Design and photophysical properties of a new molecule with a N–B–N linked chromophore

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\textbf{A B S T R A C T}

A new heterocyclic system, pyrido[6,5-a]boratrizaine, has been designed with the aid of TD DFT (TDA) and other quantum mechanical calculations aiming at tunable UV–Vis–NIR absorption and intense fluorescence, conveniently sensitive to the environment. Special emphasis has been put on solvent effects on the mentioned electronic transition energies and intensities.

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1. Introduction

A class of heterocycles possessing the N–B–N linkage, borindacenes\textsuperscript{1}, has recently come to prominence as the result of their excellent photochemical stability and intense fluorescence. Since the initial commercialization of borindacene derivatives under the trade name BODIPY\textsuperscript{2}, these N–B–N containing molecules have become increasingly popular and have been used in any imaginable fluorescence-based application, starting with analytical uses as ion, molecule and protein sensors, and going further to biomedical indicators and fluorescence imaging, photoelectronic materials and nanodevice components [1–4]. Along with their remarkably high absorption coefficients, fluorescence quantum yields and photostability, Förster photoexcitation energy transfer capabilities, FRET, and negligible triplet-state excitations, BODIPY dyes also possess several important shortcomings – small Stokes' shifts, low solubility in water, self-quenching [4] and low sensitivity to medium effects [2–4]. While new borindacene derivatives are currently intensively synthesized and studied, there is still an open field to the design of new B–N chromophores with possibly improved photochemical stability, photophysical properties and solubility, as well as FRET capabilities comparable or even better than, for example, the existing BODIPY dual chromophore dyes [5,6] (see Scheme 1).

Apart of the mentioned borindacene N–B–N derivatives, commercialized under the trademark BODIPY, several topologically similar classes of compounds have used other heteroatoms, e.g. N–B–O compounds like ketopyrroles \textsuperscript{2} [1,4], or N–B–C derivatives of traditional azo-dyes \textsuperscript{3} [7] have recently been found to possess intense fluorescence as well. The idea of boron linking a potential electron pair donating atom, while substituting H from another proton donating atom in the case of ketopyrrole derivatives \textsuperscript{2}, has been widely exploited in a series of recent works with excellent results, see e.g. compound \textsuperscript{4}, Scheme 2 [8]. Other heterocyclic derivatives of classic dyes with N–B–O fragments have been patented much earlier, 5–7, Scheme 2 [9], but no photophysical properties have been reported, to the best of our knowledge.

We dedicate our attention to the design of a series of so far unknown heterocycles, boratrizaines 8–11, Scheme 3, which could ameliorate some of the above shortcomings of BODIPY dyes. No compound of this class has been reported so far, and no 1,2,3,6-boratrizaine derivatives are commercially available, to the best of our knowledge. All boratrizaine compounds described here are the result of our own molecular design. As long as molecular symmetry is among the reasons for the latter shortcomings, the choice of non-symmetrical boratrizaine molecules would seem appropriate. No special provisions seem necessary to obtain these compounds in order to improve their spectral sensitivity to medium effects and enhance the Stokes' shift, while their expected significant molecular polarity would be a better prerequisite to solubility in polar solvents and even water.

The basic tool for the intended molecular design consists of diverse quantum chemical calculations for the prediction of electronic absorption and emission spectra. Literature data indicate that UV–Vis absorption spectra of broad varieties of molecules can be routinely predicted with a precision better than 0.2 eV, or approximately 1500 cm\textsuperscript{-1}, taking full account for the solvent effects [10–15]. Similar calculations of molecular fluorescence spectra are presently less straightforward [14–16].

Synthesis of boratrizaines 8–11 is presumably straightforward, which is the main reason for our present choice. More compounds of diverse structures will be scrutinized further.

This Letter focuses on a detailed theoretical investigation of electron spectroscopic properties of compound \textsuperscript{8}. For the validation of our computational predictions milligram amounts...
of compound 8 have been synthesized upon our request and some of its photophysical characteristics have been registered experimentally.

