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Acetoxymethyl-BODIPY dyes: a universal platform for the fluorescent labeling of nucleophiles†

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Current methods for the preparation of functional small-molecule fluorophores generally require labor-intensive, multi-step synthetic routes for all the major chromophoric groups. In spite of recent significant contributions from numerous laboratories, the paucity of rapid, straightforward and wide-scope synthetic strategies in this field is limiting the development of advanced probes for bioimaging, sensing and therapeutic applications. We describe herein a general and robust methodology for the one-step fluorescent labeling of a wide variety of molecules having C-, N-, P-, O-, S-, or halide-nucleophilic centers, using stable and readily available acetoxymethyl-BODIPYs as reagents in the presence of an acid catalyst. This modular methodology allows a very facile preparation of mono- and di-functional probes incorporating a broad assortment of biomolecules, enzyme cofactors, natural products, and other chromophores, as well as chemical functionalities for a wide range of applications including bioorthogonal conjugation, polymerization, and supramolecular chemistry, among others. The photophysical properties and preliminary applications of the new probes in live-cell imaging were also studied. The described strategy enables the high-throughput engineering of novel BODIPY dyes with diverse functionalities for basic and applied science with potential for innovative technological applications.

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1. Introduction

Genetically encoded fluorescent proteins¹ and small-molecule fluorescent probes² have evolved as essential facilitating tools for the study of biology at the single cell and subcellular levels with high spatiotemporal resolution. Although small-molecule fluorophores can hardly surpass the great specificity of fluorescent proteins, their physicochemical properties and photo-

stabilities can be readily modulated through chemical modification, further allowing the introduction of appropriate functionalities for applications in biolabeling, biotargeting, and sensing that are often beyond the reach of genetic approaches.^{2,3} In general, current methods for the preparation of functional small-molecule fluorophores require labor-intensive, multi-step synthetic routes for all the major chromophoric groups.² Among these, BODIPYs have become prominent in recent years due to their high photostability, excellent photophysical properties, and high chemical versatility.⁴⁻⁶ The development of functionalization methods that are general, efficient, selective, and highly versatile is currently one of the main challenges in fluorophores' chemistry in general and in BODIPYs in particular, which display a richer chemistry than other fluorophores in current use. Although different methodologies have been described for the introduction of new functionalities at every position of the BODIPY chromophore, the vast majority involve the use of multistage routes that need to be individually tailored to each final target dye, which entails greater synthetic effort, overall loss of chemical yield and increased economic costs. For these reasons, there is great interest in the development of direct functionalization methods of pre-formed BODIPYs,^{7,8} which ideally allow the introduction of the new functionality in a single and final reaction step.

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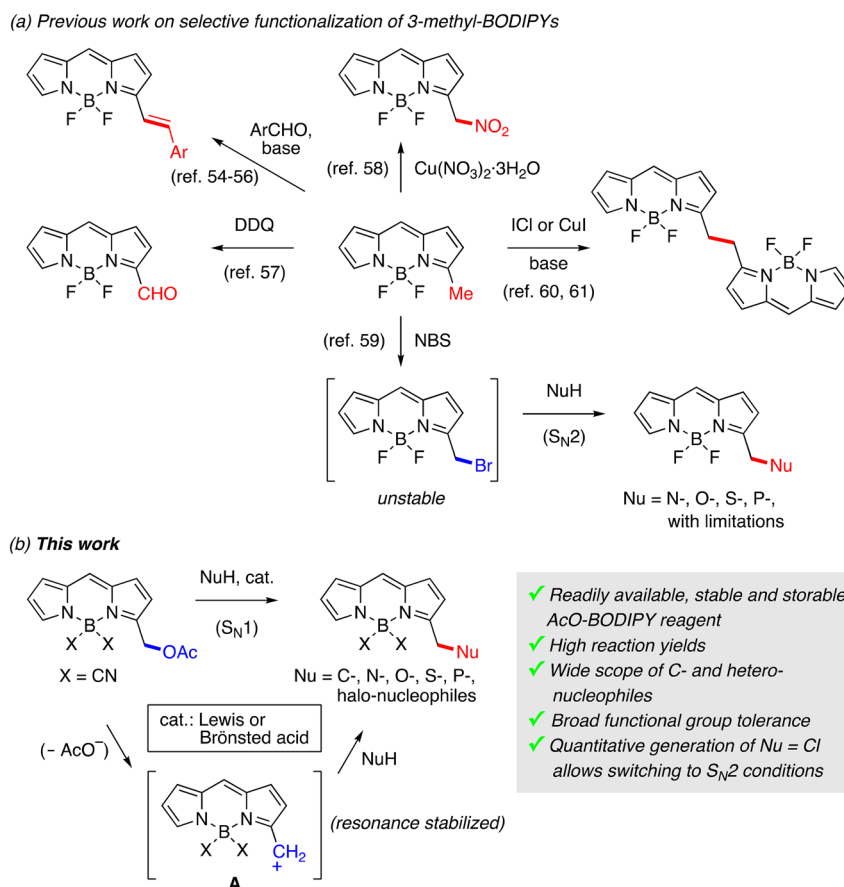
‡ These authors have contributed equally to this work.



In general, most post-functionalization strategies described for BODIPYs require the presence or prior introduction of a reactive atom or group (e.g. halogen,^{9–19} formyl,^{20–24} carboxyl,^{25–31} thioether,^{32–36} alkyne,^{37–44} azide,^{45–48} or tetrazine^{49–53}) that enables the final functionalization reaction. These reactive groups can be directly attached either to the chromophore backbone (at boron or carbon) or to peripheral positions separated by one or several bonds from the chromophoric nucleus. However, all previously described methods present limitations in terms of: (1) the variety of substituents that can be introduced under the same reaction conditions (generally, carbon and heteroatomic substituents require different conditions); (2) the type of reactive functionality that should be present in the new substituents, which affects their price, availability and structural diversity; (3) the chemical compatibility between the pre-existing functional groups on the BODIPY and on the new substituent under the reaction conditions; and (4) the yield of the post-functionalization reaction.

The objective of this work was to develop a general strategy for the post-functionalization of BODIPYs that allowed the direct and straightforward incorporation of a wide variety of molecules under similar reaction conditions. Most widely used BODIPYs have alkyl-substituted pyrrole rings, which stabilize

cations, radicals and anions at the benzylic-type carbon, particularly those at C3 and C5, offering an interesting opportunity for directly incorporating new functionality at these reactive positions. Not surprisingly, this reactivity has already been exploited in the functionalization of 3/5-methyl-substituted BODIPYs (Scheme 1a) using: (a) Knoevenagel reaction with aromatic aldehydes,^{54–56} (b) oxidation to aldehyde with DDQ,⁵⁷ (c) nitration,⁵⁸ (d) electrophilic bromination followed by *in situ* nucleophilic substitution,⁵⁹ and (e) oxidative dimerization promoted by ICl or CuI under basic conditions.^{60,61} Interestingly, Ulrich and Ziesel's⁵⁹ two-step/one-pot protocol has been successfully used for the introduction of *N*-, *O*-, *P*- and *S*-nucleophiles. However, this approach shows some drawbacks: (i) the bromo-methylated intermediate is a very unstable compound that cannot be isolated and, consequently, the bromination and substitution steps must be carried out “in a single flask” for each transformation; (ii) reaction times are highly variable, from a few minutes to several days, depending on the nucleophile; (iii) it is limited in relation to the type of nucleophiles that can participate in the reaction. Thus, in the case of *O*-nucleophiles, only alcohols have been described; in the case of *N*-nucleophiles, only azide and secondary amines render the substitution product, while primary amines generate complex reaction mixtures; and (iv) there are no examples



Scheme 1 Post-functionalization strategies of 3-methyl-BODIPYs (substituents at other positions were removed for clarity).



of introduction of *C*-nucleophiles, which is possibly its most important limitation.

Our new method (Scheme 1b) was inspired by these former functionalization strategies. A key prerequisite of our approach was the incorporation of a stable reactive group that required prior activation under catalytic conditions to participate in the functionalization reaction. Thus, the reactive but non-activated BODIPY can be easily isolated and stored for later use in the substitution reaction. A functional group that fulfills these requirements is the acetoxymethyl group, widely used in the synthesis of porphyrins,^{62–65} but, somehow surprisingly, not yet in the chemistry of BODIPYs despite the structural similarities between both families of dyes. Acid-catalyzed activation of this group can readily generate a resonance-stabilized carbocation intermediate (**A**), which will considerably expand the diversity of nucleophilic groups that can participate in the S_N1 -type process including also different types of *C*-nucleophiles, in contrast to previous methods.

In this work, we describe the preparation of acetoxymethyl-BODIPYs by direct acyloxylation of the corresponding 3/5-methyl-BODIPYs and their efficient acid-catalyzed reaction with hetero- and carbon-nucleophiles to afford a wide variety of new functional BODIPYs for multiple applications. The photophysical properties of the new probes as well as some preliminary applications in live-cell microscopy will also be described.

2. Results and discussion

2.1. Synthesis of 3/5-acetoxymethyl-BODIPYs

When we started this work, there was already an example of a BODIPY dye with acetoxymethyl groups at C3 and C5 reported by Boyer *et al.* in 1994 in an article that is better known for first describing the regioselective oxidation of the methyl groups at C3/C5 to formyl groups with DDQ.⁵⁷ The authors prepared the 3,5-di(acetoxymethyl)-BODIPY **1** by a classical method of acetylation using lead tetraacetate, which was originally reported for alkyl-substituted pyrroles⁶² and other heteroaromatic and aromatic compounds (Scheme 2a). However, attempts to hydrolyze the acetate groups under acidic or basic conditions always led to complex reaction mixtures and the compound did not awake further synthetic interest.

Although F-BODIPYs show great chemical robustness under diverse reaction conditions, strong acids and bases cause decomplexation of the BF_2 group.^{66–73} Substitution of the fluorine atoms at boron with other substituents barely affects the positions of the spectroscopic bands (absorption and emission) of the chromophore, but allows to modulate its photo- and chemo-stability. Among the substituents that have been introduced on the boron atom of BODIPYs instead of fluorine (halo-, *C*-, *O*-, and *N*-derivatives),^{7,8,68,74} the cyano group provides the greatest stability improvement in acid medium, while also enhancing the fluorescence of the chromophore.^{75–78} For our planned strategy, the introduction of cyano groups on the

boron atom was a conceivable requirement for our acetoxymethyl-BODIPY reagent to withstand the acidic conditions of the substitution reaction. Thus, we prepared 4,4'-dicyano-BODIPYs (CN-BODIPYs) **5–7** in quantitative yield from the corresponding F-BODIPYs **2–4**, respectively, following a described protocol (Scheme 2a),^{75,79} without any need for chromatographic purification.

