

Heavy Atom Free Singlet Oxygen Generation: Doubly Substituted Configurations Dominate S_1 States of Bis-BODIPYs

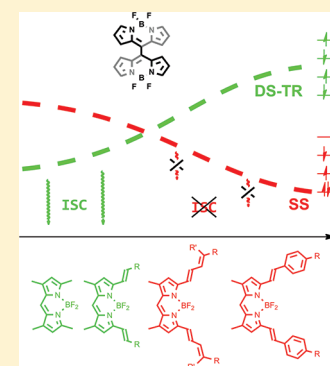
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S Supporting Information

ABSTRACT: S_0 , S_1 , and T_1 states of various orthogonal 8,8' and 8,2'-bis-boradiaza-*s*-indacene (BODIPY) dyes, recently (*Angew. Chem., Int. Ed.* **2011**, *50*, 11937) proposed as heavy atom free photosensitizers for $O_2(^1\Delta_g)$ generation, were studied by multireference quantum chemical approaches. $S_0 \rightarrow S_1$ excitation characteristics of certain bis-BODIPYs are shown to be drastically different than the parent BODIPY chromophore. Whereas a simple HOMO \rightarrow LUMO-type single substitution perfectly accounts for the BODIPY core, S_1 states of certain orthogonal bis-BODIPYs are described as linear combinations of doubly substituted (DS) configurations which overall yield four electrons in four singly occupied orbitals. Computed DS character of S_1 , strongly correlated with facile 1O_2 production, was presumed to occur via $S_1 \rightarrow T_1$ intersystem crossing (ISC) of the sensitizer. Further confirmation of this relation was provided by newly synthesized BODIPY derivatives and comparison of spectroscopic properties of their dimers and monomers. Near-IR absorption, desired for potential photodynamic therapy applications, was not pursuable for bis-chromophores by the standard strategy of π -extension, as DS singlet states are destabilized. Decreased exchange coupling in π -extended cases appears to be responsible for this destabilization. Comparisons with iodine incorporated bis-BODIPYs suggest that the dynamics of 1O_2 generation via DS S_1 states are qualitatively different from that via ISC originating from heavy atom spin-orbit coupling. Although red-shifting the absorption wavelength to enter the therapeutic window does not seem attainable for orthogonal bis-BODIPYs with DS S_1 states, modifications in the chromophore cores are shown to be promising in fine-tuning the excitation characteristics.



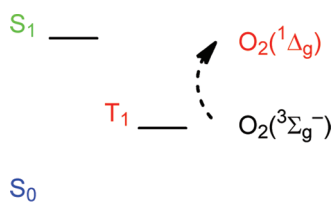
INTRODUCTION

Boradiaza-*s*-indacene (BODIPY)^{1,2} based systems have been widely studied in relation to numerous photophysical processes. One active field of research has been their utilization as potential photosensitizers in photodynamic therapy³ (PDT) where the cytotoxic first excited singlet state $O_2(^1\Delta_g)$ furnished by the photosensitizer is used to kill cells in a range of tumors.⁴ Although details of $O_2(^1\Delta_g)$ generation by photosensitizers depend on the specific molecular system and solvent environment, it is widely accepted⁵ that intersystem crossing (ISC) of the singlet photosensitizer to the triplet state allows the nearby ground-state triplet $O_2(^3\Sigma_g^-)$ molecules, to overcome the spin forbidden $^3O_2 \rightarrow ^1O_2$ transformation as shown in Scheme 1. The $T_1 + ^3O_2$ supersystem is then coupled

into a singlet and yields $S_0 + ^1O_2$ in an overall spin-allowed fashion. Therefore, one critical component of singlet oxygen generation has been the design and synthesis of molecules that will effectively cross to triplet surface, presumably via a $S_0 \rightarrow S_1 \rightarrow T_1$ transition upon irradiation.

Incorporation of heavy atoms into the BODIPY core has been a well-established recipe for furnishing photosensitizers that efficiently undergo singlet \rightarrow triplet conversion by means of the relatively large spin orbit coupling constants that these high nuclear charge atoms possess. ISC without heavy atoms can only be accomplished by a limited number of photosensitizers such as metal free porphyrins^{6,7} and rhodamine;⁷ hence, substantial effort is dedicated to the search of novel compounds and strategies. Establishing design principles that should allow bypassing the use of high nuclear charge atoms is particularly desirable as it would help eliminate dark toxicity.⁸ A recent report⁹ on utilizing an *N*-methylpyridinium cation substituent at the meso (C8) position of BODIPY in an orthogonal arrangement invoking rapid ISC to afford the triplet state was particularly interesting in this regard. Spatial orthogonality of substituents to chromophore cores have been shown to yield

Scheme 1



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interesting features in the excited states mainly due to charge transfer.^{9–14} These include unprecedented nonadiabatic hops to other electronic/spin surfaces; however, different electronic structure perspectives may be needed to explain efficiency of triplet state formation for different chemical systems.

Recently, we synthesized heavy-atom-free unsubstituted 8,8'- and 8,2'-1,3,5,7-tetramethylBODIPY dimers **2** and **3** (Figure 1)

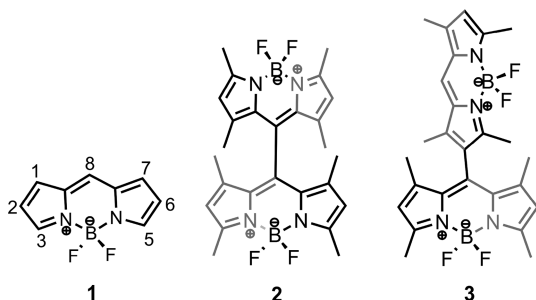


Figure 1. Molecular structure and numbering of 4,4-difluoro-4-bora-3a,4a-diaza-*s*-indacane (BODIPY) (**1**), 8,8' (**2**), and 8,2' (**3**) orthogonal tetramethylBODIPY dimers.

that have been proven to be efficient (ca. 50% quantum yield) singlet oxygen generators by various spectroscopic methods as well as cell culture studies.¹⁵ Detailed analyses of the electronic structures of both orthogonal dimers with multiconfigurational self-consistent field (MCSCF) techniques revealed a remarkable electronic structure motif in their S_1 states. Fascinating from an electronic structure viewpoint was the presence of four unpaired electrons in the highest molecular orbitals (MO) in an overall singlet coupled fashion. We have designated this phenomenon of the existence of four singly occupied highly delocalized MOs, distributed essentially equally over both BODIPY cores, as tetra-radical (TR). Contrary to the locality implied in the definition of a radical, the electron density in the four singly occupied MOs (SOMO) was perfectly delocalized over both cores, and there was no spin localization.

