The 2,6-diiodoBODIPY **1a** was reacted with two equivalents of *m*-Me-CB in refluxing 1,4-dioxane using the
 273 Pd₂(dba)₃ (3 mol%) and Pd(P(*t*-Bu)₃)₂ (6 mol%) catalytic system,^[29] in the presence of Cy₂NMe as a base.
 274 Under these conditions, the reaction proceeded smoothly in 12 h with full conversion of the starting materials
 275 affording the target compound **2** in 43% isolated yield (β,β-isomer). Successful incorporation of the carborane
 276 cage was easily confirmed by the presence of the BH broad band in the upfield region of the ¹H NMR (Figure
 277 2, top). Additionally, protons from C_C-CH₃ are identified near 1.65 ppm, which was consistent with the *m*-Me
 278 substitution pathway of the carborane cage. The ¹H NMR spectrum confirmed the symmetric structure of the
 279 dye, showing the benzylic protons signal of the spacer at 3.18 ppm and the two equivalent methyl signals of

280 the fluorophore scaffold at 2.74 and 1.47 ppm. Moreover, analysis of the coupling constant for the olefinic
 281 proton doublets at 6.87 ppm and 6.63 ppm revealed the full *trans*-selectivity of the cross coupling reaction
 282 ($^3J_{\text{HH}} = 16.5$ Hz). Although the formation of geminal substituted olefins in the cationic Heck reaction of 4-
 283 substituted styrenes should be suppressed by the presence of the strong electron-withdrawing carboranyl
 284 cage,^[30] a small amount of α,β -isomer **2a** (6%) was also isolated from the reaction mixture, while no α,α -
 285 isomer was detected (Scheme 1).^[21] The presence of both the terminal olefinic protons (5.84 ppm and 5.10
 286 ppm respectively, $^2J_{\text{HH}} = 1.3$ Hz) and the more deshielded *trans*-olefinic protons ($^3J_{\text{HH}} = 16.5$ Hz) in the ^1H
 287 NMR spectrum of **2a** (Figure 2, bottom) revealed the asymmetric substitution pathway, alongside with the
 288 splitting of the four methyl groups of the BODIPY unit.



289

290 **Figure 2.** ^1H NMR spectra of bis- β,β -styrenyl carborane BODIPY derivative **2** (top) and its α,β -isomer **2a**
 291 (bottom) in CDCl_3 . * H_2O signal; ** residual CDCl_3 peak.

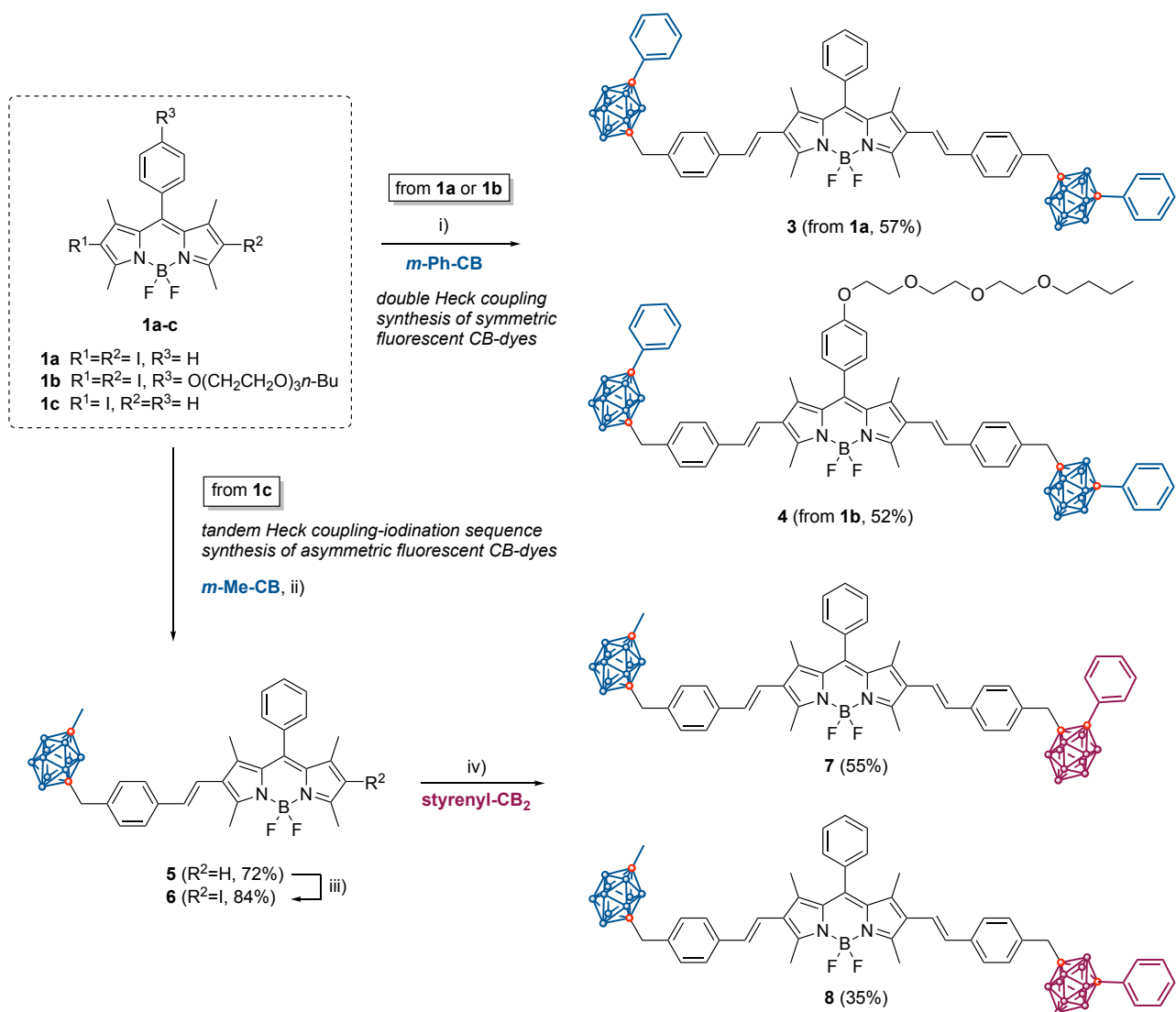
292

293 Analysis of the $^{11}\text{B}\{^1\text{H}\}$ NMR spectra further confirmed the formation of the expected compounds, showing
 294 one resonance centered at 0.99 ppm for β,β -isomer **2** and at 1.01 ppm for α,β -isomer **2a** assigned to the $-\text{BF}_2$
 295 unit. In addition to the $-\text{BF}_2$ resonance, these compounds show broad resonances in the region from -6.17 to -

296 13.04 ppm with the typical 1:1:6:2 pattern characteristic of *m*-carborane clusters.^[12f] The ¹³C{¹H} NMR
297 spectrum of β,β-isomer **2** shows a resonance at 42.8 ppm assigned to the two equivalent benzylic carbon atoms
298 (split into two different signals at 42.7 and 42.6 ppm for the asymmetric α,β-isomer **2a**), and the C_C-CH₃ can
299 be identified from 24.0–25.0 ppm for both isomers.