We first tested the reaction of F-BODIPYs **2** and **3** with $Pb(OAc)_4$ in acetic acid using the reported procedure,⁵⁷ with minor modifications (Scheme 2b; see the ESI† for details). In the case of the peralkylated BODIPY **2**, the reaction led to the regioselective formation of 3,5-bis(acetoxymethyl)-BODIPY **1**, as described.⁵⁷ In contrast, the reaction of BODIPY **3**, with an aryl group at C8, was slower and gave exclusively the mono-acetoxy derivative **8** under the same conditions. The acyloxylation of CN-BODIPY **5** (Scheme 2b) with $Pb(OAc)_4$ (2.4 equiv.) at room temperature exclusively yielded the mono-acetoxy product **9** in good yield, in contrast to its parent F-BODIPY **2**, which generated the diacetoxy-F-BODIPY **1** under these conditions. Using a higher temperature (40–50 °C) and a higher excess of $Pb(OAc)_4$ (3–4 equiv.) gave the diacetoxy-CN-BODIPY **10** in very good yield. Compound **10** was not stable on prolonged contact with silica gel, but it could be easily purified by recrystallization from hexane/ CH_2Cl_2 . The acyloxylation of CN-BODIPY **7** proceeded under the same thermal conditions to afford a mixture of mono- and di-acetoxy-CN-BODIPY (**11** and **12**, respectively), together with minor amounts of triacetoxy-CN-BODIPY **13**. Interestingly, these acetoxy-CN-BODIPYs could be purified on silica gel column chromatography without decomposition.

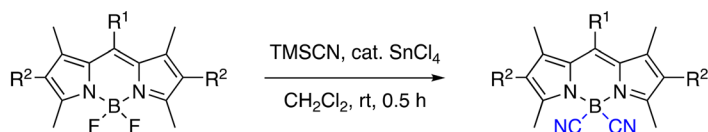
The structure of **9** was confirmed by X-ray diffraction (Fig. 1). As previously described⁵⁷ for **1**, the acetyl group adopts an orthogonal orientation with respect to the median plane of the chromophore, which is the most suitable electronic prealignment for the heterolytic cleavage of the C–OAc bond after Lewis acid complexation, with generation of intermediate carbocation **A** (see Scheme 1). As observed for other CN-BODIPYs,⁷⁶ the B–N bond lengths (1.531 and 1.538 Å) are slightly shorter than the mean value of 1.540 Å determined for its F-BODIPY precursor **2**.⁸⁰ The boron atom has an almost ideal tetrahedral geometry with bond angles for N–B–N, C–B–N and C–B–C of 108.4, 109.6 (mean value), and 110.0°, respectively.

A plausible mechanistic proposal for this reaction is discussed in the ESI† to explain the lower reactivity observed for compounds with better electron-withdrawing groups (CN- *versus* F-BODIPYs: **5** and **2**, respectively; and 8-phenyl- *versus* 8-methyl-BODIPYs: **4** and **2**, respectively).

With a view to subsequent chemical transformations that would require a non-acetoxy leaving group, we tried to deacetylate **8** to generate the hydroxymethyl-derivative **14**, which can also be a suitable leaving group in the S_N1 reaction. As observed by Boyer *et al.*,⁵⁷ the transesterification reaction of **2** in MeOH under different basic conditions (NaOMe, K_2CO_3 or Et_3N) always led to complex reaction mixtures. We finally found very mild deprotection conditions⁸¹ using metallic mag-



a) Synthesis of starting CN-BODIPYs

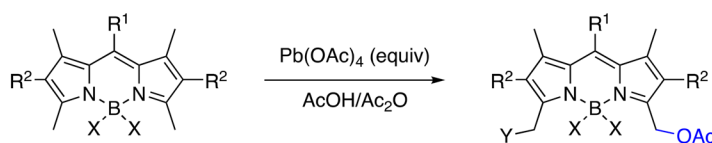
2, R¹ = Me, R² = Et3, R¹ = 2,4,6-Me₃C₆H₂ (Mes), R² = H4, R¹ = Ph, R² = Et

5, quant.

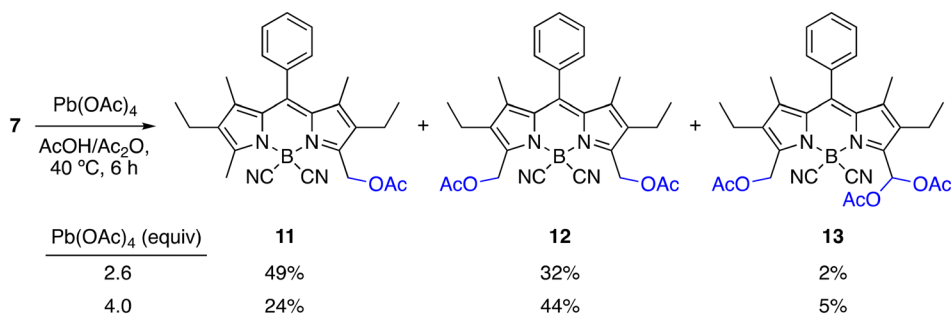
6, 96%

7, 99%

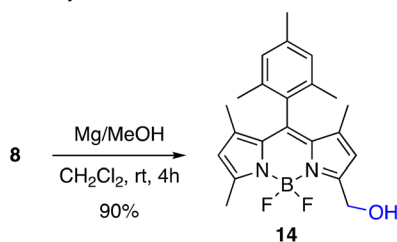
b) Acyloxylation reactions



Starting BODIPY	R ¹	R ²	X	Pb(OAc) ₄ (equiv)	Temp. (°C)	Time (h)	Product	Y	Yield (%)
2	Me	Et	F	2.1	0-25	4.5	1	AcO	66
3	Mes	H	F	2.1	0-25	3.0	8	H	62
5	Me	Et	CN	2.4	0-25	2.5	9	H	72
5	Me	Et	CN	3.0	50	5.5	10	AcO	87



c) Deacetylation reaction



Scheme 2 Synthesis of starting CN-BODIPYs and acetyloxy-methyl-BODIPYs, and deacetylation of the latter.

nesium in MeOH at room temperature, which afforded **14** in very good yield (Scheme 2c). However, due to the success of our initial approach for directly activating the acetate group (see below), this alternative route was not further explored.

2.2. Reaction of 3-acetyloxy-methyl-BODIPYs with carbon and heteroatom nucleophiles

Preliminary studies of the substitution reaction of acetyloxy-methyl-F-BODIPYs **1** with isobutanol as model nucleophile in

CH₂Cl₂ or MeCN at room temperature using either Brønsted (*p*-TsOH) or Lewis (Et₂O·BF₃, TMSOTf, Sc(OTf)₃, Cu(OTf)₂) acid catalysts (2.5 mol%) afforded complex reaction mixtures with generation of very polar non-fluorescent products in all cases. This result points to a probably acid-promoted decomposition of the BF₂ group generating the corresponding dipyrromethene.^{68–73} We next assayed the CN-BODIPY derivative **9**, with an expected significantly enhanced stability under acidic conditions, as commented above. A qualitative parallel



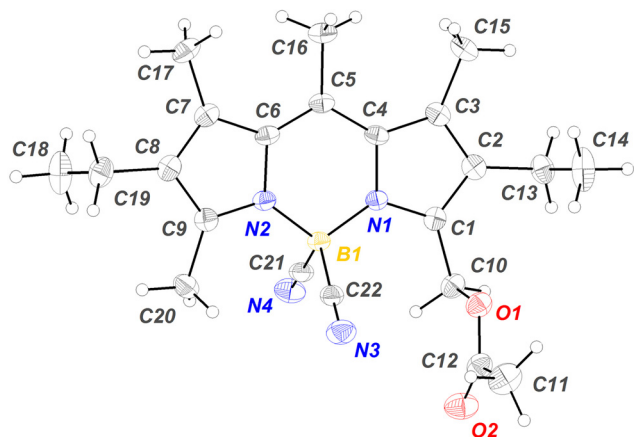


Fig. 1 Molecular structure of compound **9** from X-ray crystal structure analysis.

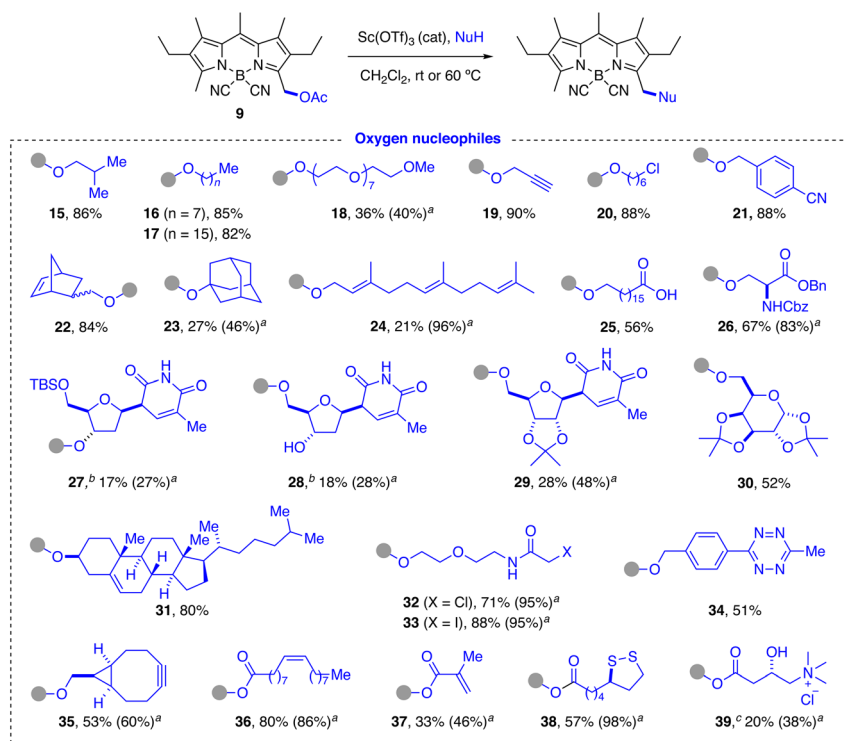
screening with a larger group of acid catalysts using the same model test reaction with **9** (see ESI† for details) showed that Sc(OTf)₃ was the most efficient and general acid catalyst and was therefore selected for most of the substitution reactions described below.

2.2.1. Synthesis of mono-substituted BODIPYs. The initial optimization study with a simple alcohol, allowed us to generalize this new methodology for the efficient incorporation of a wide array of hetero- and *C*-nucleophiles. The general procedure consisted of treating an acetoxy-methyl-CN-BODIPY

with a small excess of the nucleophile (1.2–2.0 equiv.) in anhydrous solvent (CH₂Cl₂ or MeCN) at room temperature in the presence of 2.5–15.0 mol% of the acid catalyst (generally Sc(OTf)₃), without the need to use an inert atmosphere.

***O*-Nucleophiles.** A wide variety of *O*-nucleophiles were incorporated at the methylene group of 3-acetoxy-methyl-CN-BODIPY **9** using the general reaction conditions (Scheme 3). Primary (**15–18**, **20**, **22**, **25**, **26**, **28–30**, **32**, **33**, **35**), secondary (**27**, **31**) and tertiary (**23**) alkanols, as well as benzylic (**21**, **34**), allylic (**24**) and propargylic alcohols (**19**) were successfully labeled in moderate to very good yields. The reaction is compatible with the presence of ester (**26**), nitrile (**21**), carbamoyl (**26**), carboxamido (**32**, **33**), imido (**27–29**), trialkylsilyl ether (**27**), isopropylidene acetal (**29**, **30**), 1,2,4,5-tetrazino (**34**), disulfide (**38**), and chloro-/iodo-alkyl groups (**20**, **32**, **33**). Carboxylic acids were also good substrates, although a larger excess of the nucleophile (up to 5 equiv.) was generally required to obtain good product yields (**36–39**). In this case, the reaction is actually in thermodynamic equilibrium with the acetic acid released in the substitution reaction. This equilibrium can also explain the chemoselectivity observed in the reaction with simple hydroxy acids (**25**). However, in the case of more complex hydroxy acids (**39**) with a secondary hydroxyl group, the corresponding ester was obtained, although in moderate yield.