Exploring the properties of these bis-BODIPYs further, in order to delineate the causes, extent, and control of this interesting electronic structure motif, is important as the substantial 1O_2 generation yield in this new class of heavy atom free photosensitizers is presumably linked to the extraordinary character developed in $S_0 \rightarrow S_1$ excitation. Applications such as cell culture studies were successfully pursued; however, further studies were required to answer numerous questions about the S_1 state regarding the breadth of the orthogonality principle and control of excitation properties under structural perturbations. Although general principles for regulating the frontier orbital levels via substituents are available,^{16,17} they have not been tested for fine-tuning orthogonal bis-BODIPYs to operate at longer wavelengths of the spectrum. Thus, strategies for optimizing the excitation properties of orthogonal bis-BODIPYs, in particular in order to enter the therapeutic window (620–850 nm), should be developed. Currently it is unclear how to generalize the no-heavy-atom ISC approach to bis-BODIPYs and/or to any orthogonal bis-chromophore. Comparison of the orthogonal bis-chromophore approach with heavy atom incorporation is also expected to provide new insights.

The generality of the points raised above might require numerous sets of molecules to be synthesized and tested for 1O_2 production and/or ISC performance; however, by

employing detailed quantum mechanical calculations that will allow in depth examination of the wave functions of the excited states, a comprehensive understanding of the nature of S_1 states in orthogonally positioned bis-BODIPYs could be achieved.

Herein, we present results of MCSCF electronic structure calculations with the complete active space (CAS) SCF method as well as density functional theory (DFT) in order to illuminate the electronic structure details that possibly govern the mechanism of efficient ISC yielding cytotoxic 1O_2 generation in numerous orthogonal 8,8' and 8,2' bis-BODIPYs. Links of the excited-state properties to ground-state electron density distribution are demonstrated, and the reliability of utilizing the excitation characteristics of the singlet excited states, as an electronic structure descriptor in assessment of ISC performance, has been established. In doing so, we also report synthesis and spectroscopic properties of a novel orthogonal BODIPY dimer and experimental comparison of excitation characteristics of selected monomers and dimers. All of the available data clearly confirm predictions of the quantum chemical calculations on excited states.

The quest is discovering rational design principles in order to extend the unprecedented behavior of **2** and **3**; hence, structural relations to **2** and **3** are apparent features of the molecules investigated. Utilizing key features of dimers **2** and **3**, quantum chemical modeling of candidate sensitizers, whose synthesis may hopefully be available in the near future, are performed. Our results suggest that practical demands on photosensitizers could be met with concerted experimental and theoretical studies aimed at judicious designing of the chromophore cores.

COMPUTATIONAL DETAILS

Geometries, including excited states, were fully optimized with the ab initio complete active-space self-consistent field (CASSCF)^{18,19} methodology and B3LYP^{20–26} density functional theory^{20,27–29} employing various all-electron Pople- and Dunning-type basis sets and effective core potentials (ECP) including 6-31G(d,p), 6-311G(d,p), cc-pVDZ, CEP-31G, and LANL2DZ.^{30–32} Harmonic vibrational frequencies were computed to ensure that the species did not possess any imaginary frequencies and hence correspond to true minima. For selected species, with no significant multi reference character, TD-DFT calculations in combination with a polarizable continuum model (PCM) were performed to investigate the excitation characteristics. Excited-state MCSCF calculations used the state averaged (SA) formalism with equal weights for all the states involved. No restrictions on symmetry were imposed.

Spectroscopic properties were investigated at various levels to find DFT and TD-DFT levels of reasonable performance. This was primarily done by studying the differences in Kohn–Sham eigenvalues (as HOMO and LUMO energies) for BODIPY and tetramethyl BODIPY S_0 states, as a measure of experimental λ_{abs} .³³ Calculations at various levels (Tables S1 and S2, Supporting Information) suggest that excitation energies via frontier orbital energy differences of ground-state DFT calculations are blue-shifted by ca. 60 nm at the UB3LYP/cc-pVTZ//CEP-31G level of theory. The improvement at the time-dependent TD-UB3LYP/cc-pVTZ//CEP-31G level was relatively small (ca. 10 nm). Akin to its recent use in similar systems³⁴ as well as calculation of frontier orbital energy differences³⁵ and spin-orbit coupling³⁶ calculations, CEP-31G showed a balanced behavior for the systems studied in this work.

Active spaces (electrons, orbitals) in the CASSCF calculations were selected from the highest lying π MOs. Six electrons distributed over six orbitals (6,6) CAS for the 8,2' dimers and four electrons distributed over four orbitals (4,4) CAS for the 8,8' dimers were found to be necessary. Enlarged active spaces up to 12,12 also reproduced the key features of interest. For the sake of consistency, a six electrons in six

orbitals CAS is used for both dimers. CAS(4,4) calculations for the 8,8' dimers were also performed. CAS(4,4) and CAS(6,6) calculations for the 8,8' dimers predict the same type of excitation characteristics. Natural orbitals of the CASSCF wave functions and configuration-state function coefficients were analyzed to understand the nature of the electronic state as being a single electron HOMO→LUMO type or multiply substituted type. BODIPY core S_1 is a clean HOMO→LUMO-dominated $\pi\rightarrow\pi^*$ state and was mainly described by a single configuration. Key details of the CAS wave functions, such as the orbital occupancies and leading configurations, which are of utmost interest herein, are not affected by perturbation corrections on the CAS wave functions; however, CAS-MP2³⁷ treatments (in order to capture more of the dynamical correlation) were performed for selected dimers. Both of the CAS and CAS-MP2 levels verify that not a HOMO→LUMO-type excited state but the doubly substituted state is S_1 . Given the size of the computations, perturbation treatment on the CASSCF wave functions was technically not possible for all the species studied; nevertheless, both CASSCF and CAS-MP2//CASSCF calculations on excited states of 2, 3, and 9 were in satisfactory agreement with the experiments. Note that since CEP-31G ECPs (a relatively small choice for a correlated wave function based calculation) were used in the CAS-MP2 calculations, quantitatively more reliable treatment of all species at higher levels of theory which may become available in the future will provide improved results, but these are currently computationally prohibitive. Crossing points between different electronic states were also excluded for computational feasibility. Increasing the basis set size and/or augmenting the active space was performed for some key species (Table S12, Supporting Information), and no significant changes were observed for the main parameters probed.

Nonadiabatic coupling of different spin states were studied by computing the spin-orbit coupling constants (SOCCs) using the full Pauli-Breit Hamiltonian,^{38–40} which includes both one-electron and two-electron terms. Details about the spin-orbit calculations and the computer implementation are available from Fedorov and Gordon⁴⁰ and Furlani and King.^{41,42} To examine the uniformity of the CAS, natural orbitals (NO) were carefully analyzed for all the species discussed. NOs diagonalize the one-electron density matrix with nonintegral diagonal elements from 0 to 2 being the occupation numbers (NOON), and they are a convenient way of building the MCSCF wave function as they provide the shortest CI expansion possible. NOONs and orbital isosurface plots were used to eliminate solutions with undesired orbital rotations. Conservation of the active orbitals for each case was carefully checked and, fortunately, did not require excessive runs of manually performed orbital rotations.