300 The Heck coupling procedure was successfully applied to the styrenyl substituted *m*-carborane derivative *m*-
301 **Ph-CB** bearing a phenyl ring at one C atom of the cluster (C_C) to achieve symmetric dyes **3** and **4** (Scheme 2).
302 To our delight, the reaction of iodinated BODIPY **1a** using *m*-**Ph-CB** as coupling partner proceeded smoothly,
303 affording the corresponding dye **3** in 57% isolated yield. Also halogenated BODIPY dyes **1b**, incorporating a
304 nonionic amphiphile oligoethylene glycol alkyl chain at the *meso*-position,^[31] was successfully reacted with
305 *m*-**Ph-CB** derivative affording dye **4** in 52% isolated yield. The ¹H NMR spectra clearly confirmed the
306 symmetric structure of the dyes and the incorporation of the carborane cage, showing the typical BH broad
307 band of the *closo*-carborane cluster in the upfield region and the benzylic protons signal of the spacer at 3.18
308 (**3**) and 3.26 ppm (**4**). The ¹¹B{¹H} NMR spectra of these compounds exhibited a resonance at 0.93 ppm (**3**)
309 and at 0.95 ppm (**4**) attributed to the -BF₂ unit, alongside with broad resonances in the region from -5.90 to -
310 13.51 ppm with the typical 2:6:2 pattern of *m*-carborane clusters.

311



312

313 **Scheme 2.** Synthesis of symmetric and asymmetric carborane-BODIPY dyes **3-4** and **7-8**. Reaction conditions:

314 i) substrate **1a-b** (1 eq.), **m-Ph-CB** (2 eq.), Pd₂(dba)₃ (3 mol%), Pd(P(*t*-Bu)₃)₂ (6 mol%), Cy₂NMe (5 eq.). ii)

315 **1c** (1.1 eq.), **m-Me-CB** (1 eq.), Pd₂(dba)₃ (1.2 mol%), Pd(P(*t*-Bu)₃)₂ (1.6 mol%), Cy₂NMe (1.4 eq.), dry 1,4-

316 dioxane, 100 °C, 12 h. iii) **5** (1 equiv.), *N*-iodosuccinimide (2 eq.), DCM, RT, 12 h. iv) **6** (1.1 eq.), **styrenyl-**

317 **CB₂** (1 eq.), Pd₂(dba)₃ (5 mol%), Pd(P(*t*-Bu)₃)₂ (5 mol%), Cy₂NMe (1.4 eq.), dry 1,4-dioxane, 100 °C, 12 h.

318

319 As a further application of this methodology, we then envisaged the possibility to extend the feasibility of our

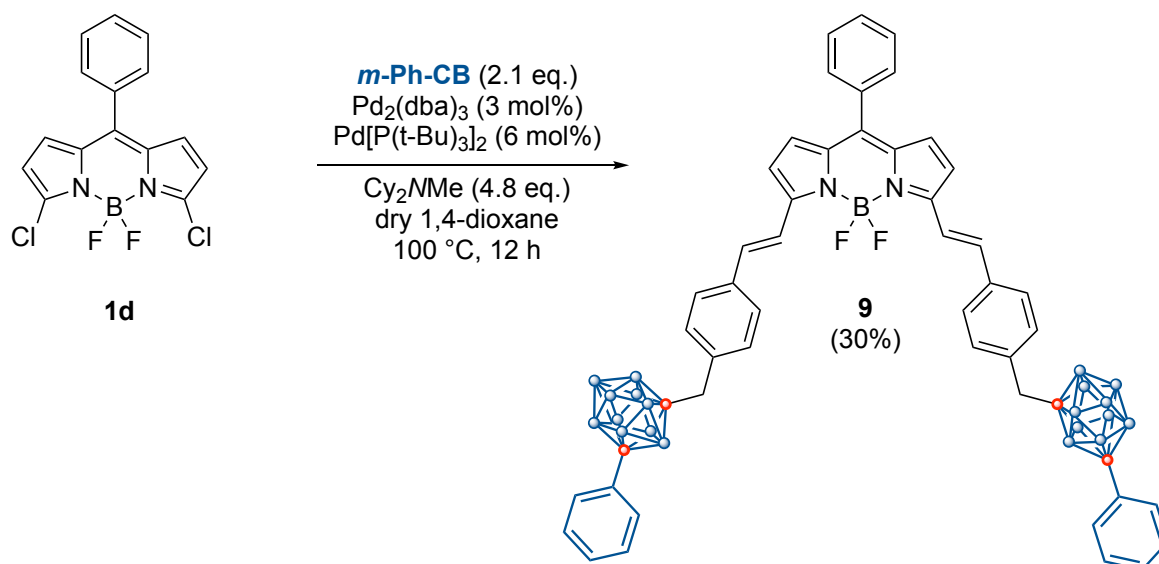
320 approach to the synthesis of asymmetric compounds bearing two different C-substituted carborane units. We

321 thus planned a tandem cross coupling/iodination/cross coupling approach starting from the mono-iodinated

322 1,3,5,7-tetramethylBODIPY dye **1c** (Scheme 2). Reaction of BODIPY **1c** with a stoichiometric amount of the

323 *m*-substituted styrenyl-carborane ***m*-Me-CB** afforded the corresponding mono-substituted derivative **5** in good
324 yield (72%), which was easily converted into a new potential coupling partner **6** by mild iodination at the 6-
325 position in the presence of *N*-iodosuccinimide (NIS). Although the final Heck coupling between substrate **6**
326 and styrenyl-carboranes ***o*-Ph-CB** and ***m*-Ph-CB** required a higher catalyst loading, asymmetric dyes **7** and **8**
327 were successfully isolated with moderate yields of 55% and 35%, respectively. Analysis of the ¹H NMR spectra
328 revealed the asymmetric substitution pathway, showing two different benzylic signals of the spacers at 3.18
329 and 3.07 ppm (**7**) and at 3.26 and 3.18 (**8**). Moreover, the ¹H NMR of **7** exhibited two resolved *trans*-olefinic
330 systems belonging to the different styrenyl carborane units (³*J*_{HH} = 16.3 Hz and ³*J*_{HH} = 16.5 Hz), confirming
331 the stereoselectivity of each Heck coupling reaction of the tandem sequence. The ¹¹B{¹H} NMR spectrum of
332 **7**, bearing two different carborane isomers, one *m*- and one *o*-carborane, displayed the -BF₂ unit centered at
333 1.08 ppm and a set of broad resonances in the range from -3.17 to -12.93 ppm, with a 2:1:1:14:2 pattern
334 reflecting the combined *m*- (1:1:6:2) and *o*- (2:8) typical distributions of *closo*-carboranes. Analysis of the
335 ¹¹B{¹H} NMR spectrum of **8** showed a resonance of the -BF₂ unit at 1.01 ppm and the 1:1:6:2 pattern of broad
336 resonances in the region from -6.05 to -13.01 ppm, ascribed to the two Me and Ph-substituted *m*-carborane
337 clusters.

