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Fluorescent 2-(2'-Hydroxybenzofuran) benzoxazole (HBBO) borate complexes: Synthesis, Optical Properties and Theoretical Calculations

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ABSTRACT

The multi-step synthesis, structural and optical properties of original luminescent borate complexes derived from 2-(2'-hydroxybenzofuran)benzoxazole (HBBO) are reported. Functionalization at position 3 of the benzofuran ring was readily achieved through an electrophilic cyclization key step followed by a Sonogashira cross-coupling reaction. The optical properties of the resulting boron difluoride dyes highlight different photophysical behaviors depending on the nature of the substitution at position 3 of the benzofuran core ([']Bu-phenylacetylene or NⁿBu₂-phenylacetylene). The NⁿBu₂-phenylacetylene moiety favors a sizeable intramolecular charge transfer as evidenced by a strong solvatochromism; a feature further confirmed by *ab initio* calculations.

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The elaboration of original luminescent emitters has become a major concern due to the large panel of applications targeted by light-emitting molecular devices. From organic optoelectronics¹ to biological labeling, sensing and medical imaging,² dyes have proven to be of paramount importance as light-interacting synthetic small molecules. The search for original, easily scalable, modular fluorophores whose brightness surpasses that of traditional luminophores has motivated the development of luminescent tetrahedral boron complexes in recent years. Among them, boron dipyrromethene dyes (BODIPY) have been, by far, the leading family of boron(III) complexes and emerged as some of the most promising dyes due to outstanding chemical and optical properties, e.g. sharp and narrow absorption and fluorescence profiles, high absorption coefficients, high quantum yields, good solubility and strong chemical and photochemical stability.3 The main drawback of BODIPY dyes lies in the fact that they are weakly luminescent in the solid-state due to strong intermolecular interactions in the molecular packing. Circumvention of aggregation-caused quenching can be achieved by functionalizing the BODIPY core with bulky substitutents leading to enhanced solid-state luminescence.⁴ More recently, coordination of a π -conjugated chelate to a boron(III) fragment, as BF_2 or BAr_2 led to the development of alternative B(III) luminescent complexes which have been engineered from saturated bidentate N^N⁵ and N^O⁶ chelates.⁷ Among the latter, 2-(2'-hydroxyphenyl) benzoxazole (HBO) have proven to be efficient chelates for $BF_2^{\ 8}$ or $BPh_2^{\ 9}$ fragments giving stable borate complexes with tunable optical properties. These dyes display an intense fluorescence emission spanning from the UV to the visible, both in solution and in the solid state. Moreover, extension of the conjugation of the HBO core with ethynyl fragments leads to different photophysical profiles depending on the nature of the electronic substitution and its position on the phenolic ring.¹⁰ Enlargement of the π -conjugated system is indeed a common synthetic strategy to red-shift the optical properties of a given dye while rigidification of molecular structures often leads to improved quantum yields.11

We wish herein to further investigate the influence of conjugation extension and rigidification on the optical properties of HBO borate dyes. We have thus chosen to structurally modify the HBO core by introducing a rigid benzofuran skeleton. This heterocycle seems to be a tool of choice to enhance the photophysical properties of the resulting boron(III) complexes because it is a flat, rigid scaffold whose synthetic access is well-described due to its ubiquity in numerous structures ranging from natural products to medicinal drugs.¹²

In this article, we describe the synthesis, structural and optical properties along with Time-Dependent Density Functional Theory (TD-DFT) calculations of novel rigidified 2-(2'-hydroxybenzofuran)benzoxazole (HBBO) borate complexes based on a decorated benzofuran scaffold (Figure 1).



Figure 1. 2-(2'-Hydroxybenzofuran)benzoxazole (HBBO) Borate complexes 1 and 2.

HBBO borate complexes 1 and 2 substituted with an ethynyl substituent at position 3 of the benzofuran ring were prepared following a synthetic route which can be divided into two schemes

(Schemes 1 and 2). The key intermediate benzofuran 6 was synthesized in four steps as outlined in Scheme 1. Salicylaldehyde 3 can be obtained by selective monoiodination from commercially available 4-methoxysalicylaldehyde using one equivalent of iodine monochloride in acetic acid.^{10a} Subsequent Sonogashira crosscoupling reaction using 5% of [PdCl₂(PPh₃)₂] as a catalyst with 10% of CuI in toluene/triethylamine (3/1 v:v) in the presence of an excess of 4-methoxyphenylacetylene¹³ leads to ethynyl-substituted salicylaldehyde 4 in 88% yield. To avoid iodine-mediated oxidation of the phenol, 4 was protected with an acetate group using an excess of acetic anhydride in dichloromethane with a catalytic amount of pyridine. Acetate protected salicylaldehyde 5 was isolated in 94% yield. Substituted benzofuran 6 was obtained following an electrophilic cyclization reaction using molecular iodine as first developed by Larock et al.14 Heterocycle 6 was obtained in 74% yield as yellow single crystals suitable for X-Ray diffraction analysis (vide infra).