Expectation value of the total spin operator $\langle S^2 \rangle$ for DFT calculations was monitored and did not show any problems due to possible deficiencies in the single reference approach. At all times, DFT and TD-DFT calculations were reliable for the monomers; however, excited singlet states of some of the dimers possessed a substantial amount of multiconfigurational character. Relative energies of excited states in reference to S_0 states and frontier orbital energies/energy differences are reported in eV mol⁻¹.

BODIPY monomers obtained by substitutions at the 1, 3, 5, and 7 positions are designated with numbers from 4 to 11, and bis BODIPYs are designated by adding the suffix bis- to monomer labels. The two coupling schemes for orthogonal binding are indicated by prime (8,2') or no-prime (8,8') on monomer designations. Only for bis-4 and bis-4' are special numbers (2 and 3) given. Species bearing iodine at the 2 and 6 positions are named by appending "I" to the labels of noniodo species. MCSCF calculations were performed with MOLCAS 7.4,⁴³ GAMESS-US (versions = 11 APR 2008 (R1) and 12 JAN 2009 (R3)),⁴⁴ and Gaussian 03 (D.01)⁴⁵ software suites. Most DFT and TD-DFT calculations were performed using the Gaussian package. All SOC computations were handled by GAMESS-US.

RESULTS AND DISCUSSION

Electronic Structure Details of 8,8'- and 8,2'-Bis-BODIPYs. Syntheses of 2 and 3 have been recently reported.¹⁵

An important structural feature of both dimers is the orthogonally arranged chromophore cores, with respective calculated interplane angles of 91.0° and 89.9° for 2 and 3, in excellent agreement with the 90 ± 0.5° X-ray crystallographic data. Spatial orthogonality is decisive on the excitation properties of 2 and 3 as it prevents the π -mixing among cores and maintains two essentially undisturbed chromophores almost retaining their monomeric orbital energies and electron density distributions. With the survival of BODIPY core levels in the dimer, its $S_0\rightarrow S_1$ excitation should then be composed of the inherent HOMO→LUMO transitions of both monomers. Comparison of the absorption spectra for core BODIPY, 2, and 3 as given in Figure S4 (Supporting Information), clearly shows that monomer levels are essentially conserved in both dimers. Realization of this feature allows us to envisage the $S_0\rightarrow S_1$ excitation to mainly include double substitutions with the reference wave function as depicted in Figure 2 via construction of a conceptually useful valence bond^{46,47} (VB) wave function for S_1 .

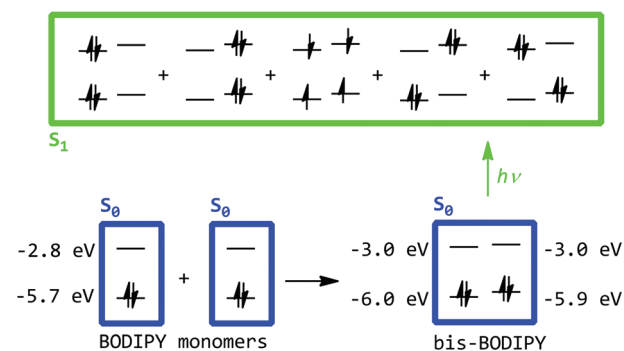


Figure 2. Building up bis-BODIPY S_1 wave function. MO energies are for the 8,8' dimer (3). In the S_1 state, only the leading configurations are shown, and minus signs to restrain antisymmetry are intentionally excluded for clarity.

The general view demonstrated in Figure 2 is verified by the computed excited-state MO plots and NOONs as well as the details of the multiconfigurational expansion given in Figures 3 and 4, respectively. The effect of constructing the S_1 wave function from essentially unperturbed monomeric states is clearly visible on NOONs since the sum over all five configurations in Figure 2 for S_1 (after normalization in the basis of the five configurations) yields a single electron in each of the four MOs, provided that the five configurations are essentially equally weighted. Four electrons in four molecular orbitals in an overall singlet coupled fashion, as confirmed by the NOONs of the CASSCF wave functions, is the basis for the TR designation. Moreover, distributions of the SOMOs for S_1 are found to be linear combinations of the HOMO and LUMO of isolated BODIPY cores, a feature predicted to be an outcome of spatial orthogonality of monomers. A higher degree of symmetry in 2 is the reason for the $|\text{HOMO} \pm \text{HOMO}\rangle$ and $|\text{LUMO} \pm \text{LUMO}\rangle$ motif seen in the S_1 state. For S_1 SOMOs of 3 however, $|\pm \text{HOMO} \pm \text{LUMO}\rangle$ type of linear combination is observed.⁴⁸ Lack of connection among rings of S_1 SOMOs in 3, as opposed to connection of electron density at the meso carbon in the two highest lying SOMOs of 2 is interesting. Contrary to 2, 3 did not show any significant ($\Phi_F < 1\%$) emission, presumably caused by the less hindered rotation of chromophore cores, i.e., due to the decreased

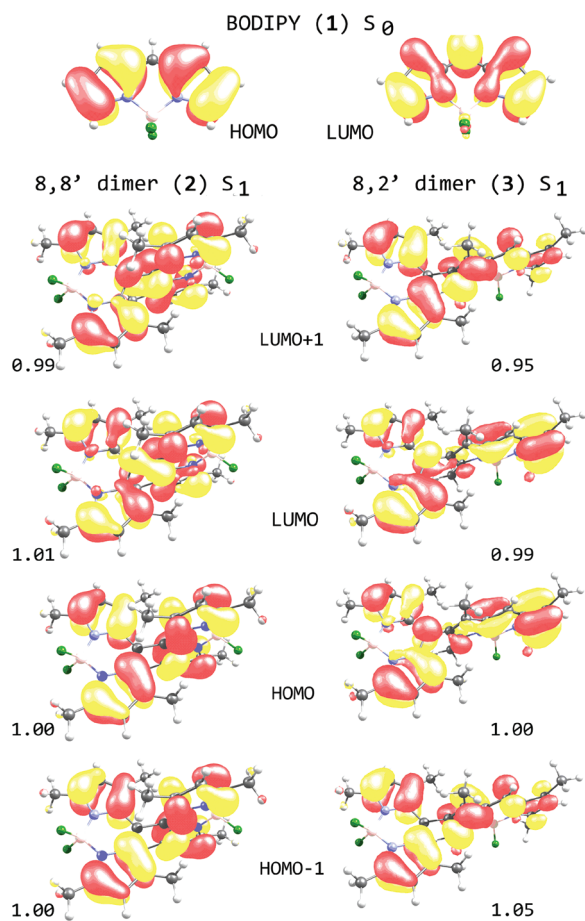


Figure 3. (Top) BODIPY HOMO and LUMO. (Bottom) Frontier orbitals and natural orbital occupation numbers of S_1 states of dimers 2 and 3. SOMO designations for the S_1 state refer to frontier MOs of S_0 . Surfaces are plotted at 0.275 au.