338 With the aim to compare the photophysical properties of this new class of red-shifted 2,6-disubstituted
339 carborane-BODIPY dyes with other similar dyes with different substitution patterns, we finally envisaged the
340 possibility to exploit our synthetic methodology for the introduction of two styrenyl-containing carboranes on
341 the BODIPY core at the 3,5-positions. To this purpose, we planned a short one-step synthesis of the symmetric
342 dye **9** bearing two ***m*-Ph-CB** units starting from the corresponding 3,5-dichloroBODIPY **1d** (Scheme 3). The
343 3,5-dichloro-*meso*-phenyl-BODIPY dye **1d** was synthesized by acidic condensation of pyrrole with
344 benzaldehyde followed by chlorination/oxidation, and exhibits an absorption maxima centered at 517 nm (Φ_F
345 = 0.13).^[32] Pleasingly, the 3,5-dichloroBODIPY **1d** reacted smoothly in 12 h with two equivalents of ***m*-Ph-**
346 **CB** in refluxing 1,4-dioxane under our Heck coupling conditions, affording the desired 3,5-disubstituted
347 BODIPY **9** in 30% isolated yield. More details about the structural characterization of all the compounds can
348 be found in the Supporting Information.



349

350 **Scheme 3.** Synthesis of symmetric 3,5-disubstituted BODIPY dye **9**.

351

352 **3.2. Photophysical properties**

353 The photophysical behavior of the final compounds was investigated, and the most significant spectroscopic
 354 properties are collected in Table 1. Figure 3 shows UV/Vis and fluorescence spectra of dyes in THF solution
 355 at 298 K. The optical properties of the new synthesized compounds were compared with the parent 2,6-styrenyl
 356 disubstituted BODIPY dye **DS-BDP** (*meso*-phenyl-2,6-distyrylBODIPY)^[21] and the 3,5-styrenyl disubstituted
 357 BODIPY analogue **3,5-BDP** (*meso*-phenyl-3,5-distyrylBODIPY),^[33] both lacking the carborane cages.

358

359

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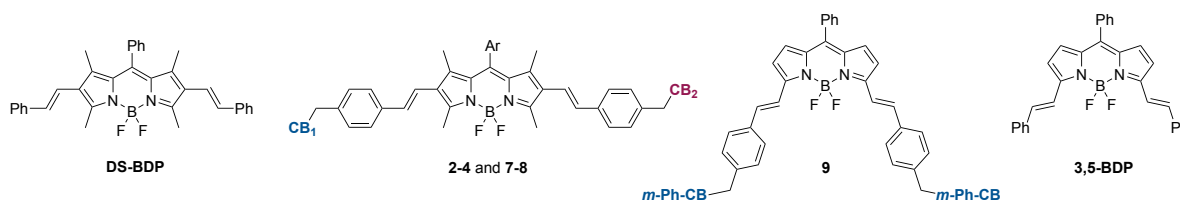
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364

365 **Table 1.** Selected photophysical data for the reported compounds **2**, **2a**, **3**, **4** and **7-9**.^[a] BODIPY dyes **DS-**
 366 **BDP** (entry 1)^[b] and **3,5-BDP** (entry 9)^[c] were added for comparison.



367

Entry	Compound	λ_{abs} (nm)	λ_{em} (nm)	$\epsilon/10^6$ ($\text{M}^{-1} \text{cm}^{-1}$)	Φ_{F} ^[d]	Stokes shift/ 10^3 (cm^{-1})	$\epsilon \Phi_{\text{F}}$ ($\text{M}^{-1} \text{cm}^{-1}$)
1	DS-BDP	575	633	0.031	0.01	1.59	310
2	2	584	640	0.056	0.14	1.50	7840
3	2a	548	627	0.030	0.05	2.30	1500
4	3	578	643	0.035	0.11	1.75	3850
5	4	580	640	0.029	0.14	1.62	4060
6	7	578	643	0.049	0.12	1.75	5880
7	8	582	641	0.058	0.12	1.58	6960
8	9	641	651	0.087	0.36	0.24	31320
9	3,5-BDP	633	646	0.104	0.83	0.32	86320

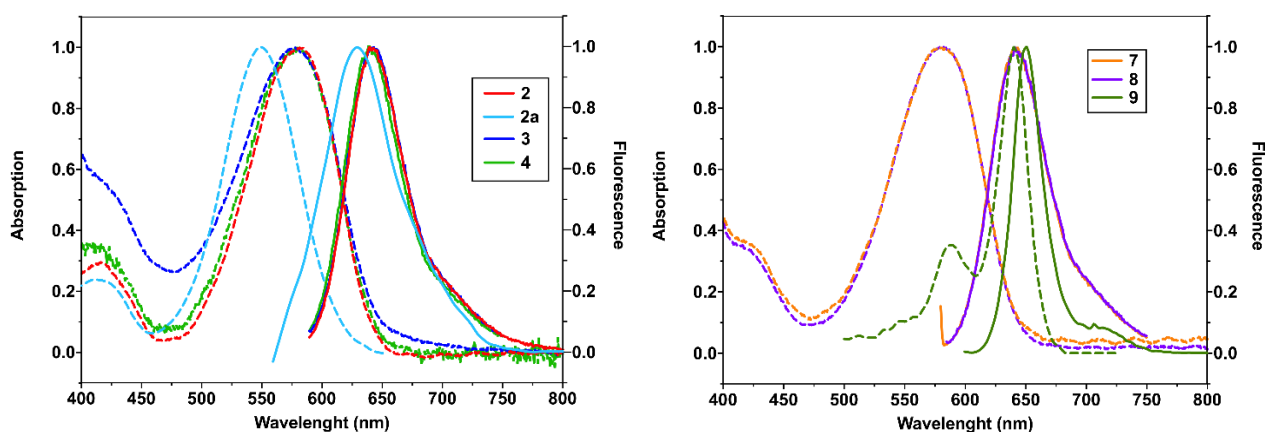
368 [a] Measured in THF at room temperature. [b] Data for **DS-BDP** are reported in the literature in CH_2Cl_2 (see ref.
 369 [21]). [c] Data for **3,5-BDP** are reported in the literature in THF (see ref. [33]) [d] Fluorescence quantum yields
 370 were determined using solutions of Rhodamine 101 in methanol ($\Phi_{\text{F}}=1$) as standard.^[22]

371

372 Generally, the absorption spectra of compounds **2-4** and **7-8** exhibited a significant bathochromic shift
 373 compared to their parent fluorophore scaffolds (*meso*-phenyl-1,3,5,7-tetramethyl BODIPY, $\lambda_{\text{abs}} = 500$ nm in
 374 THF),^[34] but slightly red-shifted (3-9 nm) with respect to the **DS-BDP** (*meso*-phenyl-2,6-distyrylBODIPY),^[21]
 375 showing a very small influence of the carborane cage and their respective C_C -substituents (Me or Ph).
 376 Remarkably, all the compounds showed an enhanced fluorescence emission efficiency compared to the
 377 reference compound **DS-BDP**, resulting in a ten-fold increase of the fluorescence quantum yield (Table 1).
 378 This result might be ascribed to the well-known influence of the carborane cage on the photoluminescent
 379 properties of CB-containing dyes,^[12f] along with a lower degree of conformational flexibility in the S_1 excited
 380 state provided by the incorporation of the carborane clusters.^[21] Moreover, compounds **2-4** and **7-8** showed
 381 large Stokes shifts (56-65 nm) compared to other BODIPY dyes, which suffer of some experimental limitations
 382 such as self-quenching.^[35] The simplest symmetrical BODIPY derivative **2**, containing the *m*-Me-CB unit,