The method allowed us to fluorescently label natural products (farnesol: **24**), as well as a wide variety of biomolecules, including lipids (cholesterol: **31**, oleic acid: **36**), carbohydrates



Scheme 3 Reaction with *O*-nucleophiles. Reaction conditions: Sc(OTf)₃ (2.5–10 mol%), NuH (1.2–5.0 equiv.), 0.5–30 h (see ESI† for further details). ^aYield based on converted **9**. ^bProducts formed in the same reaction. ^cIn MeCN.

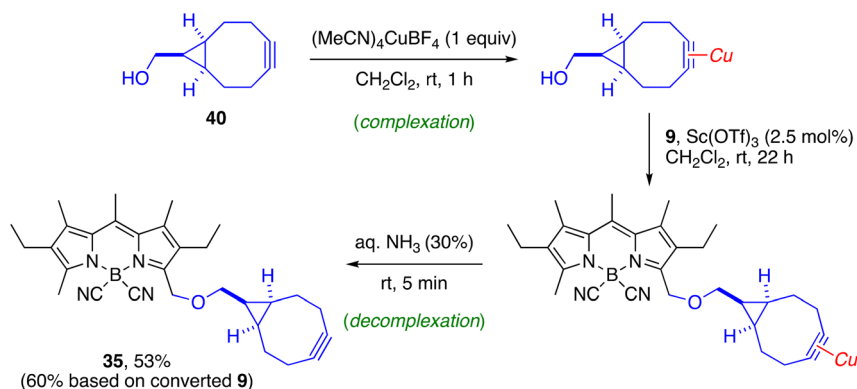


(D-galactose: **30**), nucleosides (partially protected derivatives of D-deoxyribose: **27**, **28**, and D-ribose: **29**), amino acids (L-serine: **26**), hydroxy acids with a tetraalkylammonium group (carnitine: **39**), or enzyme cofactors (lipoic acid: **38**). In addition, we were able to introduce functionalities for complexation with cyclodextrins (adamantyl group: **23**), for polymerization (methacrylate group for radical polymerization: **37**; norbornene group for ring-opening alkene metathesis-polymerization (ROMP): **22**), for bioorthogonal conjugation^{82–84} (propargyl group for Cu(I)-catalyzed “click” cycloaddition reaction: **19**; cyclooctyne group for strain-promoted alkyne-azide cycloaddition (SPAAC): **35**; chloro-/iodo-acetamido group for selective labeling of cysteines: **32**, **33**; 1,2,4,5-tetrazine ring for inverse-electron-demand Diels–Alder cycloadditions:⁸⁵ **34**), and for selective fluorescent labeling of HaloTag fusion proteins (6-chlorohexyl chain: **20**).^{86–88}

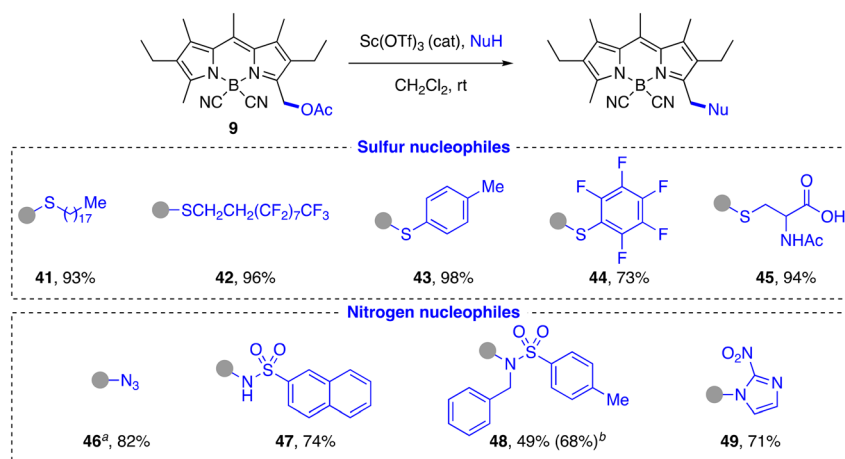
The diversity of O-substituents included in this study allowed us to identify some limitations of the method. The first, as already mentioned, is the need to use an excess of nucleophile in the case of carboxylic acids, due to the reversibility of the substitution reaction under acidic conditions. As

expected, yields decreased in the case of molecules with acid-sensitive groups, such as acetals (**29**, **30**) or trialkylsilyl ethers (**27**). In the latter case, the reaction afforded the expected product **27** together with the corresponding desilylated derivative **28**. Not surprisingly, polyoxygenated substrates (**18**, **26–30**, **32**, **33**, **39**) slowed down the reaction due to their ability to complex the metal catalyst in competition with the activation of the acetate group, which required the use of a greater amount of catalyst and/or a higher reaction temperature, including microwave irradiation in some cases (**39**) (see ESI† for experimental details). Other strong metal chelating groups, such as the cyclooctyne group, sequestered the scandium catalyst very effectively. The incorporation of the cyclooctyne unit **40** could only be achieved following a described strategy for transient protection of the cyclooctyne by 1:1 complexation with a cationic copper(I) salt, which allowed the preparation of **35** in moderate overall yield (Scheme 4).^{89,90}

S-Nucleophiles. As expected from their higher nucleophilicity, the substitution reaction with thiols was faster and more efficient than with alcohols (Scheme 5). Aliphatic (**41**, **42**, **45**) and aromatic (**43**, **44**) thiols were readily incorporated in high



Scheme 4 Synthesis of cyclooctyne-functionalized probe **35** from acetoxymethyl-BODIPY **9** by a transient protection strategy of the cyclooctyne.



Scheme 5 Reaction with S- and N-nucleophiles. ^aNuH: TMSN₃. ^bBased on converted **9**.



yield (70–90%), including polyfluorinated systems (**42**, **44**) and partially protected biomolecules such as *N*-acetyl-L-cysteine (**45**). In the latter case, the observed chemoselectivity is both of kinetic origin, due to the higher nucleophilicity of the thiol group in comparison with the carboxylic acid group, and of thermodynamic origin, due to the reversibility of the reaction with the carboxylate group.

***N*-Nucleophiles.** As we already verified in the study of *O*- and *S*-nucleophiles, amides and carbamates are not good substrates in this substitution reaction, nor would amines be expected to react due to their incompatibility with the acid catalysis conditions. Thus, we decided to test other types of *N*-nucleophiles that did not present these problems, either because of their greater acidity, as in the case of sulfonamides or 2-nitroimidazole, or because of their higher nucleophilicity, as occurs with the azide anion. Thus, primary and secondary sulfonamides (**47**, **48**, respectively), which can generate a transient nucleophilic anion, enabled the reaction in moderate to good yield, the former being more reactive due to the lower steric hindrance (Scheme 5). Trimethylsilyl azide yielded the azidomethyl-CN-BODIPY **46** in high yield and with appreciably faster kinetics than in the case of sulfonamides. Compound **46** is an interesting fluorescent reagent for bioorthogonal conjugation and sensing.^{46,91,92} (NH)-Heterocycles, such as 2-nitroimidazole, were efficiently alkylated under the standard conditions, affording in this case a potential nitroreductase probe (**49**).⁹³

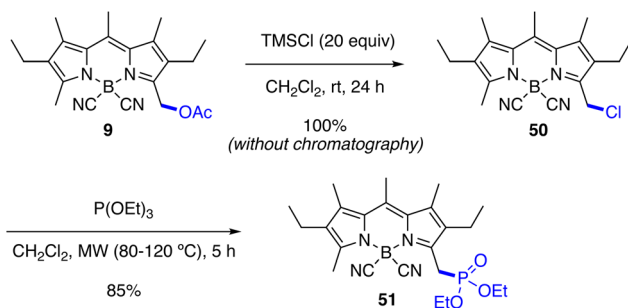
***Cl*- and *P*-Nucleophiles.** The reaction of **9** with an excess of TMSCl (20 equiv.) in CH₂Cl₂ at room temperature quantitatively furnished the chloromethyl-derivative **50** in the absence of a metal catalyst, where the reagent acted as acid catalyst as well as nucleophile precursor (Scheme 6). Although **50** was unstable on silica gel, it could be isolated in quantitative yield and high purity by simple evaporation of the reaction mixture.⁵⁹ This chlorinated compound can be directly used for S_N2-type substitution transformations, as described for its bromo-analogue.⁵⁹ Thus, the Arbuzov reaction with triethyl phosphite under microwave irradiation yielded the phosphonate **51** in good yield (Scheme 6).

***C*-Nucleophiles.** In contrast to previously described approaches,⁵⁹ the same reaction conditions that were efficient for the functionalization of heteronucleophiles proved to be

equally effective for the introduction of *C*-nucleophiles. Thus, electron-rich aromatic (phenols: **56**, **57**, **58**; azulene: **59**) and heteroaromatic (pyrrole: **60**; indole: **61**) compounds efficiently yielded the BODIPY-labeled product in a Friedel–Crafts-type process (Scheme 7). The reaction with phenols was highly chemo- and regioselective, exclusively affording the 2-hydroxyphenyl-derivative in very good yields. No trace of the alternative *O*-alkylated derivative or the 4-hydroxyphenyl-regioisomer were detected. The method allowed us to fluorescently label partially protected L-tyrosine (**57**) and a polyfunctional natural product such as resveratrol (**58**). The reaction with the tyrosine derivative proceeded with high chemo- and regioselectivity and was fully compatible with the presence of the carbamate and the methyl ester groups. The reaction with resveratrol required the use of a greater amount of catalyst, longer reaction time and a higher temperature, but proceeded regioselectively to give the *C*-derivative **58** in moderate yield as major product, with the BODIPY chromophore covalently bonded to the most electron-rich aromatic ring at the most electron-rich carbon. The reaction with guaiazulene, a natural derivative of azulene, was also highly regioselective, affording exclusively the product alkylated at the electron-rich 5-membered ring. The structures of these compounds were fully confirmed by careful one- and two-dimensional ¹H and ¹³C NMR studies. Indole and pyrrole also gave the substitution reaction with good or very good yields under the standard conditions, with the expected regioselectivity for electrophilic attack on this type of heterocycles. The good reactivity observed for pyrroles led us to also test BODIPYs with a free position on the pyrrolic rings as nucleophiles. To avoid decomposition in the presence of the acid catalyst, we used a 4,4'-dicyano-BODIPY (**6**) as acceptor (Scheme 2a). Despite the presence of alkyl substituents flanking the reactive CH carbon of the pyrrole rings of **6**, the reaction of an equimolar mixture of **6** and **9** under the standard conditions led to formation of the expected statistical mixture of mono- and di-substitution products **62** and **63**, respectively, in close to the expected theoretical yields (50% and 25%, respectively).