structural rigidity in the 8,2' coupling motif with respect to 8,8' binding. These differences do not alter the main excitation characteristics of the two dimers, and simultaneous switching on of the two essentially isolated fluorophores affords four delocalized SOMOs in the S_1 state for both.⁴⁹

CASSCF wave functions given in Figure 4 basically confirm the viewpoint developed about building up the wave function of orthogonal bis-BODIPY (vide supra). Ground-singlet and triplet-state wave functions do not show any unexpected features and are dominated by the default configurations. On the other hand, S_1 is far from being the result of a simple HOMO→LUMO transition presumed for most chromophore S_1 states in closed-shell organic molecules. Five essentially equally contributing, doubly substituted configurations make up the S_1 state. This feature, caused by near-degeneracy of S_0 frontier orbitals of 2 and 3, led us to designate such S_1 states as doubly substituted (DS). The similarity of DS configurations to zwitterionic excited states, known to have interesting manifestations in photochemical reactions,^{50,51} is notable; however, the highly delocalized nature of SOMOs in the S_1 states, do not imply formation of opposite charge centers present in chemical zwitterions. Moreover, a resemblance to zwitterionic electronic states studied in dimethylenes and derivatives,^{52,53} with small or no net charge polarization, should be noted.

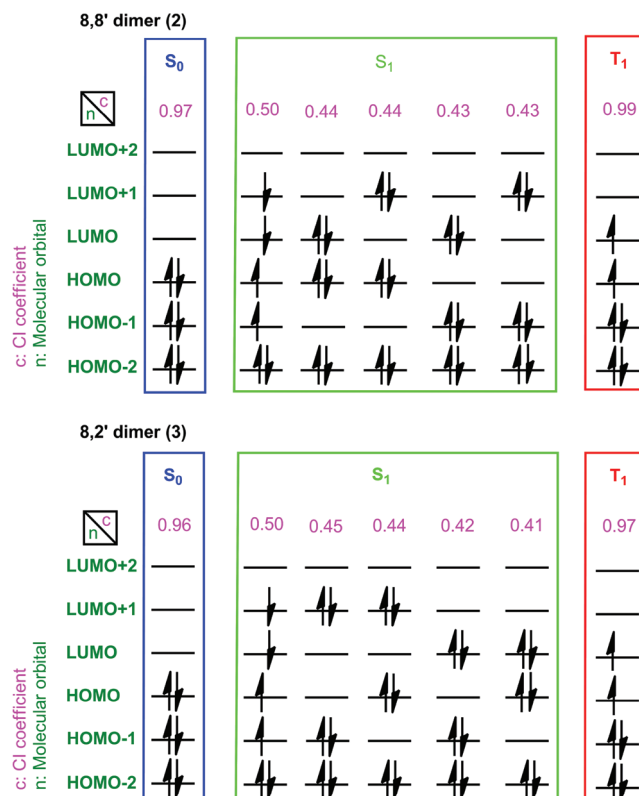


Figure 4. Leading configurations of S_0 , S_1 , and T_1 CASSCF wave functions for 2 and 3.

It is important to note that S_1 states of 2 and 3 are not true radicals since, among the five dominant configurations, the first one is in favor of a radical and the rest are of ionic nature. Given that the weights of the DS configurations are essentially the same and normalization in the space of these four configurations yields a single electron in each MO, the contributions to the NOONs from the four DS configurations do not alter the TR picture; however, the radical contribution is essentially only one-fifth of the total wave function. This extremely interesting nature of the S_1 states of 2 and 3 is clearly explained by the VB wave function depicted in Figure 2. Thus, dictated by orthogonality and lack of π -mixing, S_1 states with four SOMOs contain both radical and DS contributions. We emphasize that localization of electron density in S_1 states was not observed.

Referring to the two key features of the excited states, we hereafter denote S_1 states similar to those of 2 and 3 as DS-TR. This is mainly a designation for the specific configurational features (DS) of the multi reference wave function and frontier orbital occupancy pattern (TR). Simple HOMO→LUMO-type excitations are accordingly termed as singly substituted (SS) in this work. Fortunately, the unexpected electronic structure motif, DS-TR, is fairly reproducible at different CASSCF levels.

In order to clarify the adapted terminology, it is useful to note the difference between substitutions in a determinantal wave function and electronic excitations of the chemical system. Using a closed-shell Hartree–Fock determinant (also called as configuration) Φ_0 as the reference, each electronic state (Ψ^n) is defined as a linear combination of the reference and a number of n -tuply substituted analogues corresponding to an n -tuple-substitution (excitation) with respect to the reference, where

coefficients c_i in eq 1 show the contribution of configuration Φ_i to the wave function Ψ^n .

$$\Psi^1 = \sum c_i \Phi_i \quad (1)$$

$$\Phi_0 = |\phi_{1(\downarrow\uparrow)}\phi_{2(\downarrow\uparrow)}\dots\phi_{k(\downarrow\uparrow)}\phi_{k+1(\downarrow)}\dots\phi_n(\downarrow)| \quad (2)$$

$$\Phi_1 = |\phi_{1(\downarrow\uparrow)}\phi_{2(\downarrow\uparrow)}\dots\phi_{k(\uparrow)}\phi_{k+1(\downarrow)}\dots\phi_n(\downarrow)| \quad (3)$$

Consequently, whereas Ψ^1 is a representation for the first excited state, Φ_1 in eq 3 is only a singly excited determinant among many other possible singly excited determinants and depending on the chemistry involved, it may or may not be of interest. Thus, we emphasize that, within the limitations of the MCSCF methodology, Ψ^n is the correct representation of the n th excited state but excited configurations Φ_n are substituted determinants. Each one of these substituted determinants can hardly describe an excited state correctly, and it is more likely that an excited state in reality requires more than one determinant. Saebo and Pulay⁵⁴ noted the pedagogically misleading use of the term *excitation*. Hence, substitutions giving Φ_n usually do not correspond to real states alone, and we prefer to term them as *mathematical excitations*. Therefore, simple HOMO→LUMO-type descriptions of excited states valid in the case of most fluorophore cores including the BODIPY core (despite their common usage) are not universally correct. Moreover, situations where this simple description is inadequate are significant from an electronic structure viewpoint alone. S_1 states of **2** and **3** possess such unusual character and should be described with multiple configurations even for a qualitatively correct treatment.⁵⁵