383 showed the highest fluorescence quantum yield ($\Phi_F = 14\%$) of the series bearing a phenyl group at the *meso*-
384 position (Table 1, entry 2). The photophysical features of **2** are easily distinguishable from the side product **2a**
385 containing one α -styrenyl substituted unit. A remarkable hypsochromic shift in the absorption (548 nm) and
386 emission (627 nm) spectra of **2a** in THF were observed (Table 1, entry 3), together with a larger Stokes shift
387 and a significantly lower Φ_F , compared to the β,β -isomer **2**. These differences can be readily attributed to the
388 lower degree of conjugation between the α -styrenyl substituent and the BODIPY scaffold, and to the increased
389 HOMO-LUMO gap resulting from the stabilization effect of the α -styrenyl substituent exclusively on the
390 HOMO.^[21] The introduction of a phenyl ring on the same *m*-carborane isomer in **3** had minimal to no effect
391 on the photophysical features of the compound (Table 1, entry 4), which were depicted by comparable λ_{abs} ,
392 λ_{em} , whereas a drop of the Φ_F was observed ($\Phi_F = 11\%$). When Ph-substituted *m*-carborane derivatives were
393 compared (**3** and **4**), a slight increase of the fluorescence efficiency ($\Phi_F = 14\%$) was produced by introducing
394 a short-term oligoethylene glycol alkyl chain on the *meso*-phenyl ring (**4**, Table 1, entry 5). This latter was of
395 particular synthetic value since it allowed the design of pre- or post-functionalization strategies for the
396 introduction of amphiphilic solubilizing groups on the fluorophore core without affecting the PL properties.
397 Regarding the asymmetric BODIPY dyes **7** and **8**, similar results were obtained for both compounds (Table 1,
398 entries 6-7), exhibiting comparable photophysical features in the series, although slightly lower quantum
399 efficiencies were obtained when compared to their symmetric analogues **2-4**. The replacement of one *m*-Me-
400 CB in **2** with a different CB moiety (*o*-Ph-CB or *m*-Ph-CB) in **7** had no significant impact neither on the
401 BODIPY solubility in various solvents nor on the photophysical features as expected. Interestingly, shifting
402 the substituents on the BODIPY core from the positions 2,6- in **3** to the positions 3,5- in **9** (Table 1, entry 8)
403 caused a remarkable effect on the photophysical properties. The absorption spectrum of **9** (Figure 3, right)
404 exhibited the typical narrow and intense structured $S_0 \rightarrow S_1$ transition with $\lambda_{\text{abs}} = 641$ nm, slightly red-shifted
405 (8 nm) with respect to the reference compound **3,5-BDP** (*meso*-phenyl-3,5-distyrylBODIPY, $\lambda_{\text{abs}} = 633$ nm).
406 The absorption maxima of **3** (578 nm) was largely blue-shifted in comparison to **9** suggesting a less planar
407 conformation also characterized by a lower extinction coefficient. Noteworthy, compound **9** shows the highest
408 molar extinction coefficient of the series which is comparable with the reference **3,5-BDP**. On the other hand,
409 the fluorescence properties were similar in terms of quantum yields, while emission maximum of **9** was slightly

410 red-shifted (7 nm) compared to **3**. Compound **9** showed a smaller Stokes shift compared to reference **3,5-BDP**
411 (13 nm) and **3** (65 nm) in THF, which can be rationalized on the basis of the dihedral angle between the two
412 styrenyl substituents and the BODIPY moieties in the excited state.^[21] Although 3,5-styrenyl disubstituted
413 BODIPY dyes showed higher fluorescence quantum yields compared to their 2,6-analogues (e.g. entries 1 and
414 **9**) due to a lower nonradioactive decay, the presence of two carborane cages in **9** significantly lower the
415 fluorescence quantum yields with respect to **3,5-BDP** (Table 1). We have also calculated the brightness of
416 these dyes, which is the product of the molar extinction coefficient at the excitation wavelength and the
417 fluorescence quantum yield [$\epsilon(\lambda) \cdot \Phi_F$]. As expected, the 3,5-disubstituted compound **9** showed the highest
418 brightness of the series ($31320 \text{ M}^{-1} \text{ cm}^{-1}$), while among the 2,6-substituted dyes the highest value of brightness
419 was found for BODIPY derivative **2** ($7840 \text{ M}^{-1} \text{ cm}^{-1}$), followed by the asymmetric derivatives **8** ($6960 \text{ M}^{-1} \text{ cm}^{-1}$)
420 **1**) and **7** ($5880 \text{ M}^{-1} \text{ cm}^{-1}$).



421

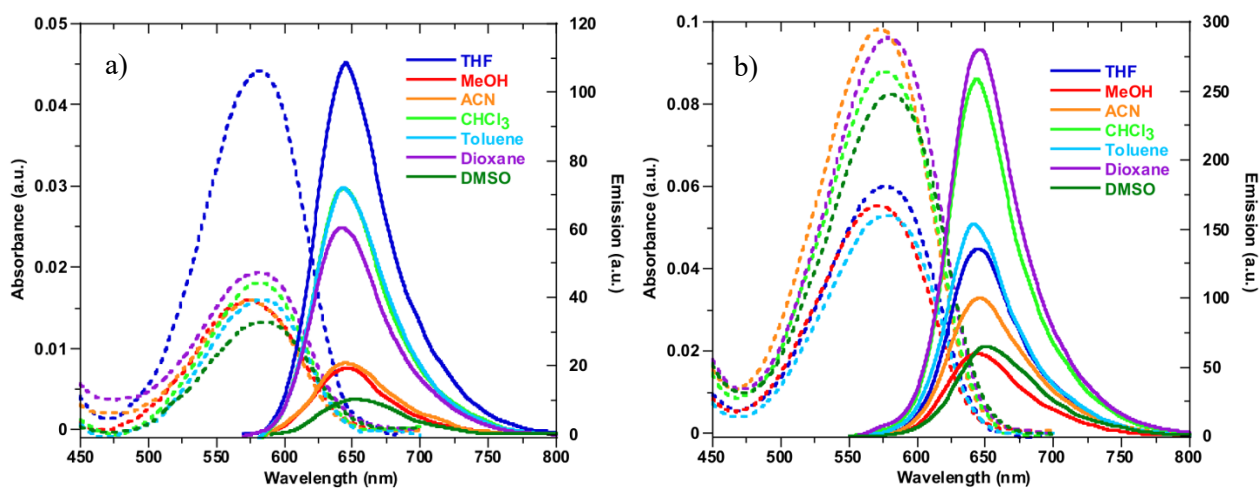
422 **Figure 3.** Normalized absorption (dashed) and emission (solid) spectra of symmetric (**2-4**, left), asymmetric
423 (**7-8**, right) and **9** (right) carborane-BODIPY derivatives in THF.