2. Computational and experimental details

TD (Tamm-Dancoff approximation, TDA) DFT calculations of absorption spectra (singlet excitation energies) in gas phase are carried out using the GAUSSIAN 03 [17] and ORCA programs [18], using the generalized gradient hybrid PBE0 functional [19,20] and the double-hybrid correlation functional B2PLYP [21–23] at the respective completely relaxed geometries. Ground state molecular geometries are initially optimized at the 6-311G(d,p) basis set level [24,25], using PBE0 and B2PLYP. The solvent effects are modeled through the continuum dielectric PCM [26] and the COSMO conductor-like [27] approaches for the PBE0 and B2PLYP case, respectively. Single point TD B2PLYP/6-311++G(2d,2p) COSMO calculations, as well as TD PBE0/6-311+G(2d,p) PCM calculations, are carried out at the optimized ground state geometries as mentioned above. For the emission energies, TD DFT optimizations of the first excited singlet state are carried out using GAMESS [28], with analytical TD DFT gradients for PBE0 and B3LYP functionals in the gas phase. (6,6) MCSCF calculations with six electrons in six orbitals for the ground $S_0$ and the first excited $S_1$ electronic states of 8 are also carried out with GAMESS. Finally, single point calculations of $S_0$–$S_1$, respectively $S_1$–$S_0$ vertical absorption and fluorescence emission energies at the corresponding $S_0$ and $S_1$ optimized geometries are done with the symmetry adapted cluster–configuration interaction method, SAC-Cl [29–31], as implemented in GAUSSIAN 03.

UV–Vis absorption spectra of compound 8, $N_2$-phenyl-1,1-difluorobora-pyrido-[2,1,a]-2,3,6-triazine are recorded on a Specord UV–Vis Carl Zeiss Jena spectrometer. Steady-state fluorescence emission spectra in different solvents are registered on a SLM.
8100 Aminco spectrofluorimeter upon excitation at the maxima of the respective longest wavelength absorption bands. Fluorescence decay measurements at the maxima of emission bands are performed on a Time Correlated Single Photon Counting (TCSPC) FL900 Edinburgh Instruments Spectrometer. Spectrophotometric grade organic solvents and deionized water (Mili-Q system) are used in all measurements.

3. Results and discussion

Some of the computationally predicted geometry parameters of 8 are shown in Fig. 1. The pyrido-boratriazine system in its ground electronic state is approximately planar, with a slightly puckered boratriazine ring with BF$_2$ on top of the half-chair six-membered ring.

Normalized absorption and emission spectra of the designed compound 8 in different solvents are shown in Fig. 2. Time-resolved fluorescence intensity apparently shows a two-exponential decay, which cannot be clearly resolved due to the low observed signal. The fluorescence lifetime average is 9.6 ns in THF and decreases to 6.2 ns in water. A somewhat unexpected finding is that increase of solvent polarity leads to hypsochromic shift of the longest wavelength absorption maximum, Table 1. This ‘inverse’ solvatochromic effect is not an unusual phenomenon with donor–acceptor dyes. It appears to be observed more or less regularly with boron-containing acceptor chromophores [8], as well as with such classic, even though less used quinazoline chromophores [32].

The observed ‘inverse’ solvatochromic effect on the absorption spectra of 8 can be readily rationalized by inspection of its molecular orbitals, Fig. 3. TD DFT calculations show that the vertical S$_0$–S$_1$ transition is dominated by the HOMO–LUMO excitation to ca. 65%, with another 10–15% contributed by the HOMO–LUMO+1 excitation. The squared CI coefficients of other excitations are usually lower than 10%. Excitation of a π-electron from HOMO to LUMO leads to increased localization of electronic density on the acceptor part of the molecule, bearing the N–B–N fragment. Even stronger localization on the same B–N pyridine fragment of the chromophore should occur with excitations to the second lowest virtual orbital, LUMO+1, Fig. 3. This electron density localization in the lowest excited states of 8 explains the absence of bathochromic shift of the absorption maximum upon increase of solvent polarity. To further explain the origin of the observed blue shift of absorption in polar solvents, we calculate the dipole moments of the respective electronic states. The calculated dipole moment for the ground S$_0$ state of 8 is 6.84 D [RHF/6-311G(d,p)], while for the S$_1$ vertically excited state at the S$_0$ geometry we obtain a value of 5.57 D [CIS/6-311G(d,p)]. Corresponding DFT values are 5.43 D [S$_0$, B3LYP/6-31G(d)] and 2.51 D [S$_1$, TD B3LYP/6-31G(d)], respectively. Thus, the polar solvent should stabilize S$_0$ to a greater extent than S$_1$ after the vertical electronic transition and thereby increase the vertical S$_0$–S$_1$ excitation energy by resisting the lowering of the dipole moment.