The DS-TR natures of **2** and **3** are repeatedly observed at CASSCF levels employing varying numbers of active electrons and orbitals and with different basis sets, suggesting DS-TR to emerge as a qualitative and simple descriptor for S_1 states of the dimers. Facile 1O_2 production by **2** and **3** despite the absence of high nuclear charge atoms suggest that ISC is invoked via a specific electronic structure pattern as the general view⁵ of 1O_2 generation includes an effective hop of the photosensitizer to the triplet surface. We attribute ISC-promoted 1O_2 production by **2** and **3** to the DS-TR nature of S_1 states, as doubly substituted singlets are reported to better couple with triplets.^{56,57} Similarly, charge separation, yielding facile access of excited dyads to the triplet manifold, implies the significance of zwitterionic (charge separated) excited states in ISC dynamics.⁹

Effect of Orthogonality on the S_1 State. Structural orthogonality of chromophore planes is argued to be the key, in accessing DS-TR S_1 states, in the above view. This was further verified by the following computational experiment regarding the effect of relative orientation of the two chromophore cores on excitation characteristics. Selecting the interplane angle as the transformation coordinate as shown in Figure 5, and fixing all the remaining internal coordinates at their equilibrium values, CASSCF wave functions of the S_1 state were optimized for the corresponding conformations. Compound **1** instead of tetramethyl BODIPY was used in this analysis, as the methyl groups in the latter introduce huge steric effects even at small deviations from orthogonality. The one-electron density matrix for the S_1 states of corresponding conformations (Table S7, Supporting Information) revealed that the DS-TR nature of S_1 does not survive at small interplane angles and the classical HOMO→LUMO-type SS excited state is generated at near

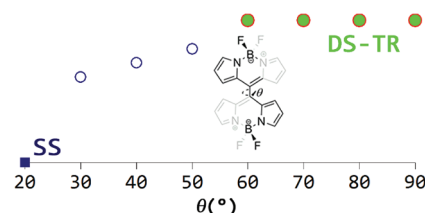


Figure 5. Effect of interplane angle (θ) variation on $S_0 \rightarrow S_1$ excitation characteristics (DS-TR/SS). Numerical values of SS, DS-TR, and the intermediates between 30° to 50° scale with NOONs as given in Table S7, Supporting Information. SS corresponds to zero and DS-TR to unity on the y-axis.

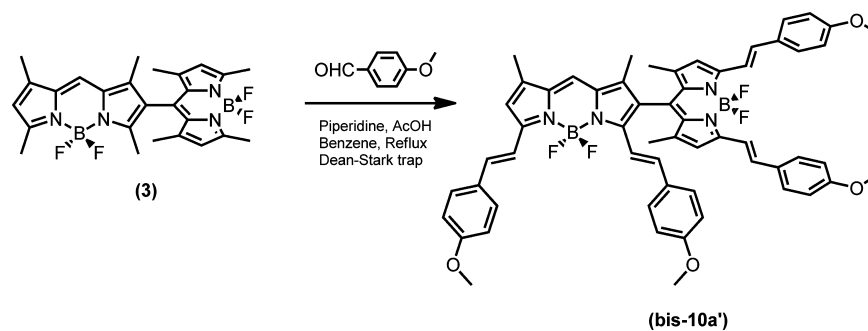
planarity, where the π -systems start to mix significantly. Hence, spatial orthogonality of the two monomers is central to generating a DS-TR S_1 state.

Synthesis and Spectroscopic Properties of an Extended Conjugation Bis-BODIPY Derivative. The above results were motivating, particularly for utilizing many chromophores in heavy atom free ISC by only dimerizing them in an orthogonal fashion. Consequently, we aimed to surpass the accomplishments of **2** and **3** by synthesizing modified orthogonal bis-BODIPYs that will operate at the red end of the spectrum and, hence, potentially be better suited for photodynamic applications. The well-known modification to red shift λ_{abs} , i.e., decrease the energy gap between frontier orbitals is, extending^{16,17} the π -system of the chromophore core. For this purpose, synthesis of bis-8,2'-distyrylBODIPY derivative shown in Scheme 2 was performed.

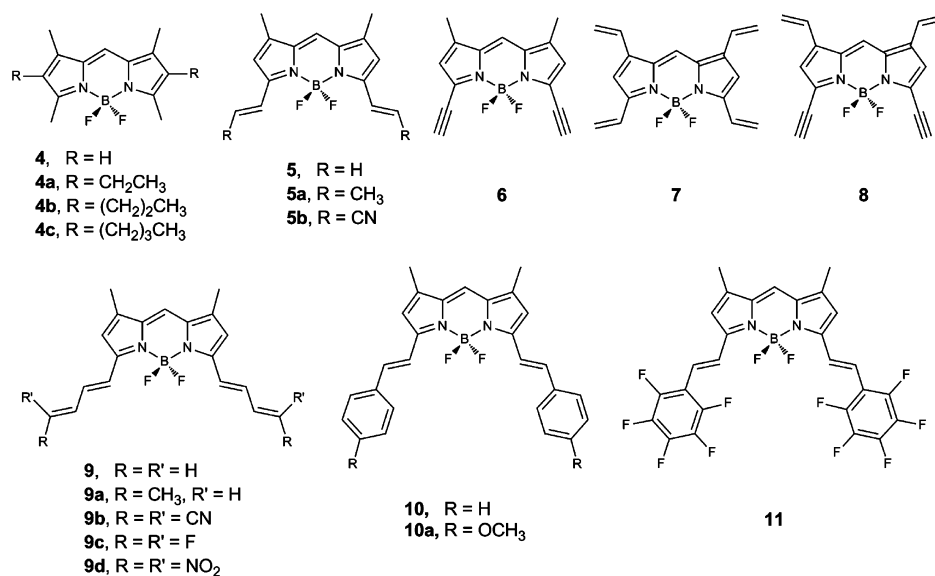
Spectroscopic properties of **bis-10a'** (Figures S5 and S7, Table S15, Supporting Information) was investigated, and an emission at 680 nm together with a negligible triplet quantum yield were surprisingly observed, contrary to the expectations followed from the computed structural orthogonality (interplane angle = 90.1°). 1O_2 phosphorescence measurements (Table S15, Supporting Information) around 1270 nm also confirmed that this red-absorbing dye essentially did not undergo the presumed ISC to the triplet manifold. These results either suggest that excitation characteristics established for **2** and **3** by the CASSCF calculations are not complete descriptors for ISC or orthogonality alone does not afford the excited states bearing the features of interest. The former seems questionable in light of the reports on facile nonadiabatic reactions of related singlet states.^{56,58–61} The latter hypothesis, on additional requirements to generate DS-TR S_1 states besides orthogonality, was tested via CASSCF calculations on the S_1 state of **bis-10a'**.