The intermediate HBBO 7 and 8 were formed by condensation of 6 with 2-hydroxyaniline or 5-'Bu-2-hydroxylaniline respectively in refluxing ethanol followed by oxidation of the intermediate carbinolamine with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) (Scheme 2). Compounds 7 and 8 display a characteristic proton NMR signal (around 12 ppm) for the H-bonded phenolic proton. Moreover, their formation can be readily monitored by the appearance of a strong fluorescence in the solid-state due to an Excited-State Intramolecular Proton Transfer (ESIPT).¹⁵ Insertion of a 'Bu-phenyl or N"Bu2-phenyl ethynyl fragment was possible through Sonogashira cross-coupling reactions using 5% of [PdCl₂(PPh₃)₂] as a catalyst with 10% of CuI in the presence of an excess of the corresponding substituted phenylacetylene. Note that an additional 'Bu group was inserted in 10 as R_1 for solubility issues. Pure HBBO dyes 9 and 10 were isolated in 71 and 43% respectively as yellow powders. Boron complexation was achieved using BF₃.Et₂O in the presence of a base (DIEA) affording pure HBBO borate complex 1 and 2 in 74 and 79% yields respectively. The purity of all new compounds was assessed by ¹H, ¹³C NMR along with mass spectrometry and elemental analysis.

As already observed on related examples,^{8a,10} boron complexation to the N^O chelate leads to the disappearance of the downfield distinctive phenolic proton in ¹H NMR along with a splitting of the aromatic protons. The two para-substituted phenyl rings exhibit two AA'BB' systems at $\delta = 8.21/6.95$ ppm (J = 8.5Hz) and at $\delta = 7.50/6.66$ (J = 8.8 Hz). The methoxy and dibutylamino protons are in good accordance with the signals expected such functional groups in terms of chemical shifts and integration. Finally, the ¹³C NMR provides definitive proof of the complex **2** structure by displaying accounted signals for all tertiary and quaternary carbons. In particular, the sp carbons of the acetylenic spacer are observed at 97.6 and 99.0 ppm. The five signals in the upfield region match with expected signals for the

methylene carbons present in the butyl chains and the methoxy group.

Single crystals of compound **6** suitable for X-Ray diffraction were obtained by slow evaporation of a concentrated dichloromethane solution. The ORTEP diagram of **6** and the overlay of the two conformers observed are represented on Figure 2. Compound **6** crystallizes in the centrosymmetric triclinic space group with two molecules in the asymmetric unit. If both conformers are basically planar except for the acetate substituent, which is orthogonal to the rest of the molecule, they differ by having the methoxy and acetate groups pointing to opposite directions (Figure 2).







Figure 2. (Left) ORTEP view for 6 showing the atom-labelling scheme for one conformer. Thermal ellipsoids are plotted at the 50% level. (Right) Overlay of the two conformers present in the asymmetric unit of the single crystal of 6.



Figure 3. (a) Partial view detailing the stacking interactions for compound 6. (b) Partial view perpendicular to the layer plane.

Moreover, the anisole ring is less coplanar with the benzofuran group in the first conformer than in the other one. As for the crystal packing, the molecules are lying within the (1 2 4) plane with interplanar distance of 3.56 Å. Within each layer, molecules are associated through reciprocal interactions $C - H \cdots C$ between carbon sp2 and methyl group of the inversion-related isomer and I····O from the aldehyde group between pseudo-inversion related molecules.

The photophysical properties of HBBO borate complexes **1** and **2** have been studied in various solvents and are summarized in Table 1 and the experimental curves shown in Figure 4 for **1** and Figure 5 for **2**. The two complexes exhibit similar absorption profiles that is a low-energy band with a maximum at 360-397 nm and a higher-energy band around 300 nm typical of π - π * transitions. Absorption coefficients range from 14600 to 35700 M⁻¹.cm⁻¹ for the low-energy band. Excitation at 350-385 nm leads to an emission band in the

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visible region at 470 and 491 nm with quantum yields reaching 27 and 41% in toluene and CH_2Cl_2 respectively for complex **1**. As expected, the emission of **1** is only slightly affected by the dipolar moment of the solvent. The nanosecond lifetimes determined are consistent with a singlet emitting state.

 Table 1. Optical data for HBBO dyes 1 and 2 in various solvents at room temperature.