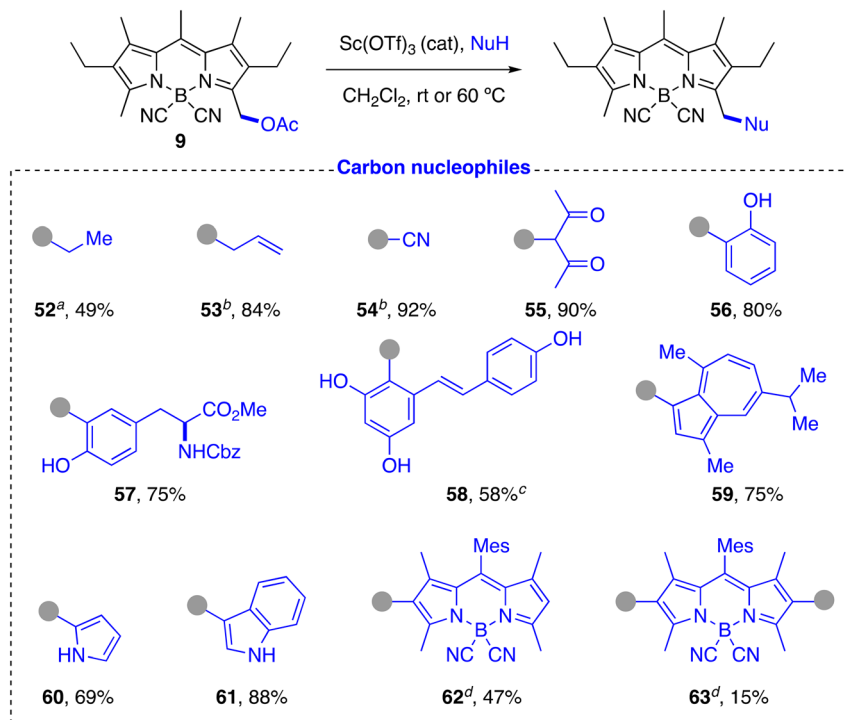
In addition to carbocyclic and heterocyclic systems, acyclic *C*-nucleophiles can also be incorporated. Thus, *C*-trimethylsilyl derivatives, including allyltrimethylsilane and trimethylsilyl cyanide, as well as compounds with an active methylene group such as acetylacetone, reacted very efficiently to yield the expected alkylation products **53**, **54**, and **55**, respectively, in high yield. Compound **55** presented the characteristic keto–enol equilibrium in solution, with a practically equimolar ratio of both species in CDCl₃ at room temperature, as observed by ¹H NMR (see ESI†).^{94,95} Simple organometallic compounds such as diethylzinc were also successfully tested, although in this case it was necessary to use a stoichiometric amount of trimethylsilyl triflate as promoter to afford the alkylated product **52**, which indicates the probable participation of a triflate intermediate in the substitution reaction.⁹⁶

Unlike other related methods, the great versatility of the described post-functionalization strategy allowed not only to incorporate a wide diversity of heteronucleophiles in BODIPYs,



Scheme 6 Reaction with halogen and phosphorous nucleophiles.





Scheme 7 Reaction with carbon nucleophiles. ^aNuH: Et₂Zn, using Me₃SiOTf as catalyst. ^bNuH: Me₃SiNu. ^cYield of the mixture of regioisomers. Major regioisomer is shown, isolated by recrystallization. ^dProducts formed in the same reaction (Mes: mesityl).

but also to extend the carbon chain of the chromophore with a broad variety of cyclic and acyclic *C*-nucleophiles, including biomolecules (tyrosine: **57**), natural products (resveratrol: **58**, guaiazulene: **59**), and other chromophores (**62** and **63**) in a direct and very efficient way using similar reaction conditions.

2.2.2. Synthesis of bifunctional BODIPYs. Our methodology can also be applied to the preparation of homo- and hetero-bifunctional BODIPYs, starting from the corresponding 3,5-bis(acetoxymethyl)-CN-BODIPY **12** (Scheme 8). Unlike monoacetoxy-BODIPYs, the efficient activation of the diacetoxyated derivative required mild thermal activation (50–60 °C). Under these conditions, the reaction with an excess of *O*-, *S*- or *C*-nucleophiles (>2 equiv.), afforded the expected homodisubstituted-BODIPYs **64–66**, respectively, in moderate yields. Compound **64** contains two tetraethylene glycol monomethyl ether chains to improve its solubility in water, while compounds **65** and **66** are interesting fluorescent cross-linkers for bioconjugation or peptide clamping⁹⁷ and for radical or ring-opening metathesis polymerization in the preparation of photonic materials, respectively.

Heterobifunctional BODIPYs can also be obtained in a two-step procedure employing two different nucleophiles, as exemplified by fluorescent probe **68** displaying a chlorohexyl chain as a selective ligand for halotagged fusion proteins,^{86–88,98} and an azido group for biorthogonal conjugation to a second functional molecule of interest⁹⁹ (Scheme 8). The chlorohexyl substituent was first connected to a tetraethylene glycol chain, following a described method,¹⁰⁰ in order to improve the water

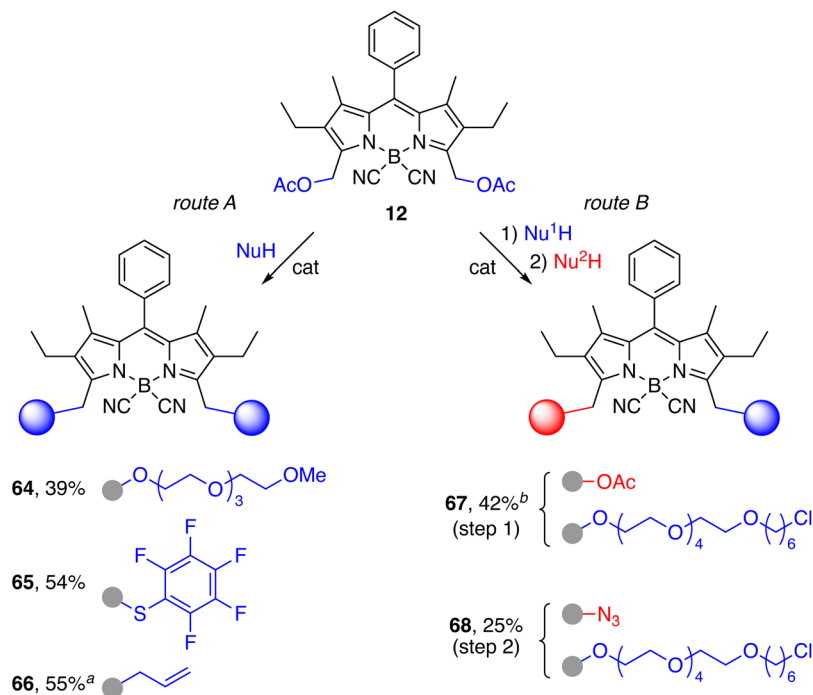
solubility of the probe and also to increase the distance between the chromophore and the protein to boost the efficiency of the bioconjugation reaction. A two-fold excess of diacetoxy-BODIPY **12** was used with respect to the alcohol in order to optimize the ratio of the monofunctionalization product **67**. As already observed for other polyoxygenated alcohols, the reaction required the use of a larger amount of Sc(OTf)₃ and a higher temperature than the standard procedure. Mono-substituted product **67** was obtained in moderate yield (42%; 70% based on total conversion of **12**), along with a small amount of homodisubstituted derivative **69** (6%) and unreacted **12** (40%) (see ESI†). The azide group was introduced next under similar conditions using TMSN₃ as the nucleophile to afford the heterobifunctional BODIPY **68** in a modest 25% yield.

2.3. Photophysical study of some representative compounds

With a view to their possible applications in live-cell microscopy, we carried out a primary study of the photophysical properties of some of the most representative fluorescent probes obtained. The new BODIPYs were studied in three different solvents to determine the influence of the polarity of the medium: AcOEt, as a lipophilic aprotic polar organic solvent; MeOH, as a protic polar organic solvent; and phosphate-buffered saline (PBS), as the typical aqueous medium used in live-cell microscopy experiments.

Table S1† lists the photophysical properties determined in the three solvents for the most representative compounds





Scheme 8 Synthesis of homo- and hetero-bifunctional probes. Reaction conditions: NuH (5 equiv.), Tf₂NH (15–32 mol%), MeCN, 60 °C, 1.5–7.0 h (route A); Nu¹H (0.5 equiv.), Sc(OTf)₃ (14 mol%), CH₂Cl₂, 50 °C, 24 h (route B, step 1); Nu²H: TMSN₃ (1.5 equiv.), Sc(OTf)₃ (10 mol%), 50 °C, 24 h (route B, step 2). ^aSc(OTf)₃ (10 mol%) was used as catalyst. ^bHomo-disubstituted product with two chloroalkyl chains (**69**, 6% yield; see ESI† for details) and unreacted **12** (40%) were also isolated.

derived from *O*-nucleophiles (**15–39**), including the starting acetoxy-methyl-derivative **9** (Fig. S1†). Compound **9** shows a similar photophysical behavior as previously reported for its parent CN-BODIPY **5**, without the acetoxy group.⁷⁹ In aqueous medium (PBS), a considerable drop in the molar absorption coefficient and fluorescent emission accompanied by band broadening was also observed together with the appearance of a shorter lifetime (3 ns) than that typical of BODIPYs (6–7 ns). These observations can be explained by the formation of dye aggregates in this very polar medium. The same tendency was observed for other compounds in this series, with some exceptions that will be discussed below (Fig. S2†). In general, quantum yields were maintained or only slightly decreased when going from AcOEt to MeOH, but significantly drop in PBS for the compounds with the most lipophilic substituents, as observed for **9**. In contrast, compounds **18**, **28**, **29**, and **32**, with more hydrophilic substituents that improve water solubility, maintained a high fluorescence in the three solvents studied. Compound **34**, with a 6-phenyl-1,2,4,5-tetrazine ring, showed very poor or almost no fluorescent emission, likely assigned to a FRET process (the absorption of tetrazine overlap with the emission of BODIPY),^{49,101–104} but possibly also to a PET process (from BODIPY to tetrazine, which is a strong electron withdrawer).¹⁰⁵ Like other previously described tetrazine-BODIPYs, compound **34** is an excellent reagent in inverse electron demand Diels–Alder cycloadditions (IEDDA)^{86,106} with a wide variety of dienophiles, particularly strained alkenes and alkynes. The cycloaddition reaction,

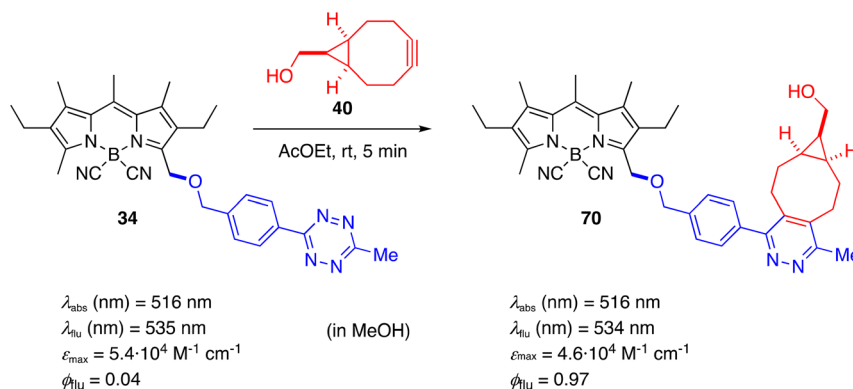
which occurs with loss of N₂, deactivates the energy transfer process and restores the fluorescent emission. Thus, addition of strained cyclooctyne **40** to a solution of **34** at room temperature very rapidly (<2 min) yielded the cycloaddition product **70** with a 24-fold increase in fluorescence emission (Scheme 9). Compound **34** is an interesting fluorogenic probe for bioorthogonal conjugation in no-wash live-cell microscopy.