424

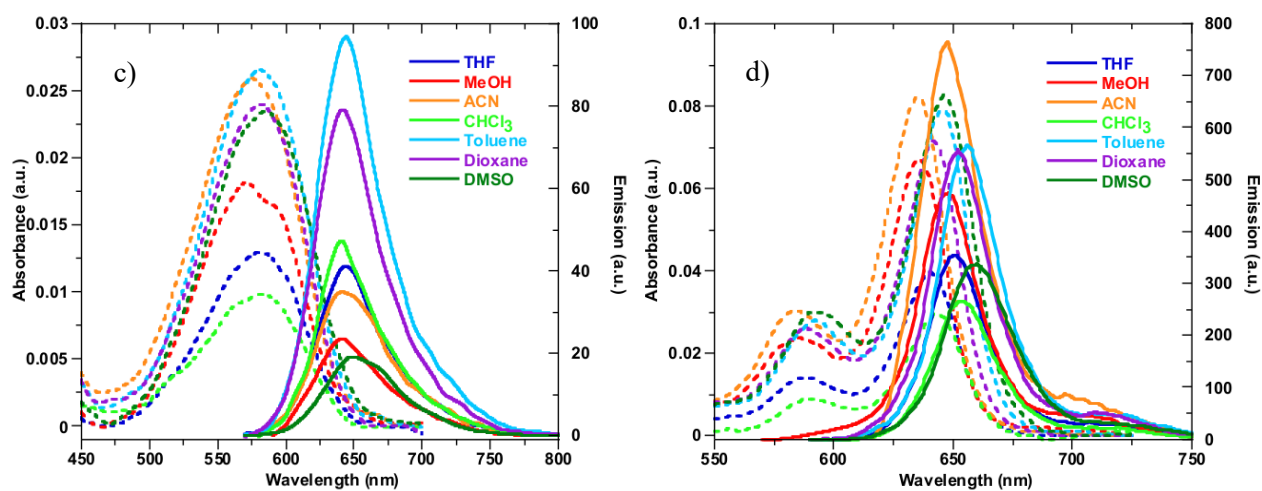
425 The most performing probes have been also investigated in different solvents to evaluate their solubility, spot
426 potential aggregation issues and screen the photophysical properties related to various polar environments. Of
427 these, the polarity-induced change in the optical properties, often denoted as fluorescence solvatochromism,^[36]
428 is of wide interest in order both to identify several polarity-dependent molecular events, and in advancing the
429 design of novel functional dyes. Among the new compounds, one representative candidate for each class was

430 selected on the basis of the most promising optical features (Φ_F and brightness). The UV-Vis absorption and
431 fluorescence spectra of carborane-BODIPY dyes **2** (*m*-Me symmetric), **3** (*m*-Ph symmetric), **7** (asymmetric)
432 and 3,5-disubstituted analogue **9** were recorded in solvents with different dielectric constants (2.25–46.7) at
433 298 K (Figure 4). The scarce influence of solvent polarity observed on the absorption spectra of the new
434 compounds reflected the typical photophysical behavior of BODIPY chromophores.^[37] Compound **2** showed
435 a weak dependence of the absorption (575-584 nm) and the emission (642-652 nm) maxima on the
436 environmental polarity (Figure 5a), as expected in symmetrical scaffolds due to the lack of an intrinsic
437 molecular dipole moment. As a consequence, a similar behavior was observed for compound **3** bearing the
438 phenyl substituted *m*-carborane cage, showing very little solvent effects on the absorption maxima (572-581
439 nm) and fluorescence emission maxima slightly modulated in the 640-650 nm range (Figure 5b). The
440 introduction of two different substituted *o*- and *m*-carborane units in the fluorophore core did not affect
441 significantly the intrinsic molecular dipole moment of asymmetric carborane-BODIPY dyes, as a matter of
442 fact the influence of solvent polarity on the PL properties of **7** (Figure 5c) remained very small ($\lambda_{\text{abs}} = 572$ -584
443 nm and $\lambda_{\text{em}} = 640$ -650 nm). A similar behavior was observed for the symmetric compound **9** (Figure 5d), as a
444 consequence of the low molecular dipole moment. None of the investigated compounds had shown
445 precipitation in different solutions or aggregation phenomena detectable by absorption or emission
446 spectroscopies. **Water AF**

447 which make these dyes as promising candidates for further investigations in in live-cell imaging and bio-
448 supramolecular assays.



449



450

451 **Figure 4.** UV-Vis absorption and fluorescence spectra of BODIPY dyes (a) **2**, (b) **3**, (c) **7** and (d) **9** recorded
 452 in different solvents (ϵ) at 298 K: dioxane (2.25), toluene (2.38), CHCl_3 (4.81), THF (7.58), CH_3OH (32.7),
 453 CH_3CN (37.5), and DMSO (46.7). See Supporting Information for normalized spectra.

454

455 4. Conclusions

456

457 In summary, a set of new red-light emitting 2,6-distyrenyl-substituted carborane-BODIPY dyes with enhanced
 458 boron content was successfully synthesized by a versatile Pd-catalyzed Heck coupling reaction, starting from
 459 a styrenyl-containing carborane and a halogenated dipyrromethene fluorophore. The synthetic procedure was
 460 successfully applied to different types of carborane derivatives with moderate yields, allowing both the
 461 introduction of two identical carborane cages into the fluorophore core and the extension of the π -conjugation
 462 within a single synthetic step. Of particular synthetic value, this methodology allowed the preparation of
 463 asymmetric dyes, bearing two different substituted carborane cages, by means of a tandem cross
 464 coupling/iodination/cross coupling sequence. The final compounds were fully characterized and their
 465 photophysical behavior was investigated. Absorption and photoluminescence (PL) emission patterns of
 466 synthesized dyes were almost unaffected by the different substituents on the C_c of the carborane cage or the
 467 cluster isomer. The 2,6-disubstituted dyes exhibited a significant bathochromic shift compared to their parent
 468 fluorophore scaffold (without carborane clusters) with a significant increase of the emission fluorescent
 469 quantum yields, while the introduction of the two carborane units in 3,5-positions of the fluorophore led to a
 470 significant depletion of the fluorescence efficiency with regards to its homologous fluorophore. Remarkably,
 471 the introduction of a short-term oligoethylene glycol alkyl chain on the *meso*-phenyl ring had no effect on the

472 PL properties of the dyes, allowing the design of pre- or post-functionalization strategies for the introduction
473 of solubilizing groups on the fluorophore core. The scarce influence of solvent polarity observed on the
474 absorption spectra of the new compounds, together with the absence of precipitation or aggregation
475 phenomena, suggested high stability for all of them in solution and make these types of dyes promising
476 candidates for further investigations in live-cell imaging and bio-supramolecular assays.