Interestingly, the S_1 CASSCF wave function for **bis-10a'** was of SS nature and clearly described a HOMO→LUMO-type excitation. The same type of excitation characteristics were obtained for the 8,8' analogue of **bis-10a'** (vide infra). Spectroscopic measurements on **bis-10a'** lend support to the safe use of DS-TR S_1 states in assessing ISC performance, since our multireference calculations clearly show the SS nature of the S_1 state. From a different viewpoint, however, the SS open-shell singlet electronic structure of **bis-10a'** challenges the link between orthogonality and DS-TR S_1 . This may suggest the existence of other requirements for a DS-TR S_1 state; however, there may also be a very specific feature for **bis-10a'** only. To better understand this complex issue, we analyzed low-lying electronic states of numerous bis-BODIPYs.

Scheme 2



Scheme 3



Electronic Structure Calculations on Substituted 8,8'- and 8,2'-Bis-BODIPYs. Since the disappearance of DS-TR character was apparently a result of extending the π framework, it is desirable to analyze the effect of increasing the size of the π -system with a smooth transition from **2** or **3** to **bis-10a'**. This will enable us to monitor the cause of the drastic change in excitation characteristics from DS-TR (**bis-4** and **bis-4'**) to SS (**bis-10a'**). Therefore, we first generated computational models where BODIPYs bear only ethenyl/ethynyl substituents on various positions of the core. Further extension of the π -system was performed until SS- S_1 character persisted in the dimers. Also important was searching for any correlations between the characteristics of S_1 states of the bis-BODIPYs and the monomer electronic structure. Consequently, the set of monomers given in Scheme 3 and their 8,8' and/or 8,2' orthogonal dimers were studied.

Extending the conjugated π -systems of the monomers yielded four major sets of BODIPYs possessing the following substituents neighboring the core; none (**4**); ethenyl and/or ethynyl (**5** to **8**); butadienyl (**9**); and styryl (**10**, **11**). All these models preserved an essentially planar geometry within the monomer, and their dimers were computed to be spatially orthogonal. Table 1 shows frontier orbital energies of ground states of all the monomers and dimers as well as the relative energies of S_1 and T_1 states of the orthogonal dimers. Excitation characteristics of the S_1 state (DS-TR or SS) of bis-BODIPYs are also shown.

It is clear from the frontier orbital energy differences that, orthogonality dictates formation of two pairs of near-degenerate orbitals in the dimer that effectively preserve monomeric character, as supported by orbital isodensity plots. (Figure S1, Supporting Information). Extension of the π -system lowered the HOMO–LUMO gaps as anticipated, and interestingly, beyond the very first double bond added to the chromophore core; i.e., for set (**9** to **11**), the DS-TR character of S_1 state disappears. In such cases, S_1 MOs were no longer delocalized on both chromophore cores (Figure S2, Supporting Information), which is also the case for **bis-10a'**. The lowering of the HOMO–LUMO gap and disappearance of DS-TR character of S_1 do correlate; however, it is illusory to conclude that DS-TR fades with decreased HOMO–LUMO gaps since the energy gap decrease itself is caused by a structural perturbation that extends the π -system. Thus, the fundamental reason of switching from DS-TR to SS type S_1 states needs further investigation (*vide infra*). Inspection of the relative energetic positioning of T_1 and S_1 states does not provide an answer since T_1 is roughly equally separated from S_0 and S_1 states for all species and there is no significant pattern in favor of the DS-TR- S_1 or SS- S_1 possessing species. Incorporation of functional groups in order to donate or withdraw electron density as in the series of species **5**, **9**, **10**, and **11** do result in deviations (from core BODIPY) in the anticipated directions for frontier MO levels but do not switch the excitation characteristics of S_1 . Extension of the π -system shutting down

Table 1. Selected Parameters for Modified BODIPY Cores and Associated Orthogonal Bis-BODIPYs

species ^a	monomer				dimer								
	E_H (eV)	E_L (eV)	ΔE_{H-L} (eV)	ΔE_{H-L} (nm)	E_{H-1} (eV)	E_H (eV)	E_L (eV)	E_{L+1} (eV)	$\Delta E_{L-(H-1)}$ (eV)	$\Delta E_{(L+1)-H}$ (eV)	S_1^b	$E(T_1)^c$ (eV)	$E(S_1)^c$ (eV)
4	-5.69	-2.78	2.91	426	-6.01	-5.92	-3.04	-3.04	2.97	2.88	DS-TR	1.79	3.69
4'					-6.04	-5.69	-3.11	-2.76	2.93	2.93	DS-TR	2.35	4.16
4a	-5.47	-2.60	2.87	432	-5.71	-5.62	-2.84	-2.81	2.87	2.81	DS-TR	2.28	3.90
4b	-5.46	-2.60	2.86	433	-5.70	-5.60	-2.82	-2.80	2.88	2.80	DS-TR	1.69	3.45
4c	-5.45	-2.59	2.86	433	-5.67	-5.58	-2.81	-2.77	2.86	2.81	DS-TR	1.69	3.44
5	-5.51	-3.03	2.48	499	-5.82	-5.75	-3.39	-3.23	2.44	2.52	DS-TR	1.62	3.77
5'					-5.84	-5.52	-3.33	-3.02	2.51	2.50	DS-TR	2.14	3.81
5a	-5.22	-2.78	2.43	509	-5.46	-5.39	-3.07	-2.91	2.39	2.48	DS-TR	1.62	3.33
5a'					-5.46	-5.21	-3.01	-2.75	2.45	2.46	DS-TR	1.69	3.33
5b	-6.30	-3.97	2.33	532	-6.85	-6.79	-4.49	-4.34	2.36	2.45	DS-TR	1.57	3.68
5b'					-6.81	-6.50	-4.44	-4.16	2.36	2.34	DS-TR	1.83	3.51
6	-5.86	-3.31	2.55	487	-6.39	-6.33	-3.79	-3.62	2.60	2.72	DS-TR	1.66	3.43
6'					-6.44	-5.84	-3.76	-3.29	2.68	2.55	DS-TR	1.71	3.41
7	-5.65	-3.30	2.35	527	-6.02	-5.87	-3.53	-3.46	2.49	2.41	DS-TR	1.34	2.71
7'					-5.90	-5.62	-3.56	-3.30	2.34	2.33	DS-TR	1.58	3.18
8	-5.95	-3.55	2.40	517	-6.42	-6.31	-3.89	-3.82	2.53	2.49	DS-TR	1.22	2.87
8'					-6.25	-5.88	-3.86	-3.51	2.38	2.37	DS-TR	1.63	3.30
9	-5.19	-3.03	2.16	574	-5.40	-5.35	-3.24	-3.24	2.16	2.10	SS	1.51	3.48
9'					-5.39	-5.20	-3.23	-3.02	2.16	2.17	SS	1.60	3.18
9a	-4.95	-2.83	2.12	584	-5.10	-5.05	-2.99	-2.98	2.12	2.07	SS	1.46	3.17
9a'					-5.09	-4.93	-2.98	-2.79	2.11	2.14	SS	1.60	3.17
9b	-6.44	-4.49	1.95	636	-6.92	-6.87	-4.83	-4.83	2.09	2.05	SS	1.47	3.18
9b'					-6.90	-6.54	-4.90	-4.57	1.99	1.96	SS	1.50	3.06
9c	-5.59	-3.42	2.17	570	-5.93	-5.86	-3.74	-3.72	2.19	2.14	SS	1.50	3.37
9c'					-5.91	-5.65	-3.72	-3.46	2.19	2.19	SS	1.59	3.20
9d	-6.91	-5.03	1.88	659	-7.60	-7.47	-5.67	-5.40	1.93	2.07	SS	1.38	3.19
9d'					-7.45	-7.05	-5.50	-5.14	1.95	1.91	SS	1.51	3.10
10	-5.09	-2.97	2.12	584	-5.28	-5.23	-3.16	-3.14	2.12	2.09	SS	1.54	3.26
10'					-5.25	-5.09	-3.13	-2.95	2.12	2.15	SS	1.61	3.17
10a	-4.84	-2.78	2.05	604	-4.91	-4.85	-2.92	-2.88	1.99	1.97	SS	1.55	2.76
10a'					-4.92	-4.82	-2.89	-2.75	2.04	2.08	SS	1.59	3.14
11	-5.98	-3.81	2.18	570	-6.30	-6.25	-4.12	-4.10	2.17	2.15	SS	1.53	2.56
11'					-6.35	-6.09	-4.16	-3.90	2.19	2.19	SS	1.54	2.52