In general, the *S*-derivatives have a higher solubility in aqueous medium and better fluorescent emission than similar *O*-derivatives (Table S2 and Fig. S3†). In this group, compounds with a polyfluorinated substituent (**42** and **44**) showed higher molar absorption coefficient and higher fluorescent emission in AcOEt than similar non-fluorinated analogs (**41** and **43**, respectively). The more hydrophilic *N*-acetyl-L-cysteine derivative **45** maintained a moderately high fluorescent efficiency in PBS medium.

The derivatives of the *N*-nucleophiles (**46–49**), showed high fluorescence quantum yields ($\phi \geq 0.84$) in both AcOEt and MeOH, with the exception of the 2-nitroimidazolyl-BODIPY **49** (Table S2†). However, these compounds were not fluorescent in PBS, unlike their *O*- and *S*-derivative analogs, possibly due to their lower solubility in water (Fig. S3†). Although it is known that nitro-derivatives are usually non-fluorescent, mainly by activation of an intersystem crossing process,^{107,108} compound **49** showed moderate fluorescence efficiency in AcOEt and MeOH.

The presence of chlorine (**50**) or a phosphonate group (**51**) (Table S2 and Fig. S3†) barely affected the absorption and





Scheme 9 Inverse electron demand Diels–Alder cycloaddition reaction of tetrazine **34** with cyclooctyne **40**.

emission bands, but significantly improved fluorescent emission in aqueous medium (PBS), probably due to the lower lipophilic nature of these derivatives.

The photophysical properties of the *C*-derivatives were highly dependent on the nature of the newly introduced carbon moiety (Table S3†). Thus, compounds with acyclic alkyl systems (**52–55**) and the phenol derivative **56** have very similar properties to their parent **9**, while compounds with electron-rich aromatic systems, including guaiazulene (**59**) (Fig. S4†), pyrrole (**60**), and indole (**61**) derivatives, showed very low fluorescence in the three solvents studied. These results could be interpreted in terms of a photoinduced electron transfer (PET) process taking place between the newly introduced electron-rich ring and the BODIPY chromophore, which quenches fluorescence. The contribution of this PET process was theoretically modeled by DFT calculations in the case of compounds **59–61**, where the guaiazulene, pyrrole and indole rings act as electron donors (reductive PET). The calculations indicate that the lowest energy electronic transition occurs from the HOMO–1 to the LUMO, both located mainly on the BODIPY chromophoric system (Fig. 2 and Fig. S5†). The thermodynamically feasible electron transfer from HOMO (mainly located on the guaiazulene and indole system) to the semi-

vacant HOMO–1 after excitation prevents the excited electron from returning to its own ground state, thus causing a non-radiative decay that is responsible for the dramatic quenching of fluorescence observed for these compounds in all solvents studied (Table S3†). A similar effect on fluorescence has been described in other BODIPY derivatives with azulene¹⁰⁹ or indole¹¹⁰ substituents. The multichromophoric systems **62** and **63** showed an intense absorption capacity (high molar absorption coefficient) due to the presence of two and three BODIPY units, respectively, and kept an efficient emission in AcOEt. These photophysical features are impaired in MeOH and PBS due to the inherent organophilic nature of these compounds (Table S3†).

Table S4† lists the photophysical properties of the di-substituted derivatives **64** and **66**, together with their parent diacetoxy-compound **12** (Fig. S6†). As with the monosubstituted analogs, the nature of the new substituents had a negligible effect on the absorption and emission frequencies, but their lipophilic/hydrophilic character had a substantial impact on the molar absorption coefficient and fluorescent emission. Thus, a considerable drop in the magnitude of both properties was observed in PBS for the more lipophilic and less water-soluble **12** and, in particular, for **66**, attributed to dye aggregation. In fact, their fluorescent decay curves became biexponential in this solvent with the appearance of a very short lifetime (<0.1 ns), than that typical for BODIPYs. In contrast, the introduction of the two hydrophilic tetraethylene glycol substituents in compound **64** endowed it with a better water solubility that aided to maintain a moderately good fluorescence quantum yield in PBS leading to a monoexponential decay curve.

2.4. Live-cell microscopy studies

We have carried out a preliminary screening of the new compounds as fluorescent probes in live-cell microscopy, using two different cancer cell lines: HeLa and SCC38 (from human cervix and larynx squamous cell carcinoma, respectively). The compounds were incubated with live cells at three different concentrations (50 nM, 100 nM and 500 nM) for 30 minutes, before washing with PBS to remove excess dye. The most suit-

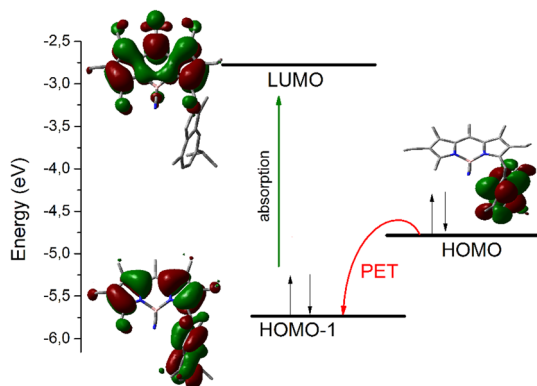


Fig. 2 Deactivation of the fluorescence of compound **59** by photoinduced electron transfer (PET), modeled by DFT calculations (B3LYP/6-311+G*).



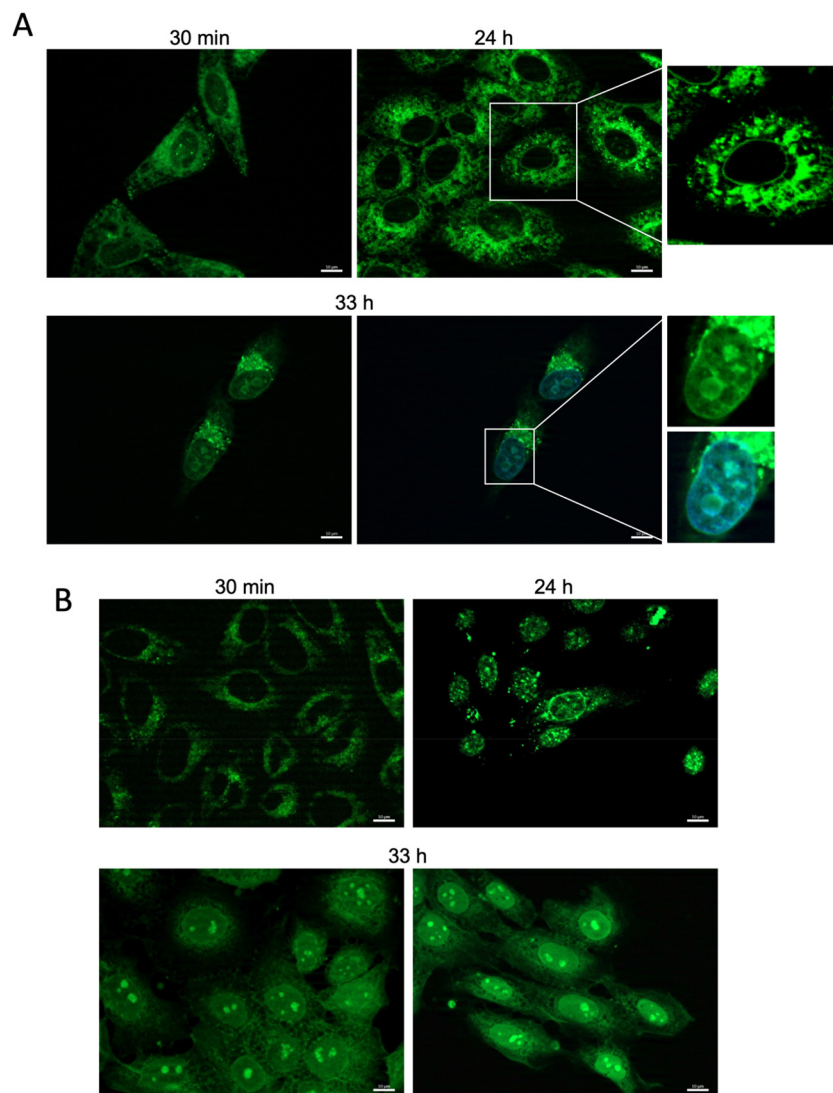


Fig. 3 Representative images of HeLa (A) and SCC38 (B) cells stained with compound **28** (500 nm) for 30 minutes, 24 h or 33 h, as indicated. In panel A (33 h), cells were finally fixed and stained with DAPI (4',6-diamidino-2-fenilindol), a fluorescent dye that binds to adenine and thymine enriched regions in the DNA. Insets in A show magnified images to better visualize the staining of the nuclear envelope (picture above) and the nucleoli (pictures below) in HeLa cells. Images clearly show time-dependent migration of the fluorescence from the cytoplasm (30 min) to the nuclear envelope (24 h) and the nucleoli (33 h) in the two cell lines. Scale bar: 10 μ m.

able concentrations for visualization were 50 nm and 100 nm. In general, this screening showed that most compounds were able to cross the cell membrane and gave a specific subcellular staining without showing any cytotoxicity, with the exception of the following (the new substituent is indicated in parentheses): **9** (acetoxymethyl), **17** (hexadecanol), **18** (octaethylene glycol), **37** (methacrylic ester), **41** (octadecanethiol), **42** (heptadecafluorodecanethiol), **44** (pentafluorophenyl ring), **47** (naphthalenesulfonamide), and **55** (acetylacetone), which were found to be cytotoxic at the concentrations tested. Some compounds showed only weak cell staining due to their low water solubility and/or low permeability through the cell membrane: **36** (oleic ester), **38** (lipoic ester), **46** (azide), **51** (diethyl phosphonate), and **54** (cyano). As mentioned, some of the new probes showed specific

subcellular staining in this preliminary screening (Fig. S7 and S8[†]). Fig. 3 shows live-cell microscopy images of compound **28** (thymidine derivative), as an illustrative example of those compounds with strong and specific subcellular staining. An interesting time-dependent staining involving the nuclear membrane and nucleoli was observed in this case, while maintaining a good cell viability over a 33 h-incubation time. This dynamic phenomenon is under investigation in our group.

3. Conclusions

We have developed a general and robust methodology for the direct incorporation of a wide variety of *C*-, *N*-, *P*-, *O*-, *S*-, and



halo-nucleophiles into functional BODIPY conjugates in a single reaction step. The new method employs stable 3-acetoxy-methyl- or 3,5-diacetoxymethyl-4,4-dicyano-BODIPYs as reagents, which are readily available in two high yielding steps from the corresponding 3,5-dimethyl-4,4-difluoro-derivatives using previously described procedures. The nucleophilic substitution reaction takes place under mild acid-catalyzed conditions with remarkably broad substrate scope and functional group tolerance. Alcohols of all kinds, carboxylic acids, hydroxyacids, alkylic and aromatic thiols, primary and secondary sulfonamides, 1H-N-heterocycles, azide, chloride, and trialkyl-phosphites can all be easily attached to the BODIPY reagent in good yields using the same procedure. Unlike previously described approaches,⁵⁹ our strategy also allows the incorporation of a broad diversity of C-nucleophiles, including electron-rich aromatic and heteroaromatic compounds, trimethylsilyl carbon nucleophiles, active methylene compounds, and organometallic reagents. Our approach provided a direct access to mono- and di-functional probes incorporating biomolecules (lipids, carbohydrates, nucleosides, amino acids, L-carnitine), enzyme cofactors (lipoic acid), and natural products (farnesol, guaiazulene), as well as chemical functionalities for a wide range of applications including bioorthogonal conjugation, polymerization, and supramolecular chemistry, among others. In addition, this strategy also proved successful in the one-step synthesis of new multichromophoric systems, including BODIPY oligomers and a BODIPY-azulene diad. We believe that this novel and simple approach will significantly expand the synthetic toolbox for the preparation of functional BODIPY-based probes and could be easily implemented by specialists and non-specialists alike to rapidly tailor and deploy advanced probes for innovative applications in bio-imaging, sensing and the preparation of new photonic materials.