477

478 **Declaration of competing interest**

479 The authors declare that they have no known competing financial interests or personal relationships that could
480 have appeared to influence the work reported in this paper.

481

482 **CRedit authorship contribution statement**

483 **Chiara Bellomo**: investigation, data curation, formal analysis. **Davide Zanetti**: investigation, data curation,
484 formal analysis. **Francesca Cardano**: investigation, data curation, formal analysis. **Sohini Sinha**:
485 investigation, data curation, formal analysis. **Mahdi Chaari**: investigation, data curation, formal analysis.
486 **Andrea Fin**: validation, data curation, writing-review and editing, supervision. **Rosario Núñez**:
487 conceptualization, methodology, validation, data curation, writing-original draft preparation, writing-review
488 and editing, supervision. **Marco Blangetti**: conceptualization, methodology, validation, data curation, writing-
489 original draft preparation, writing-review and editing, supervision. **Cristina Prandi**: conceptualization,
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491

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502

503 **Appendix A. Supplementary data**

504

505 Supplementary data to this article can be found online at

506

507 **References**

508

509 [1] a) R. N. Grimes, *Carboranes (3rd edition)*, Academic Press, US, **2016**, p. 1058; b) P. A. Jelliss in *Boron*
510 *Science: New Technologies and Applications*, (Ed. N. S. Hosmane), Taylor & Francis, Boca Roca, **2012**, p.
511 355.

512 [2] a) J. Cabrera-Gonzalez, A. Ferrer-Ugalde, S. Bhattacharyya, M. Chaari, F. Teixidor, J. Gierschner and R.
513 Nunez, *J. Mater. Chem. C* **2017**, *5*, 10211-10219; b) R. Núñez, I. Romero, F. Teixidor and C. Viñas, *Chem.*
514 *Soc. Rev.* **2016**, *45*, 5147-5173.

515 [3] a) J. Poater, C. Viñas, I. Bennour, S. Escayola, M. Solà and F. Teixidor, *J. Am. Chem. Soc.* **2020**, *142*,
516 9396-9407; b) J. Poater, M. Solà, C. Viñas and F. Teixidor, *Angew. Chem. Int. Ed.* **2014**, *53*, 12191-12195.

517 [4] M. Scholz and E. Hey-Hawkins, *Chem. Rev.* **2011**, *111*, 7035-7062.

518 [5] R. Núñez, P. Farràs, F. Teixidor, C. Viñas, R. Sillanpää and R. Kivekäs, *Angew. Chem. Int. Ed.* **2006**, *45*,
519 1270-1272.

520 [6] a) Z. J. Leśnikowski, *J. Med. Chem.* **2016**, *59*, 7738-7758; b) F. Issa, M. Kassiou and L. M. Rendina, *Chem.*
521 *Rev.* **2011**, *111*, 5701-5722; c) J. F. Valliant, K. J. Guenther, A. S. King, P. Morel, P. Schaffer, O. O. Sogbein
522 and K. A. Stephenson, *Coord. Chem. Rev.* **2002**, *232*, 173-230.

523 [7] a) X. Zhang and H. Yan, *Coord. Chem. Rev.* **2019**, *378*, 466-482; b) E. Hey-Hawkins and C. Viñas, *Boron-*
524 *Based Compounds*, John Wiley & Sons Ltd, Chichester, UK, **2018**, p; c) S. Duttwyler, *Pure Appl. Chem.* **2018**,
525 *90*, 733-744; d) D. Olid, R. Nunez, C. Vinas and F. Teixidor, *Chem. Soc. Rev.* **2013**, *42*, 3318-3336; e) V. I.
526 Bregadze, *Chem. Rev.* **1992**, *92*, 209-223.

527 [8] a) M. Couto, C. Alamón, S. Nievas, M. Perona, M. A. Dagrosa, F. Teixidor, P. Cabral, C. Viñas and H.
528 Cerecetto, *Chem. Eur. J.* **2020**, *26*, 14335-14340; b) C. Alamón, B. Dávila, M. F. García, C. Sánchez, M.
529 Kovacs, E. Trias, L. Barbeito, M. Gabay, N. Zeineh, M. Gavish, F. Teixidor, C. Viñas, M. Couto and H.
530 Cerecetto, *Cancers* **2020**, *12*; c) D. J. Worm, P. Hoppenz, S. Els-Heindl, M. Kellert, R. Kuhnert, S. Saretz, J.
531 Köbberling, B. Riedl, E. Hey-Hawkins and A. G. Beck-Sickinger, *J. Med. Chem.* **2020**, *63*, 2358-2371; d) C.
532 Vinas, R. Nunez, I. Bennour and F. Teixidor, *Curr. Med. Chem.* **2019**, *26*, 5036-5076; e) A. Buzharevski, S.
533 Paskas, M.-B. Sárosi, M. Laube, P. Lönnecke, W. Neumann, S. Mijatovic, D. Maksimovic-Ivanic, J. Pietzsch
534 and E. Hey-Hawkins, *ChemMedChem* **2019**, *14*, 315-321; f) G. Calabrese, A. Daou, A. Rova, E. Tseligka, I.
535 S. Vizirianakis, D. G. Fatouros and J. Tsibouklis, *MedChemComm* **2017**, *8*, 67-72; g) H. S. Ban and H.
536 Nakamura, *Chem. Rec.* **2015**, *15*, 616-635; h) M. A. Soriano-Ursúa, B. C. Das and J. G. Trujillo-Ferrara, *Expert*
537 *Opinion on Therapeutic Patents* **2014**, *24*, 485-500; i) C. Viñas, *Future Med. Chem.* **2013**, *5*, 617-619.
538 [9] Z. Yinghuai and N. S. Hosmane, *J. Organomet. Chem.* **2013**, *747*, 25-29.
539 [10] a) J. J. Schwartz, A. M. Mendoza, N. Wattanatorn, Y. Zhao, V. T. Nguyen, A. M. Spokoyny, C. A. Mirkin,
540 T. Baše and P. S. Weiss, *J. Am. Chem. Soc.* **2016**, *138*, 5957-5967; b) J. Wang, W.-Y. Wang, X.-Y. Fang and
541 Y.-Q. Qiu, *J. Mol. Model.* **2015**, *21*, 1-10; c) P. Kaszynski in *Boron Science: New Technologies and*
542 *Applications*, (Ed. N. S. Hosmane), Taylor & Francis, Bosa Roca, **2012**, p. 319.
543 [11] a) L. Gan, A. Chidambaram, P. G. Fonquernie, M. E. Light, D. Choquesillo-Lazarte, H. Huang, E. Solano,
544 J. Fraile, C. Viñas, F. Teixidor, J. A. R. Navarro, K. C. Stylianou and J. G. Planas, *J. Am. Chem. Soc.* **2020**,
545 *142*, 8299-8311; b) F. Tan, A. López-Periago, M. E. Light, J. Cirera, E. Ruiz, A. Borrás, F. Teixidor, C. Viñas,
546 C. Domingo and J. G. Planas, *Adv. Mater.* **2018**, *30*, 1800726; c) A. Saha, E. Oleshkevich, C. Vinas and F.
547 Teixidor, *Adv. Mater.* **2017**, *29*, 1704238; d) M. P. Grzelczak, S. P. Danks, R. C. Klipp, D. Belic, A. Zaulet,
548 C. Kunstmann-Olsen, D. F. Bradley, T. Tsukuda, C. Viñas, F. Teixidor, J. J. Abramson and M. Brust, *ACS*
549 *Nano* **2017**, *11*, 12492-12499; e) E. A. Qian, A. I. Wixtrom, J. C. Axtell, A. Saebi, D. Jung, P. Rehak, Y. Han,
550 E. H. Moully, D. Mosallaei, S. Chow, M. S. Messina, J. Y. Wang, A. T. Royappa, A. L. Rheingold, H. D.
551 Maynard, P. Král and A. M. Spokoyny, *Nat. Chem.* **2017**, *9*, 333-340; f) T. Sasaki, J. M. Guerrero, A. D.
552 Leonard and J. M. Tour, *Nano Res.* **2008**, *1*, 412-419; g) M. Koshino, T. Tanaka, N. Solin, K. Suenaga, H.
553 Isobe and E. Nakamura, *Science* **2007**, *316*, 853.