Calculated excitation energies correlate fairly well with the experimental absorption maxima energies in aprotic solvents,
reproducing the observed ‘inverse’ solvatochromic effect, Fig. 4. Statistically, the double-hybrid B2PLYP functional performs somewhat better than the GGA hybrid PBE0 in this particular case. The comparison of lowest singlet excitation energies computed at slightly different basis set levels, TD B2PLYP/6-311+G(2d,2p) and TD PBE0/6-311+G(2d,p), is legitimate, as far as 6-311+G(2d,p) is anyway about the convergence region of these values [10–12,14]. In fact, we also calculated PCM TD B2PLYP/6-311++G(2d,2p) singlet excitation energies for 8 in cyclohexane and acetonitrile and obtained the same values as these listed in Table 1. To the contrary, however, calculated longest wavelength absorption maxima energies for the spectra of 8 in protic solvents are almost identical, and even practically insensitive to the change of alcoholic solvent with water, Table 1. Small differences in the positions of absorption maxima in methanol and acetonitrile are an indication against protonation at the unsubstituted N3 of the chromophores, see also Table 1. Thus, the absorption maximum in water is off the relationship for other solvents and is not included in Fig. 4 since at the moment we cannot exclude chemical changes of 8 in this solvent.

Calculated dipole moment changes for vertical fluorescence transitions at the fully relaxed S1 geometry are respectively 7.78 D, S1 and 2.22 D, S0, TD PBE0/6-311G(d,p). Single point TD B2PLYP/6-311+G(2d,2p) calculations at the above geometries give for S1 a dipole moment of 9.02 D, while for S0 the computed value is 6.30 D (DFT density); 5.79 (relaxed MP2 density), B2PLYP/6-311++G(2d,2p). Thus, the emission maxima should again show hypsochromic effects with increased solvent polarity, which has not been unequivocally observed in present experiments. In any case, with the experimentally observed minimal solvent effects on the fluorescence emission of 8, we come to an increase of the observed Stokes’ shift from 4200 cm⁻¹ in cyclohexane to 5650 cm⁻¹ in acetonitrile and 6700 cm⁻¹ in the most polar solvent used, water.

The low fluorescence efficiency in solution can be explained on the basis of the computational predictions of the molecular

<table>
<thead>
<tr>
<th>Solvent</th>
<th>λmax nm</th>
<th>Emission λmax nm</th>
<th>Emission 6311+G(2d,p) S0:</th>
<th>Computation—absorption maxima</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclohexane</td>
<td>442</td>
<td>22.62</td>
<td>543</td>
<td>4200</td>
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<tr>
<td>THF</td>
<td>425</td>
<td>23.53</td>
<td>541</td>
<td>5050</td>
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<tr>
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<td></td>
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<tr>
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<tr>
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<td>24.27</td>
<td>555</td>
<td>6250</td>
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<tr>
<td>Water</td>
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<td>25.25</td>
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<td>6700</td>
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</table>

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<th>Experiment</th>
<th>Absorption λmax nm</th>
<th>λmax cm⁻¹</th>
<th>Emission λmax nm</th>
<th>Emission 6311+G(2d,p) S0:</th>
<th>Computation—absorption maxima</th>
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Fig. 4. Experimental and calculated COSMO TD B2PLYP/6-311++G(2d,2p)//B2PLYP/6-311G(d,p) energies of the longest wavelength absorption maximum of 8 in several solvents; EA, ethylacetate. For the remaining abbreviations, see Fig. 2.