^aPrime (') indicates 8,2' coupling motif of the monomers, and absence of the prime (') shows 8,8' binding. ^bDS-TR: Doubly substituted tetradical. SS: Singly substituted HOMO→LUMO-type open-shell singlet state. ^cRelative energies of T₁ and S₁ states with respect to the ground state S₀ of the dimer at the CAS(6,6) level. See Table S11 (Supporting Information) for MP2 corrections on selected species at S₀, S₁, and S₂ states.

the DS-TR S₁ state seems to be one net conclusion that could be drawn, despite the survival of near-degenerate monomer-based orbitals for all the dimers considered. Nonetheless, from the four sets of models with increasing sizes of conjugated π -systems, the only groups with a DS-TR S₁ state were (4 and 5 to 8), whose π -system extension is truncated at the very first C=C double bond. Apparently, one is only allowed to slightly modify S₀–S₁ energy difference without losing the DS-type excitation motif, and unfortunately, this does not result in the desired amount of HOMO–LUMO gap lowering.

It is important to note that relative energies with the CASSCF method may not be quantitatively reliable and perturbation treatments on the CASSCF wave function are necessary for energy differences of satisfactory quality. Unfortunately, MP2 corrections to this size of molecules is unfeasible and the scope of the current work is identifying the key electronic structure details of the orthogonal dimers that apparently undergo ISC, not a quantitatively accurate prediction of relative energies. Such a high level treatment may be available in the future, yet we were able to complete CAS-MP2 calculations for **bis-4** and **bis-4'** which are the

species of utmost interest. CAS-MP2 calculations (Table S11, Supporting Information) also suggest that the DS-TR states are above the closed shell S₀ at 2.60 and 2.85 eV and the next singlet state is at 4.58 and 4.68 eV for **bis-4** and **bis-4'**, respectively. Although CAS-MP2 treatment decreases the relative spacing between higher excited states with respect to CASSCF, the DS-TR S₁ state is still well separated from S₀ and S₂. Thus, there is little doubt that DS-TR character is the correct nature of the first excited singlet state. The issue with quantitative reliability may be even more critical depending on the system of interest as nicely demonstrated by the recent work of Martinez et al.⁶² Fortunately, our experiments show that probing for DS-TR or SS character in the S₁ state is successfully working for the systems under investigation in assessment of ISC performance.

Our TD-DFT calculations suggest that **8**, the species bearing the lowest HOMO–LUMO gap with a DS-TR S₁ for the dimer, may have an absorption maximum close to but lower than 600 nm (Table S6, Supporting Information) when our estimated errors for TD-DFT are considered. Thus, it is

questionable that π -extension would carry the features of bis-BODIPYs, desired for effective ISC, to longer wavelengths.

Effect of π -Extension on DS-TR Character of S_1 . The rationale of attributing the disappearance of DS-TR character to extension of the π -system was further tested by the following computational experiment performed on **bis-9'** and **bis-10'**. When the extension of π -conjugation is thought to be responsible for switching to SS from DS-TR, the DS-TR character of S_1 in the dimer should reappear if the π -electron density supplied by the substituents, does not communicate with the core. Freezing the core coordinates in the optimized structure, we rotated the outermost π -system, i.e., last ethenyl unit for **bis-9'** and the phenyl for **bis-10'**, with respect to the core plane as shown in Figure 6 and optimized the wave

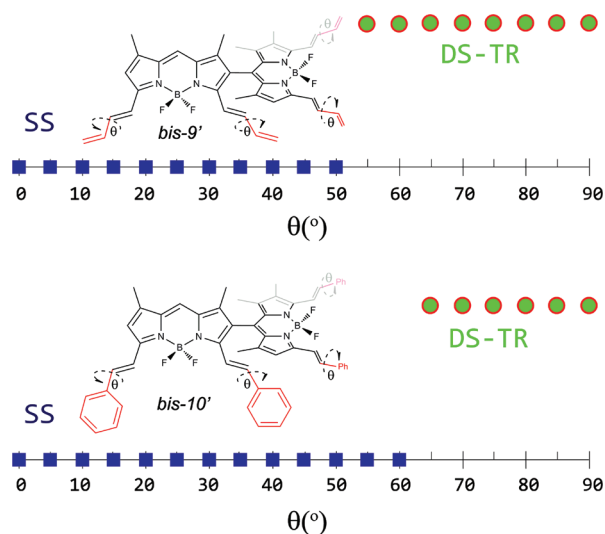


Figure 6. Relation of DS-TR character of S_1 to the extent of π conjugation in butadienyl- and styryl-substituted BODIPY dimers **bis-9'** and **bis-10'**. Numerical values for SS and DS-TR, scale with NOONs as given in Tables S8 and S9, Supporting Information. SS corresponds to zero and DS-TR to unity on y -axis.

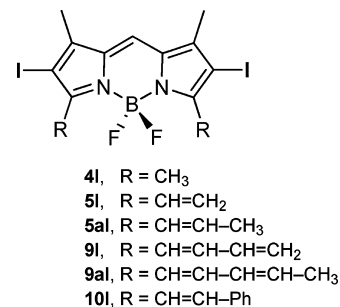
function of the S_1 state for the conformations generated accordingly. Since planarity is necessary for the conjugation of the π -system, any property caused by the extended conjugation should be affected by increasing angle θ .