554 [12] a) J. Cabrera-González, M. Chaari, F. Teixidor, C. Viñas and R. Núñez, *Molecules* **2020**, *25*, 1210; b) M.
555 Chaari, Z. Kelemen, D. Choquesillo-Lazarte, F. Teixidor, C. Viñas and R. Núñez, *Inorg. Chem. Front.* **2020**,
556 *7*, 2370-2380; c) G. Tao, Z. Duan and F. Mathey, *Org. Lett.* **2019**, *21*, 2273-2276; d) M. Chaari, J. Cabrera-
557 González, Z. Kelemen, C. Viñas, A. Ferrer-Ugalde, D. Choquesillo-Lazarte, A. Ben Salah, F. Teixidor and R.
558 Núñez, *J. Organomet. Chem.* **2018**, *865*, 206-213; e) M. Chaari, Z. Kelemen, J. G. Planas, F. Teixidor, D.
559 Choquesillo-Lazarte, A. Ben Salah, C. Viñas and R. Núñez, *Journal of Materials Chemistry C* **2018**, *6*, 11336-
560 11347; f) A. Ferrer-Ugalde, J. Cabrera-Gonzalez, E. J. Juarez-Perez, F. Teixidor, E. Perez-Inestrosa, J. M.
561 Montenegro, R. Sillanpaa, M. Haukka and R. Nunez, *Dalton Trans.* **2017**, *46*, 2091-2104; g) J. Cabrera-
562 González, S. Bhattacharyya, B. Milián-Medina, F. Teixidor, N. Farfán, R. Arcos-Ramos, V. Vargas-Reyes, J.
563 Gierschner and R. Núñez, *Eur. J. Inorg. Chem.* **2017**, *2017*, 4575-4580; h) H. Naito, K. Nishino, Y. Morisaki,
564 K. Tanaka and Y. Chujo, *Angew. Chem. Int. Ed.* **2017**, *56*, 254-259; i) J. Cabrera-González, C. Viñas, M.
565 Haukka, S. Bhattacharyya, J. Gierschner and R. Núñez, *Chem. Eur. J.* **2016**, *22*, 13588-13598; j) L. Böhlting,
566 A. Brockhinke, J. Kahlert, L. Weber, R. A. Harder, D. S. Yufit, J. A. K. Howard, J. A. H. MacBride and M.
567 A. Fox, *Eur. J. Inorg. Chem.* **2016**, *2016*, 403-412; k) J. Guo, D. Liu, J. Zhang, J. Zhang, Q. Miao and Z. Xie,
568 *Chem. Commun.* **2015**, *51*, 12004-12007; l) A. Ferrer-Ugalde, E. J. Juarez-Perez, F. Teixidor, C. Vinas, R.
569 Sillanpaa, E. Perez-Inestrosa and R. Nunez, *Chem. Eur. J.* **2012**, *18*, 544-553.

570 [13] a) J. Ochi, K. Tanaka and Y. Chujo, *Angew. Chem. Int. Ed.* **2020**, *59*, 9841-9855; b) R. Núñez, M. Tarrés,
571 A. Ferrer-Ugalde, F. F. de Biani and F. Teixidor, *Chem. Rev.* **2016**, *116*, 14307-14378; c) S. Mukherjee and P.
572 Thilagar, *Chem. Commun.* **2016**, *52*, 1070-1093.

573 [14] a) M. Chaari, Z. Kelemen, D. Choquesillo-Lazarte, N. Gaztelumendi, F. Teixidor, C. Vinas, C. Nogues
574 and R. Nunez, *Biomater. Sci.* **2019**, *7*, 5324-5337; b) K. Nishino, H. Yamamoto, J. Ochi, K. Tanaka and Y.
575 Chujo, *Chem. Asian J.* **2019**, *14*, 1577-1581; c) D. Tu, S. Cai, C. Fernandez, H. Ma, X. Wang, H. Wang, C.
576 Ma, H. Yan, C. Lu and Z. An, *Angew. Chem. Int. Ed.* **2019**, *58*, 9129-9133; d) X. Wu, J. Guo, W. Jia, J. Zhao,
577 D. Jia and H. Shan, *Dyes Pigm.* **2019**, *162*, 855-862; e) J. Li, C. Yang, X. Peng, Y. Chen, Q. Qi, X. Luo, W.-
578 Y. Lai and W. Huang, *J. Mater. Chem. C* **2018**, *6*, 19-28; f) I. Nar, A. Atsay, A. Altındal and E. Hamuryudan,
579 *Inorg. Chem.* **2018**, *57*, 2199-2208; g) X. Li, X. Tong, Y. Yin, H. Yan, C. Lu, W. Huang and Q. Zhao, *Chem.*
580 *Sci.* **2017**, *8*, 5930-5940; h) A. Wu, J. L. Kolanowski, B. B. Boumelhem, K. Yang, R. Lee, A. Kaur, S. T.
581 Fraser, E. J. New and L. M. Rendina, *Chem. Asian J.* **2017**, *12*, 1704-1708.

582 [15] a) A. Loudet and K. Burgess, *Chem. Rev.* **2007**, *107*, 4891-4932; b) G. Ulrich, R. Ziessel and A. Harriman,
583 *Angew. Chem. Int. Ed.* **2008**, *47*, 1184-1201.