λ_{abs} (nm)	ε (M ⁻¹ .cr	n^{-1}) $\lambda_{em}(nm)$	Δ_{SS} (cm ⁻¹)	$\Phi_{\rm f}{}^a$	τ (ns)	Solvent
1 392	23800	468	4200	0.52	3.4	toluene
390	25500	471	4600	0.58	4.5	CH_2Cl_2
2 397	16300	470	3900	0.27	2.5	toluene
395	17100	491	4900	0.41	5.6	CH_2Cl_2
3 368	16300	504	7300	0.32	5.7	cyclohexane
365	27500	532	8700	0.18	1.2	toluene
363	35700	546	9200	0.11	1.0	THF
362	36100	542	9600	0.12	1.6	CH_2Cl_2

366	35800	501	7400	0.23	3.9	$CH_2Cl_2 + HCl_g$
360	27100	565	10000	0.08	2.2	CHCl ₃

Interestingly, for complex **2**, a different photophysical profile is observed. The presence of a strong electron-donating 4-NnBu₂-phenylacetylene module leads to a sizeable red-shifted emission as compared to complex **1**. For example, in CH₂Cl₂, complex **2** displays an intense emission band centered at 542 nm ($\Phi = 12\%$) as compared to 491 nm ($\Phi = 41\%$) for complex **1**. The emission profile of complex **2** is also strongly dependent on the dipolar moment of the solvent. Indeed, in all solvents, complex **2** exhibits a broad emission band whose maximum stretches from 504 to 565 nm with moderate quantum yields (32 to 8%) suggesting a strong intramolecular internal charge transfer (ICT) responsible for the emissive excited state.



Figure 4. Absorption (blue), excitation (dashed blue) and emission (green) of complex 1 in (a) toluene and (b) dichloromethane at rt.



Figure 5. (left) Absorption (dashed) and emission (plain) of complex 2 in cyclohexane (navy blue), toluene (blue), CH_2Cl_2 (green), $CH_2Cl_2 + HCl_g$ (light green) THF (red) and $CHCl_3$ (purple) and (right) (a) irradiated CH_2Cl_2 solution of complex 1 and (b) irradiated solutions of complex 2 in various solvents (from left to right: cyclohexane, toluene, THF, CH_2Cl_2 , $CH_2Cl_2 + HCl_g$, $CHCl_3$) with a bench UV lamp ($\lambda_{exc} = 365$ nm).

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To validate this hypothesis, absorption and emission were recorded after bubbling HCl gas into a solution of **2**. Since the ICT character is reduced due to the protonation of the lone electron pair of the nitrogen in the 4-NⁿBu₂-phenylacetylene fragment, the emission undergoes a significant blue-shift along with an increase of the quantum yield ($\lambda_{em} = 542 \text{ mn}, \Phi = 12\%$ for **2** in CH₂Cl₂ compared to $\lambda_{em} = 501 \text{ mn}, \Phi = 23\%$ for **2** in CH₂Cl₂ + HCl₈), similar feature is observed in CHCl₃ as a shoulder due to HCl trace in this solvent.

To gain more insights into the nature of the excited-states. TD-DFT calculations were performed, following a recently proposed approach adequate for HBO structures.¹⁶ Bulk solvation effects are accounted at all steps; not only the vertical absorption energies are determined on the ground-state optimal structures, but the geometry of the first excited-state is also fully optimized, allowing a simulation of the Stokes' shift. All calculations use a range-separated hybrid accounting for dispersion effects, as this allows a consistent treatment of both charge-transfer excitations and weak interactions (see the SI for details). In CH₂Cl₂, the computed Stokes' shifts are 6598 and 9856 cm⁻¹ for **1** and **2** which are larger than the measured values especially for complex 1 (Table 1) but are in qualitative agreement with experiment, that is the Stokes' shift is larger for 2 than for 1. Ground and excited-state Cartesian coordinates for all systems are available in the SI. The most notable changes between the two geometries is relative orientations of the main core of the molecule and the p-OMe-Ph donor. For 1 (2), it goes from 10.3° (5.6°) in the ground-state to 0.4° (0.1°) in the excited-state, hinting an increased delocalization in the excitedstate, as expected. The density difference plots corresponding to the optical transition for these dyes can be found in Figure 6. In 1, an ICT is observed from the benzofuran fragment towards the benzoxazole moiety; the ethynylphenyl fragment does not significantly participate in the excited-state that acts as an electron donor (mostly in blue in Figure 6).



Figure 6. PCM(CH₂Cl₂)- ω B97X-D/6-311+G(2d,p) density difference plots obtained for (a) **1** and (b) **2** (left) and **2**+HCl_e

In contrast, for **2**, there is a sizeable ICT from the dibutylamino group This is confirmed by the large computed ICT distance,17 of 2.9 Å, that decreases upon protonation (2.5 Å). This specific ICT disappears upon protonation, to restore an excited-state similar to complex 1 (right). Blue (red) regions indicate decrease (increase) of the electron density upon transition. A contour threshold of 0.004 a.u. is used.

Conclusions

In short, a new family of fluorescent borate dyes (HBBO) incorporating a benzofuran heterocycle, which actively participates in the extension of the π -conjugation, has been synthesized. They display a significant red-shift in their maximum emission wavelength as compared to related HBO borate dyes. The presence of a strong donor residue in the 3 position promotes an ICT as confirmed by spectroscopic studies and TD-DFT calculations allowing to shift the emission up to 565 nm. This stretch paves the way for the engineering of similar dyes emitting in the near-IR.

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Supplementary Data

Supplementary data associated with this article can be found online.

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