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structure of 8. The S<sub>0</sub> electronic state has a nonplanar equilibrium structure, with the phenyl substituent at N<sub>2</sub> rotated at 26° with respect to the boratriazine cycle, PBE0/6-311+G(2d,p). The S<sub>1</sub> state is essentially planar, with a phenyl rotation angle of 2°, TD PBE0/6-311G(d,p). The optimized MCSCF/6-31G(d) geometries, however, differ from the DFT results: both S<sub>0</sub> and S<sub>1</sub> equilibrium gas phase structures are predicted nearly planar, with the N<sub>2</sub>-phenyl plane twisted with respect to the pyrido-boratriazine plane to less than 5°. The calculated phenyl rotation barrier in the ground state of 8 is ca. 4.2 kcal/mol, PBE0/6-311+G(2d,p), which is practically free rotation and accounts for the weak fluorescence emission in solution. Better fluorescence efficiency of the present boratriazine system may be achieved via hindering the internal rotation and thereby the conformational channel for radiationless deactivation of the fluorescing state by bulky substituents on boron as in the case of 3 [7] or including the substituent to N<sub>2</sub> in a rigid structure [33].

Attempts at direct calculation of fluorescence emission energies require geometry optimization of the emitting electronic state, presumably S<sub>1</sub>, as the first step. This can be achieved either by single-reference methods as CIS [34] or TD DFT [28] or by multiconfiguration MC SCF [28] methods. At present, multi-reference CI calculations do not seem feasible for this purpose. Next, the vertical S<sub>1</sub>–S<sub>0</sub> emission energy can be conveniently calculated by TD DFT or SAC–CI methods [16]. We note that theoretical emission energies obtained by any of aforementioned methods are systematically higher than experimental values, even though theory and experiment correlate reasonably with each other. In the case of 8, gas phase 6 × 6 MCSCF/6-31G(d) geometries give a SAC–CI S<sub>1</sub>–S<sub>0</sub> excitation energy of 34.57 × 10<sup>3</sup> cm<sup>-1</sup>, while the calculated SAC–CI S<sub>1</sub>–S<sub>0</sub> emission energy is 25.40 × 10<sup>3</sup> cm<sup>-1</sup>, i.e. the predicted Stokes’ shift is almost 9200 cm<sup>-1</sup>, more than twice larger than the observed in cyclohexane. B3LYP/6-311G geometries give an excitation energy of 31.72 × 10<sup>3</sup> cm<sup>-1</sup> and an emission energy of 31.39 × 10<sup>3</sup> cm<sup>-1</sup>, i.e. a Stokes’ shift of 430 cm<sup>-1</sup>, an order of magnitude less than observed. The calculated SAC–CI emission energy at the TD PBE0/6-311G S<sub>1</sub> geometry is 20.47 × 10<sup>3</sup> cm<sup>-1</sup>, which best theoretical value is some 2000 cm<sup>-1</sup> higher than the experiment. Presently, studies of solvent effects on molecular fluorescing states are still at the development stage before entering the arsenal of traditional methods of computational chemistry [15,35].

4. Conclusions

Preliminary quantum chemical calculations, more specifically TD (TDA) DFT, are a reliable tool in the design of unusual chromophores at the border of organic and inorganic compounds. Indeed, time-resolved photophysics of 8 and similar molecules is out of the reach of single-reference TD DFT calculations, and requires more detailed experiments, as well as multi-reference quantum chemical analysis. Nevertheless, we may confidently predict electron absorption and steady-state fluorescence properties of compounds 9–11 as given in this work. Designed properties of 8 meet the initial targets in terms of solvatophoric effects on absorption spectra, but are significantly short of the desired bright fluorescence.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.cplett.2009.07.075.

References