584 [16] a) P. Labra-Vázquez, R. Flores-Cruz, A. Galindo-Hernández, J. Cabrera-González, C. Guzmán-Cedillo,
585 A. Jiménez-Sánchez, P. G. Lacroix, R. Santillan, N. Farfán and R. Núñez, *Chem. Eur. J.* **2020**, *26*, 16530-
586 16540; b) I. Nar, A. Atsay, A. Buyruk, H. Pekbelgin Karaoglu, A. K. Burat and E. Hamuryudan, *New J. Chem.*
587 **2019**, *43*, 4471-4476; c) H.-Q. Wang, J.-T. Ye, Y. Zhang, Y.-Y. Zhao and Y.-Q. Qiu, *J. Mater. Chem. C* **2019**,
588 *7*, 7531-7547; d) S.-Y. Kim, Y.-J. Cho, H.-J. Son, D. W. Cho and S. O. Kang, *J. Phys. Chem. A* **2018**, *122*,
589 3391-3397; e) E. Berksun, I. Nar, A. Atsay, I. Ozcesmeci, A. Gelir and E. Hamuryudan, *Inorg. Chem. Front.*
590 **2018**, *5*, 200-207; f) S. Xuan, N. Zhao, Z. Zhou, F. R. Fronczek and M. G. H. Vicente, *J. Med. Chem.* **2016**,
591 *59*, 2109-2117; g) J. H. Gibbs, H. Wang, N. V. S. D. K. Bhupathiraju, F. R. Fronczek, K. M. Smith and M. G.
592 H. Vicente, *J. Organomet. Chem.* **2015**, *798*, 209-213; h) G. F. Jin, Y.-J. Cho, K.-R. Wee, S. A. Hong, I.-H.
593 Suh, H.-J. Son, J.-D. Lee, W.-S. Han, D. W. Cho and S. O. Kang, *Dalton Trans.* **2015**, *44*, 2780-2787; i) R.
594 Ziessel, G. Ulrich, J. H. Olivier, T. Bura and A. Sutter, *Chem. Commun.* **2010**, *46*, 7978-7980.

595 [17] a) L. Lazzarato, E. Gazzano, M. Blangetti, A. Fraix, F. Sodano, G. M. Picone, R. Fruttero, A. Gasco, C.
596 Riganti and S. Sortino, *Antioxidants* **2019**, *8*, 531; b) M. Blangetti, A. Fraix, L. Lazzarato, E. Marini, B.
597 Rolando, F. Sodano, R. Fruttero, A. Gasco and S. Sortino, *Chem. Eur. J.* **2017**, *23*, 9026-9029; c) S. Parisotto,
598 B. Lace, E. Artuso, C. Lombardi, A. Deagostino, R. Scudu, C. Garino, C. Medana and C. Prandi, *Org. Biomol.*
599 *Chem.* **2017**, *15*, 884-893; d) A. Fraix, M. Blangetti, S. Guglielmo, L. Lazzarato, N. Marino, V. Cardile, A. C.
600 E. Graziano, I. Manet, R. Fruttero, A. Gasco and S. Sortino, *Chem. Med. Chem* **2016**, *11*, 1371-1379; e) C.
601 Prandi, G. Ghigo, E. G. Occhiato, D. Scarpi, S. Begliomini, B. Lace, G. Alberto, E. Artuso and M. Blangetti,
602 *Org. Biomol. Chem.* **2014**, *12*, 2960-2968; f) C. Prandi, H. Rosso, B. Lace, E. G. Occhiato, A. Oppedisano, S.
603 Tabasso, G. Alberto and M. Blangetti, *Mol. Plant* **2013**, *6*, 113-127.

604 [18] C. Bellomo, M. Chaari, J. Cabrera-Gonzalez, M. Blangetti, C. Lombardi, A. Deagostino, C. Vinas, N.
605 Gaztelumendi, C. Nogues, R. Nunez and C. Prandi, *Chem. Eur. J.* **2018**, *24*, 15622-15630.

606 [19] Z. Guo, S. Park, J. Yoon and I. Shin, *Chem. Soc. Rev.* **2014**, *43*, 16-29.

607 [20] N. Boens, B. Verbelen and W. Dehaen, *Eur. J. Org. Chem.* **2015**, *2015*, 6577-6595.

608 [21] L. Gai, J. Mack, H. Lu, H. Yamada, D. Kuzuhara, G. Lai, Z. Li and Z. Shen, *Chem. Eur. J.* **2014**, *20*,
609 1091-1102.

- 610 [22] A. M. Brouwer, *Pure Appl. Chem.* **2011**, *83*, 2213-2228.
- 611 [23] Y. Wu, X. Ma, J. Jiao, Y. Cheng and C. Zhu, *Synlett* **2012**, *23*, 778-782.
- 612 [24] P. Yang, J. Zhao, W. Wu, X. Yu and Y. Liu, *J. Org. Chem.* **2012**, *77*, 6166-6178.
- 613 [25] Y. A. Volkova, B. Brizet, P. D. Harvey, A. D. Averin, C. Goze and F. Denat, *Eur. J. Org. Chem.* **2013**,
- 614 *2013*, 4270-4279.
- 615 [26] T. Rohand, W. Qin, N. Boens and W. Dehaen, *Eur. J. Org. Chem.* **2006**, *2006*, 4658-4663.
- 616 [27] J. H. Gibbs, L. T. Robins, Z. Zhou, P. Bobadova-Parvanova, M. Cottam, G. T. McCandless, F. R. Fronczek
- 617 and M. G. H. Vicente, *Bioorg. Med. Chem.* **2013**, *21*, 5770-5781.
- 618 [28] M. Gorbe, A. M. Costero, F. Sancenón, R. Martínez-Máñez, R. Ballesteros-Cillero, L. E. Ochando, K.
- 619 Chulvi, R. Gotor and S. Gil, *Dyes Pigm.* **2019**, *160*, 198-207.
- 620 [29] A. F. Littke and G. C. Fu, *J. Am. Chem. Soc.* **2001**, *123*, 6989-7000.
- 621 [30] P. Fristrup, S. Le Quement, D. Tanner and P. Norrby, *Organometallics* **2004**, *23*, 6160-6165.
- 622 [31] The introduction of nonionic amphiphile chains enhance aqueous solubility without a large loss of
- 623 lipophilicity. See for details: Y. Shirasaki, *J. Pharm. Sci.* **2008**, *97*, 2462-2496.
- 624 [32] E. A. Leushina, I. A. Usol'tsev, S. I. Bezzubov, A. A. Moiseeva, M. V. Terenina, A. V. Anisimov, I. V.
- 625 Taydakov and A. V. Khoroshutin, *Dalton Trans.* **2017**, *46*, 17093-17100.
- 626 [33] K. Rurack, M. Kollmannsberger and J. Daub, *New J. Chem.* **2001**, *25*, 289-292.
- 627 [34] W. Hu, Y. Lin, X.-F. Zhang, M. Feng, S. Zhao and J. Zhang, *Dyes Pigm.* **2019**, *164*, 139-147.
- 628 [35] R. Ziessel, G. Ulrich and A. Harriman, *New J. Chem.* **2007**, *31*, 496-501.
- 629 [36] W. Liptay, *Angew. Chem. Int. Ed.* **1969**, *8*, 177-188.
- 630 [37] A. Filarowski, M. Kluba, K. Cieřlik-Boczula, A. Koll, A. Kochel, L. Pandey, W. M. De Borggraeve, M.
- 631 Van der Auweraer, J. Catalán and N. Boens, *Photochem. Photobiol. Sci.* **2010**, *9*, 996-1008.

632