Author contributions

J.L.C. conceived and designed the study. V.M.-M., M.-D.C. and J.L.C. supervised the research project. A.B.-M., L.M. and E.M. performed the synthesis and structural characterization of probes. R.P.-M., A.O.-S. and V.M.-M. performed the photophysical studies. L.C., M.-D.C. and A.B.-M. performed the live-cell microscopy studies. V.M.-M. and J.L.C. performed the DFT theoretical calculations. V.M.-M., M.-D.C. and J.L.C. co-wrote the paper. All authors contributed to the final interpretation of the experimental results and critically revised the manuscript. All authors have read and approved the final version of the manuscript.

Data availability

Experimental procedures, X-ray diffraction data of **9**, DFT computational details, photophysical characterization data, live-cell microscopy images, and copies of ¹H and ¹³C NMR spectra

of compounds (PDF) can be found in the ESI.† The datasets of 1D- and 2D-NMR spectra supporting this article are available from: <https://doi.org/10.20350/digitalCSIC/14707>.

Conflicts of interest

There are no conflicts to declare.

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References

- M. Zimmer, Green Fluorescent Protein (GFP): Applications, Structure, and Related Photophysical Behavior, *Chem. Rev.*, 2002, **102**, 759–781.
- L. D. Lavis and R. T. Raines, Bright Building Blocks for Chemical Biology, *ACS Chem. Biol.*, 2014, **9**, 855–866.
- J. B. Grimm and L. D. Lavis, Caveat fluorophore: an insiders guide to small-molecule fluorescent labels, *Nat. Methods*, 2022, **19**, 149–158.
- G. Ulrich, R. Ziessel and A. Harriman, The chemistry of fluorescent Bodipy dyes: versatility unsurpassed, *Angew. Chem., Int. Ed.*, 2008, **47**, 1184–1201.
- A. Loudet and K. Burgess, BODIPY dyes and their derivatives: Syntheses and spectroscopic properties, *Chem. Rev.*, 2007, **107**, 4891–4932.
- J. Bañuelos, BODIPY Dye, the Most Versatile Fluorophore Ever?, *Chem. Rec.*, 2016, **16**, 335–348.
- R. G. Clarke and M. J. Hall, Recent developments in the synthesis of the BODIPY dyes, *Adv. Heterocycl. Chem.*, 2019, **128**, 181–261.
- N. Boens, B. Verbelen, M. J. Ortiz, L. Jiao and W. Dehaen, Synthesis of BODIPY dyes through postfunctionalization of the boron dipyrromethene core, *Coord. Chem. Rev.*, 2019, **399**, 213024.
- L. Jiao, W. Pang, J. Zhou, Y. Wei, X. Mu, G. Bai and E. Hao, Regioselective Stepwise Bromination of Boron Dipyrromethene (BODIPY) Dyes, *J. Org. Chem.*, 2011, **76**, 9988–9996.



- 10 V. Lakshmi and M. Ravikanth, Synthesis of Sterically Crowded Polyarylated Boron-Dipyrromethenes, *J. Org. Chem.*, 2011, **76**, 8466–8471.
- 11 X. Li, S. Huang and Y. Hu, Diversity-oriented derivatization of BODIPY based on regioselective bromination, *Org. Biomol. Chem.*, 2012, **10**, 2369–2372.
- 12 V. Lakshmi and M. Ravikanth, Synthesis, spectral and electrochemical properties of phenylated boron-dipyrromethenes, *Dyes Pigm.*, 2013, **96**, 665–671.
- 13 V. Leen, P. Yuan, L. Wang, N. Boens and W. Dehaen, Synthesis of Meso-Halogenated BODIPYs and Access to Meso-Substituted Analogues, *Org. Lett.*, 2012, **14**, 6150–6153.
- 14 N. Zhao, S. Xuan, F. R. Fronczek, K. M. Smith and M. G. H. Vicente, Stepwise Polychlorination of 8-Chloro-BODIPY and Regioselective Functionalization of 2,3,5,6,8-Pentachloro-BODIPY, *J. Org. Chem.*, 2015, **80**, 8377–8383.
- 15 N. Zhao, S. Xuan, B. Byrd, F. R. Fronczek, K. M. Smith and M. G. H. Vicente, Synthesis and regioselective functionalization of perhalogenated BODIPYs, *Org. Biomol. Chem.*, 2016, **14**, 6184–6188.
- 16 Z. Feng, L. Jiao, Y. Feng, C. Yu, N. Chen, Y. Wei, X. Mu and E. Hao, Regioselective and Stepwise Syntheses of Functionalized BODIPY Dyes through Palladium-Catalyzed Cross-Coupling Reactions and Direct C-H Arylations, *J. Org. Chem.*, 2016, **81**, 6281–6291.
- 17 F. J. Frank, P. G. Waddell, M. J. Hall and J. G. Knight, Synthesis and Reactivity of 3,5-Diiodo-BODIPYs via a Concerted, Double Aromatic Finkelstein Reaction, *Org. Lett.*, 2021, **23**, 8595–8599.
- 18 H. R. A. Golf, H.-U. Reissig and A. Wiehe, Nucleophilic Substitution on (Pentafluorophenyl)dipyrromethane: A New Route to Building Blocks for Functionalized BODIPYs and Tetrapyrroles, *Org. Lett.*, 2015, **17**, 982–985.
- 19 G. Vives, C. Giansante, R. Bofinger, G. Raffy, A. Del Guerso, B. Kauffmann, P. Batat, G. Jonusauskas and N. D. McClenaghan, Facile functionalization of a fully fluorescent perfluorophenyl BODIPY: photostable thiol and amine conjugates, *Chem. Commun.*, 2011, **47**, 10425–10427.
- 20 D. E. Ramírez-Ornelas, E. Alvarado-Martínez, J. Bañuelos, I. López Arbeloa, T. Arbeloa, H. M. Mora-Montes, L. A. Pérez-García and E. Peña-Cabrera, FormylBODIPYs: Privileged Building Blocks for Multicomponent Reactions. The Case of the Passerini Reaction, *J. Org. Chem.*, 2016, **81**, 2888–2898.
- 21 A. Ramos-Torres, E. Avellanal-Zaballa, A. Prieto-Castaneda, F. García-Garrido, J. Bañuelos, A. R. Agarrabeitia and M. J. Ortiz, FormylBODIPYs by PCC-Promoted Selective Oxidation of α -MethylBODIPYs. Synthetic Versatility and Applications, *Org. Lett.*, 2019, **21**, 4563–4566.
- 22 V. Lakshmi and M. Ravikanth, Synthesis of conjugated BODIPYs via the Wittig reaction, *J. Org. Chem.*, 2013, **78**, 4993–5000.
- 23 L. E. Greene, R. Lincoln, K. Krumova and G. Cosa, Development of a Fluorogenic Reactivity Palette for the Study of Nucleophilic Addition Reactions Based on meso-Formyl BODIPY Dyes, *ACS Omega*, 2017, **2**, 8618–8624.
- 24 S. Zhu, J. Bi, G. Vegesna, J. Zhang, F.-T. Luo, L. Valenzano and H. Liu, Functionalization of BODIPY dyes at 2,6-positions through formyl groups, *RSC Adv.*, 2013, **3**, 4793–4800.
- 25 T. Komatsu, Y. Urano, Y. Fujikawa, T. Kobayashi, H. Kojima, T. Terai, K. Hanaoka and T. Nagano, Development of 2,6-carboxy-substituted boron dipyrromethene (BODIPY) as a novel scaffold of ratiometric fluorescent probes for live cell imaging, *Chem. Commun.*, 2009, 7015–7017.
- 26 D. Wang, J. Fan, X. Gao, B. Wang, S. Sun and X. Peng, Carboxyl BODIPY dyes from bicarboxylic anhydrides: One-pot preparation, spectral properties, photostability, and biolabeling, *J. Org. Chem.*, 2009, **74**, 7675–7683.
- 27 S. Krajcovicova, J. Stankova, P. Dzubak, M. Hajduch, M. Soural and M. Urban, A Synthetic Approach for the Rapid Preparation of BODIPY Conjugates and their use in Imaging of Cellular Drug Uptake and Distribution, *Chem. – Eur. J.*, 2018, **24**, 4957–4966.
- 28 T. Katoh, M. Yoshikawa, T. Yamamoto, R. Arai, N. Nii, Y. Tomata, S. Suzuki, R. Koyama, N. Negoro and T. Yogo, Parallel fluorescent probe synthesis based on the large-scale preparation of BODIPY FL propionic acid, *Bioorg. Med. Chem. Lett.*, 2017, **27**, 1145–1148.
- 29 H. Chen, X. He, M. Su, W. Zhai, H. Zhang and C. Li, A General Strategy Toward Highly Fluorogenic Bioprobes Emitting across the Visible Spectrum, *J. Am. Chem. Soc.*, 2017, **139**, 10157–10163.
- 30 Y. Jang, T.-I. Kim, H. Kim, Y. Choi and Y. Kim, Photoactivatable BODIPY Platform: Light-Triggered Anticancer Drug Release and Fluorescence Monitoring, *ACS Appl. Bio Mater.*, 2019, **2**, 2567–2572.
- 31 S. Jeon, T.-I. Kim, H. Jin, U. Lee, J. Bae, J. Bouffard and Y. Kim, Amine-Reactive Activated Esters of meso-CarboxyBODIPY: Fluorogenic Assays and Labeling of Amines, Amino Acids, and Proteins, *J. Am. Chem. Soc.*, 2020, **142**, 9231–9239.
- 32 L. Betancourt-Mendiola, I. Valois-Escamilla, T. Arbeloa, J. Bañuelos, I. López Arbeloa, J. O. Flores-Rizo, R. Hu, E. Lager, C. F. A. Gómez-Durán, J. L. Belmonte-Vázquez, M. R. Martínez-González, I. J. Arroyo, C. A. Osorio-Martínez, E. Alvarado-Martínez, A. Urías-Benavides, B. D. Gutiérrez-Ramos, B. Z. Tang and E. Peña-Cabrera, Scope and Limitations of the Liebeskind-Srogl Cross-Coupling Reactions Involving the Biellmann BODIPY, *J. Org. Chem.*, 2015, **80**, 5771–5782.
- 33 J. O. Flores-Rizo, I. Esnal, C. A. Osorio-Martínez, C. F. A. Gómez-Durán, J. Bañuelos, I. López Arbeloa, K. H. Pannell, A. J. Metta-Magana and E. Peña-Cabrera, 8-Alkoxy- and 8-Aryloxy-BODIPYs: Straightforward Fluorescent Tagging of Alcohols and Phenols, *J. Org. Chem.*, 2013, **78**, 5867–5877.
- 34 J. Bañuelos, V. Martín, C. F. A. Gómez-Durán, I. J. A. Córdoba, E. Peña-Cabrera, I. García-Moreno,



- A. Costela, M. E. Pérez-Ojeda, T. Arbeloa and I. L. Arbeloa, New 8-Amino-BODIPY Derivatives: Surpassing Laser Dyes at Blue-Edge Wavelengths, *Chem. – Eur. J.*, 2011, **17**, 7261–7270.
- 35 I. J. Arroyo, R. Hu, G. Merino, B. Z. Tang and E. Peña-Cabrera, The Smallest and One of the Brightest. Efficient Preparation and Optical Description of the Parent Borondipyrromethene System, *J. Org. Chem.*, 2009, **74**, 5719–5722.
- 36 E. Peña-Cabrera, A. Aguilar-Aguilar, M. González-Domínguez, E. Lager, R. Zamudio-Vázquez, J. Godoy-Vargas and F. Villanueva-García, Simple, general, and efficient synthesis of meso-substituted borondipyrromethenes from a single platform, *Org. Lett.*, 2007, **9**, 3985–3988.
- 37 C. Uriel, A. M. Gómez, E. García, M. de la Hidalga, J. Bañuelos, I. García-Moreno and J. C. López, Access to 2,6-Dipropargylated BODIPYs as “Clickable” Congeners of Pyrromethene-567 Dye: Photostability and Synthetic Versatility, *Org. Lett.*, 2021, **23**, 6801–6806.
- 38 P. Kele, X. Li, M. Link, K. Nagy, A. Herner, K. Lorincz, S. Beni and O. S. Wolfbeis, Clickable fluorophores for biological labeling-with or without copper, *Org. Biomol. Chem.*, 2009, **7**, 3486–3490.
- 39 M. R. Martínez-González, A. Urías-Benavides, E. Alvarado-Martínez, J. C. López, A. M. Gómez, M. del Rio, I. García, A. Costela, J. Bañuelos, T. Arbeloa, I. López Arbeloa and E. Peña-Cabrera, Convenient Access to Carbohydrate-BODIPY Hybrids by Two Complementary Methods Involving One-Pot Assembly of “Clickable” BODIPY Dyes, *Eur. J. Org. Chem.*, 2014, 5659–5663.
- 40 T. B. Gontijo, R. P. de Freitas, F. S. Emery, L. F. Pedrosa, J. B. Vieira Neto, B. C. Cavalcanti, C. Pessoa, A. King, F. de Moliner, M. Vendrell and E. N. da Silva Jr., On the synthesis of quinone-based BODIPY hybrids: New insights on antitumor activity and mechanism of action in cancer cells, *Bioorg. Med. Chem. Lett.*, 2017, **27**, 4446–4456.
- 41 A. L. Nguyen, K. E. Griffin, Z. Zhou, F. R. Fronczek, K. M. Smith and M. G. H. Vicente, Syntheses of 1,2,3-triazole-BODIPYs bearing up to three carbohydrate units, *New J. Chem.*, 2018, **42**, 8241–8246.
- 42 M. E. Pérez-Ojeda, B. Trastoy, A. Rol, M. D. Chiara, I. García-Moreno and J. L. Chiara, Controlled Click-Assembly of Well-Defined Hetero-Bifunctional Cubic Silsesquioxanes and Their Application in Targeted Bioimaging, *Chem. – Eur. J.*, 2013, **19**, 6630–6640.
- 43 M. E. Pérez-Ojeda, B. Trastoy, I. López-Arbeloa, J. Bañuelos, A. Costela, I. García-Moreno and J. L. Chiara, Click Assembly of Dye-Functionalized Octasilsesquioxanes for Highly Efficient and Photostable Photonic Systems, *Chem. – Eur. J.*, 2011, **17**, 13258–13268.
- 44 B. Trastoy, M. E. Pérez-Ojeda, R. Sastre and J. L. Chiara, Octakis(3-azidopropyl)octasilsesquioxane: A Versatile Nanobuilding Block for the Efficient Preparation of Highly Functionalized Cube-Octameric Polyhedral Oligosilsesquioxane Frameworks Through Click Assembly, *Chem. – Eur. J.*, 2010, **16**, 3833–3841.
- 45 J. C. Er, M. K. Tang, C. G. Chia, H. Liew, M. Vendrell and Y.-T. Chang, MegaStokes BODIPY-triazoles as environmentally sensitive turn-on fluorescent dyes, *Chem. Sci.*, 2013, **4**, 2168–2176.
- 46 J.-J. Shie, Y.-C. Liu, Y.-M. Lee, C. Lim, J.-M. Fang and C.-H. Wong, An Azido-BODIPY Probe for Glycosylation: Initiation of Strong Fluorescence upon Triazole Formation, *J. Am. Chem. Soc.*, 2014, **136**, 9953–9961.
- 47 H. R. A. Golf, A. M. Oltmanns, D. H. Trieu, H.-U. Reissig and A. Wiehe, Synthesis of Functionalized BODIPYs, BODIPY-Corrole, and BODIPY-Porphyrin Arrays with 1,2,3-Triazole Linkers Using the 4-Azido(tetrafluorophenyl)-BODIPY Building Block, *Eur. J. Org. Chem.*, 2015, 4224–4237.
- 48 J. C. López, M. del Rio, A. Oliden, J. Bañuelos, I. López-Arbeloa, I. García-Moreno and A. M. Gómez, Solvent-Sensitive Emitting Urea-Bridged bis-BODIPYs: Ready Access by a One-Pot Tandem Staudinger/Aza-Wittig Ureation, *Chem. – Eur. J.*, 2017, **23**, 17511–17520.
- 49 J. C. T. Carlson, L. G. Meimetis, S. A. Hilderbrand and R. Weissleder, BODIPY-Tetrazine Derivatives as Superbright Bioorthogonal Turn-on Probes, *Angew. Chem., Int. Ed.*, 2013, **52**, 6917–6920.
- 50 Y. Zhou, R. C. H. Wong, G. Dai and D. K. P. Ng, A bioorthogonally activatable photosensitizer for site-specific photodynamic therapy, *Chem. Commun.*, 2020, **56**, 1078–1081.
- 51 M. Wu, X. Wu, Y. Wang, L. Gu, J. You, H. Wu and P. Feng, Alkoxy Tetrazine Substitution at a Boron Center: A Strategy for Synthesizing Highly Fluorogenic Hydrophilic Probes, *ChemBioChem*, 2018, **19**, 530–534.
- 52 H. Wu, J. Yang, J. Seckute and N. K. Devaraj, In Situ Synthesis of Alkenyl Tetrazines for Highly Fluorogenic Bioorthogonal Live-Cell Imaging Probes, *Angew. Chem., Int. Ed.*, 2014, **53**, 5805–5809.
- 53 G. Linden and O. Vázquez, Bioorthogonal turn-on BODIPY-peptide photosensitizers for tailored photodynamic therapy, *Chem. – Eur. J.*, 2020, **26**, 10014–10023.
- 54 H. G. Knaus, T. Moshhammer, K. Friedrich, H. C. Kang, R. P. Haugland and H. Glossman, In vivo labeling of L-type Ca²⁺ channels by fluorescent dihydropyridines: evidence for a functional, extracellular heparin-binding site, *Proc. Natl. Acad. Sci. U. S. A.*, 1992, **89**, 3586–3590.
- 55 O. Buyukcakir, O. A. Bozdemir, S. Kolemen, S. Erbas and E. U. Akkaya, Tetraaryl-Bodipy dyes: Convenient synthesis and characterization of elusive near IR fluorophores, *Org. Lett.*, 2009, **11**, 4644–4647.
- 56 Y.-H. Yu, A. B. Descalzo, Z. Shen, H. Rohr, Q. Liu, Y.-W. Wang, M. Spieles, Y.-Z. Li, K. Rurack and X.-Z. You, Mono- and Di(dimethylamino)styryl-substituted borondipyrromethene and borondiindomethene dyes with intense near-infrared fluorescence, *Chem. – Asian J.*, 2006, **1**, 176–187.
- 57 G. Sathyamoorthi, L. T. Wolford, A. M. Haag and J. H. Boyer, Selective side-chain oxidation of peralkylated pyrromethene-BF₂ complexes, *Heteroat. Chem.*, 1994, **5**, 245–249.



- 58 L. Yang, R. S. Yalagala, S. Hutton, A. Lough and H. Yan, Reactions of BODIPY Fluorophore with Cupric Nitrate, *Synlett*, 2014, **25**, 2661–2664.
- 59 G. Ulrich, R. Ziesel and A. Haefele, A General Synthetic Route to 3,5-Substituted Boron Dipyrromethenes: Applications and Properties, *J. Org. Chem.*, 2012, **77**, 4298–4311.
- 60 Q. Gong, K. Cheng, Q. Wu, W. Li, C. Yu, L. Jiao and E. Hao, One-Pot Access to Ethylene-Bridged BODIPY Dimers and Trimers through Single-Electron Transfer Chemistry, *J. Org. Chem.*, 2021, **86**, 15761–15767.
- 61 L. J. Patalag, L. P. Ho, P. G. Jones and D. B. Werz, Ethylene-Bridged Oligo-BODIPYs: Access to Intramolecular J-Aggregates and Superfluorophores, *J. Am. Chem. Soc.*, 2017, **139**, 15104–15113.
- 62 W. Siedel and F. Winkler, Oxidation of pyrrole derivatives with Pb tetraacetate. A new kind of porphyrin synthesis, *Justus Liebigs Ann. Chem.*, 1943, **554**, 162–201.
- 63 A. Boudif and M. Momenteau, A new convergent method for porphyrin synthesis based on a '3 + 1' condensation, *J. Chem. Soc., Perkin Trans. 1*, 1996, 1235–1242.
- 64 Q. Chen, M. T. Huggins, D. A. Lightner, W. Norona and A. F. McDonagh, Synthesis of a 10-Oxo-Bilirubin: Effects of the Oxo Group on Conformation, Transhepatic Transport, and Glucuronidation, *J. Am. Chem. Soc.*, 1999, **121**, 9253–9264.
- 65 M. G. H. Vicente and K. M. Smith, Porphyrins and derivatives: synthetic strategies and reactivity profiles, *Curr. Org. Chem.*, 2000, **4**, 139–174.
- 66 S. M. Crawford and A. Thompson, Conversion of 4,4-Difluoro-4-bora-3a,4a-diaza-s-indacenes (F-BODIPYs) to Dipyrins with a Microwave-Promoted Deprotection Strategy, *Org. Lett.*, 2010, **12**, 1424–1427.
- 67 D. A. Smithen, A. E. G. Baker, M. Offman, S. M. Crawford, T. S. Cameron and A. Thompson, Use of F-BODIPYs as a Protection Strategy for Dipyrins: Optimization of BF₂ Removal, *J. Org. Chem.*, 2012, **77**, 3439–3453.
- 68 L. Yang, R. Simionescu, A. Lough and H. Yan, Some observations relating to the stability of the BODIPY fluorophore under acidic and basic conditions, *Dyes Pigm.*, 2011, **91**, 264–267.
- 69 V. Lakshmi, T. Chatterjee and M. Ravikanth, Lewis Acid Assisted Decomplexation of F-BODIPYs to Dipyrins, *Eur. J. Org. Chem.*, 2014, 2105–2110.
- 70 T. Lundrigan, T. S. Cameron and A. Thompson, Activation and deprotection of F-BODIPYs using boron trihalides, *Chem. Commun.*, 2014, **50**, 7028–7031.
- 71 M. Yu, J. K. H. Wong, C. Tang, P. Turner, M. H. Todd and P. J. Rutledge, Efficient deprotection of F-BODIPY derivatives: removal of BF₂ using Brønsted acids, *Beilstein J. Org. Chem.*, 2015, **11**, 37–41, 35 pp.
- 72 J. Urieta, B. L. Maroto, F. Moreno, A. R. Agarrabeitia, M. J. Ortiz and S. de la Moya, Preparation of dipyrins from F-BODIPYs by treatment with methanesulfonic acids, *RSC Adv.*, 2015, **5**, 68676–68680.
- 73 C. D. Smith and A. Thompson, Facile deprotection of F-BODIPYs using methylboronic acid, *RSC Adv.*, 2020, **10**, 24273–24279.
- 74 E. Bodio and C. Goze, Investigation of B-F substitution on BODIPY and aza-BODIPY dyes: Development of B-O and B-C BODIPYs, *Dyes Pigm.*, 2019, **160**, 700–710.
- 75 L. Li, B. Nguyen and K. Burgess, Functionalization of the 4,4-difluoro-4-bora-3a,4a-diaza-s-indacene (BODIPY) core, *Bioorg. Med. Chem. Lett.*, 2008, **18**, 3112–3116.
- 76 A. L. Nguyen, M. Wang, P. Bobadova-Parvanova, Q. Do, Z. Zhou, F. R. Fronczek, K. M. Smith and M. G. H. Vicente, Synthesis and properties of B-cyano-BODIPYs, *J. Porphyrins Phthalocyanines*, 2016, **20**, 1409–1419.
- 77 M. Wang, M. G. H. Vicente, D. Mason and P. Bobadova-Parvanova, Stability of a Series of BODIPYs in Acidic Conditions: An Experimental and Computational Study into the Role of the Substituents at Boron, *ACS Omega*, 2018, **3**, 5502–5510.
- 78 C. Uriel, C. Permingeat, J. Ventura, A. M. Gómez, J. C. López, E. Avellanal-Zaballa, J. Bañuelos and I. García-Moreno, BODIPYs as Chemically Stable Fluorescent Tags for Synthetic Glycosylation Strategies towards Fluorescently Labeled Saccharides, *Chem. – Eur. J.*, 2020, **26**, 5388–5399.
- 79 G. Durán-Sampedro, I. Esnal, A. R. Agarrabeitia, J. Bañuelos Prieto, L. Cerdán, I. García-Moreno, A. Costela, I. López-Arbeloa and M. J. Ortiz, First Highly Efficient and Photostable E and C Derivatives of 4,4-Difluoro-4-bora-3a,4a-diaza-s-indacene (BODIPY) as Dye Lasers in the Liquid Phase, Thin Films, and Solid-State Rods, *Chem. – Eur. J.*, 2014, **20**, 2646–2653.
- 80 P. G. Waddell, X. Liu, T. Zhao and J. M. Cole, Rationalizing the photophysical properties of BODIPY laser dyes via aromaticity and electron-donor-based structural perturbations, *Dyes Pigm.*, 2015, **116**, 74–81.
- 81 C. Y. Xu, E. Lebeau and C. Walker, Selective deprotection of esters using magnesium and methanol, *Tetrahedron Lett.*, 1994, **35**, 6207–6210.
- 82 S. L. Scinto, D. A. Bilodeau, R. Hincapie, W. Lee, S. S. Nguyen, M. Xu, C. W. am Ende, M. G. Finn, K. Lang, Q. Lin, J. P. Pezacki, J. A. Prescher, M. S. Robillard and J. M. Fox, Bioorthogonal chemistry, *Nat. Rev. Methods Primers*, 2021, **1**, 30.
- 83 R. E. Bird, S. A. Lemmel, X. Yu and Q. A. Zhou, Bioorthogonal Chemistry and Its Applications, *Bioconjugate Chem.*, 2021, **32**, 2457–2479.
- 84 E. M. Sletten and C. R. Bertozzi, Bioorthogonal Chemistry: Fishing for Selectivity in a Sea of Functionality, *Angew. Chem., Int. Ed.*, 2009, **48**, 6974–6998.
- 85 H. Wu and N. K. Devaraj, Inverse Electron-Demand Diels-Alder Bioorthogonal Reactions, *Top. Curr. Chem.*, 2016, **374**, 1–22.
- 86 C. A. Hoelzel and X. Zhang, Visualizing and Manipulating Biological Processes by Using HaloTag and SNAP-Tag Technologies, *ChemBioChem*, 2020, **21**, 1935–1946.
- 87 C. G. England, H. Luo and W. Cai, HaloTag Technology: A Versatile Platform for Biomedical Applications, *Bioconjugate Chem.*, 2015, **26**, 975–986.



- 88 G. V. Los and K. Wood, The HaloTag: a novel technology for cell imaging and protein analysis, *Methods Mol. Biol.*, 2007, **356**, 195–208.
- 89 S. Yoshida, Y. Hatakeyama, K. Johmoto, H. Uekusa and T. Hosoya, Transient Protection of Strained Alkynes from Click Reaction via Complexation with Copper, *J. Am. Chem. Soc.*, 2014, **136**, 13590–13593.
- 90 P. Gobbo, T. Romagnoli, S. M. Barbon, J. T. Price, J. Keir, J. B. Gilroy and M. S. Workentin, Expanding the scope of strained-alkyne chemistry: a protection-deprotection strategy via the formation of a dicobalt-hexacarbonyl complex, *Chem. Commun.*, 2015, **51**, 6647–6650.
- 91 Q. Zhao, C. Yin, J. Kang, Y. Wen and F. Huo, A viscosity sensitive azide-pyridine BODIPY-based fluorescent dye for imaging of hydrogen sulfide in living cells, *Dyes Pigm.*, 2018, **159**, 166–172.
- 92 C. Wang, F. Xie, N. Suthiwangcharoen, J. Sun and Q. Wang, Tuning the optical properties of BODIPY dye through Cu(I) catalyzed azide-alkyne cycloaddition (CuAAC) reaction, *Sci. China: Chem.*, 2012, **55**, 125–130.
- 93 X. Ao, S. A. Bright, N. C. Taylor and R. B. P. Elmes, 2-Nitroimidazole based fluorescent probes for nitroreductase; monitoring reductive stress in cellulose, *Org. Biomol. Chem.*, 2017, **15**, 6104–6108.
- 94 B. D. Gutiérrez-Ramos, J. Bañuelos, T. Arbeloa, I. L. Arbeloa, P. E. González-Navarro, K. Wrobel, L. Cerdán, I. García-Moreno, A. Costela and E. Peña-Cabrera, Straightforward Synthetic Protocol for the Introduction of Stabilized C Nucleophiles in the BODIPY Core for Advanced Sensing and Photonic Applications, *Chem. – Eur. J.*, 2015, **21**, 1755–1764.
- 95 V. Leen, M. Laine, J. M. Ngongo, P. Lipkowski, B. Verbelen, A. Kochel, W. Dehaen, M. Van der Auweraer, V. Nadtochenko and A. Filarowski, Impact of the Keto-Enol Tautomeric Equilibrium on the BODIPY Chromophore, *J. Phys. Chem. A*, 2018, **122**, 5955–5961.
- 96 H. Zaimoku, T. Hatta, T. Taniguchi and H. Ishibashi, Iodine-Mediated α -Acetoxylation of 2,3-Disubstituted Indoles, *Org. Lett.*, 2012, **14**, 6088–6091.
- 97 W. D. G. Brittain and C. R. Coxon, Perfluoroaryl and Perfluoroheteroaryl Reagents as Emerging New Tools for Peptide Synthesis, Modification and Bioconjugation, *Chem. – Eur. J.*, 2022, **28**, 10–23.
- 98 M. Macias-Contreras and L. Zhu, The Collective Power of Genetically Encoded Protein/Peptide Tags and Bioorthogonal Chemistry in Biological Fluorescence Imaging, *ChemPhotoChem*, 2021, **5**, 187–216.
- 99 H. E. Murrey, J. C. Judkins, C. W. am Ende, T. E. Ballard, Y. Fang, K. Riccardi, L. Di, E. R. Guilmette, J. W. Schwartz, J. M. Fox and D. S. Johnson, Systematic Evaluation of Bioorthogonal Reactions in Live Cells with Clickable HaloTag Ligands: Implications for Intracellular Imaging, *J. Am. Chem. Soc.*, 2015, **137**, 11461–11475.
- 100 C. Aonbangkhen, H. Zhang, D. Z. Wu, M. A. Lampson and D. M. Chenoweth, Reversible Control of Protein Localization in Living Cells Using a Photocaged-Photocleavable Chemical Dimerizer, *J. Am. Chem. Soc.*, 2018, **140**, 11926–11930.
- 101 N. K. Devaraj, S. Hilderbrand, R. Upadhyay, R. Mazitschek and R. Weissleder, Bioorthogonal Turn-On Probes for Imaging Small Molecules inside Living Cells, *Angew. Chem., Int. Ed.*, 2010, **49**, 2869–2872.
- 102 C. Dumas-Verdes, F. Miomandre, E. Lepicier, O. Galangau, T. T. Vu, G. Clavier, R. Meallet-Renault and P. Audebert, BODIPY-Tetrazine Multichromophoric Derivatives, *Eur. J. Org. Chem.*, 2010, 2525–2535.
- 103 A. M. Courtis, S. A. Santos, Y. Guan, J. A. Hendricks, B. Ghosh, D. M. Szantai-Kis, S. A. Reis, J. V. Shah and R. Mazitschek, Monoalkoxy BODIPYs - A Fluorophore Class for Bioimaging, *Bioconjugate Chem.*, 2014, **25**, 1043–1051.
- 104 A. Wieczorek, T. Buckup and R. Wombacher, Rigid tetrazine fluorophore conjugates with fluorogenic properties in the inverse electron demand Diels-Alder reaction, *Org. Biomol. Chem.*, 2014, **12**, 4177–4185.
- 105 G. Beliu, A. J. Kurz, A. C. Kuhlemann, L. Behringer-Pliess, M. Meub, N. Wolf, J. Seibel, Z.-D. Shi, M. Schnermann, J. B. Grimm, L. D. Lavis, S. Doose and M. Sauer, Bioorthogonal labeling with tetrazine-dyes for super-resolution microscopy, *Commun. Biol.*, 2019, **2**, 1–13.
- 106 B. L. Oliveira, Z. Guo and G. J. L. Bernardes, Inverse electron demand Diels-Alder reactions in chemical biology, *Chem. Soc. Rev.*, 2017, **46**, 4895–4950.
- 107 M.-C. Chen, D.-G. Chen and P.-T. Chou, Fluorescent Chromophores Containing the Nitro Group: Relatively Unexplored Emissive Properties, *ChemPlusChem*, 2021, **86**, 11–27.
- 108 Y. M. Poronik, B. Sadowski, K. Szychta, F. H. Quina, V. I. Vullev and D. T. Gryko, Revisiting the non-fluorescence of nitroaromatics: presumption versus reality, *J. Mater. Chem. C*, 2022, **10**, 2870–2904.
- 109 L. Gai, J. Chen, Y. Zhao, J. Mack, H. Lu and Z. Shen, Synthesis and properties of azulene-functionalized BODIPYs, *RSC Adv.*, 2016, **6**, 32124–32129.
- 110 E. Ozcan, H. H. Kazan and B. Cosut, Recent chemo-/bio-sensor and bioimaging studies based on indole-decorated BODIPYs, *Luminescence*, 2020, **35**, 168–177.