In line with the expectations, we observe that DS-TR is regenerated at large angles where the π -delocalization between the rotated units and the rest of the chromophore ceases. NOONs for the conformations tested above are close to 2, 1, or 0 at all times in line with SS or DS-TR nature of S_1 (Tables S8 and S9, Supporting Information). These findings suggest that π -extended bis-chromophores should not possess the target electronic structure motif with structural orthogonality alone. This failure encourages searching alternative strategies for tuning frontier MO energies; however, before moving further, we have to search for any insights provided from the analysis of electronic structure of excited singlet states in related heavy atom incorporated systems, that are well-known for facilitated ISC.

Electronic Structure Calculations on 2,6-Diodinated 8,8'- and 8,2'-Bis-BODIPYs. 1O_2 generation capabilities of 2,6-halo-substituted BODIPYs with various ligands are substantial, and many examples are already available in the literature.^{8,63} Their ISC performance is caused by relatively high

nuclear charge atoms such as Br and I.^{8,64,65} Aimed for elucidating any possible connection among electronic structure patterns observed for orthogonal heavy atom free bis-BODIPYs and heavy atom incorporated BODIPYs, the set of 2,6-diiodo monomers given in Scheme 4 and their 8,8' orthogonal dimers

Scheme 4



were studied. The results summarized in Table 2 suggest that the excitation characteristics and electronic structure of S_1 states of the selected species are analogous to their heavy atom free counterparts.

Similar to noniodo species, retention of monomer frontier MO levels are observed with the anticipated deviations due to substituents. The critical observation is obtaining same class of S_1 states with (Table 2) and without (Table 1) iodine incorporation. While S_1 states of **bis-4**, **bis-4I**, **bis-5**, **bis-5I**, **bis-5a**, and **bis-5aI** have DS-TR characters, those of **bis-9**, **bis-9I**, **bis-9a**, **bis-9aI**, **bis-10**, and **bis-10I** bear the SS motif. This evidence suggests that the dynamics of ISC yielding effective 1O_2 generation via utilizing orthogonality in bis-BODIPYs is different than that by BODIPYs with heavy atoms. Therefore, orthogonal bis-chromophores may constitute a promising class of photosensitizers, for heavy atom free ISC. Nonetheless, the underlying factors causing the disappearance of DS-TR singlet state in spite of the survival of near degenerate orbitals need to be resolved.

DS-TR SS Switching. In questioning the rationale of DS-TR to SS switching as a result of π -extension, we compared the electron density distribution of frontier MOs of bis-BODIPYs from both S_1 classes. In the SS cases, contrary to the delocalized SOMOs of DS-TR states, MOs were clearly concentrated on a single monomer (Figure S2, Supporting Information), which implied negligible coupling among monomer cores. This suggests that, the so-called antiferromagnetic coupling of electrons among SOMOs weakens with increased size of the π -framework in a SOMO. Such a view well agrees with the foundations of electron correlation, which is more of a local effect.^{54,66} Equivalently, the superexchange path is lost when electrons are more and more spread out in space. This difficulty encountered (for relatively largely separated electron densities) in obtaining a significant amount of quantum mechanical exchange energy is apparently manifested in a relative destabilization of the DS-TR with respect to the SS state.

Although this emergent electronic structure viewpoint was previously unnoted, Wiederrecht et al.¹¹ mentioned the role of exchange in ISC performance in donor–acceptor dyads, and Harriman, Ziesel, and co-workers^{9,12} emphasized the importance of close spacing of dyads on ISC performance. We surmise the locality of electron correlation (or the ineffectiveness of superexchange for electrons at large separation) to be a valid explanation for switching from DS-TR to SS states, which

Table 2. Selected Parameters for 2,6-Diiodo-BODIPY Monomers and Associated Orthogonal Dimers

species	monomer				dimer							
	E_H (eV)	E_L (eV)	ΔE_{H-L} (eV)	ΔE_{H-L} (nm)	E_{H-1} (eV)	E_H (eV)	E_L (eV)	E_{L+1} (eV)	$\Delta E_{L-(H-1)}$ (eV)	$\Delta E_{(L+1)-H}$ (eV)	S_1^a	
4I	-5.99	-3.15	2.84	437	-6.31	-6.23	-3.51	-3.49	2.80	2.73	DS-TR	
5I	-5.81	-3.38	2.43	510	-6.10	-6.03	-3.72	-3.53	2.37	2.50	DS-TR	
5aI	-5.53	-3.12	2.41	514	-5.22	-5.70	-3.41	-3.34	2.36	2.36	DS-TR	
9I	-5.42	-3.32	2.10	589	-5.59	-5.53	-3.55	-3.48	2.04	2.06	SS	
9aI	-5.18	-3.12	2.07	599	-5.36	-5.30	-3.33	-3.25	2.04	2.05	SS	
10I	-5.33	-3.23	2.10	592	-5.62	-5.56	-3.50	-3.42	2.12	2.15	SS	

^aDS-TR: Doubly substituted tetradical. SS: Singly substituted HOMO→LUMO type open shell singlet state.

points out survival of a DS-TR singlet state despite a destabilization penalty. Such a destabilization will scale with the phenomenological exchange sum:

$$\langle \text{HOMO-1}_\alpha, \text{LUMO}_\alpha | \text{LUMO}_\alpha, \text{HOMO-1}_\alpha \rangle \\ + \langle \text{HOMO}_\beta, \text{LUMO+1}_\beta | \text{LUMO+1}_\beta, \text{HOMO}_\beta \rangle$$

The above sum accounts for the major contribution via exchange of same spin electrons in the four SOMOs in a DS-TR singlet. Note that it is only a rough representation and does not explicitly deal with multiple occupation patterns in the multiconfigurational expansion. This approach was motivating in investigating DS-TR singlets lying higher than S_1 for π -extended bis-BODIPYs, and we were successful in locating DS-TR singlet states for **bis-9**, **bis-9'**, **bis-10**, **bis-10'**, **bis-10a**, and **bis-10a'** as S_2 or S_3 (Table S10, Supporting Information). Severe convergence problems in the computation of the highly excited states were encountered, and the quantitative reliability of relative energies may be questionable; however, a useful trend of qualitative nature is noteworthy. It is clear that whenever the S_1 state is not computed to be DS-TR as a result of the π -electron increasing structural perturbation that does not allow a superexchange path for vastly spread out SOMO electrons, an S_n ($n > 1$) state with DS-TR character exists. Thus, instead of envisioning DS-TR singlet states to disappear with extending the conjugation, we should better term this phenomenon as destabilizing the DS-TR singlet state as a result of decreasing quantum mechanical exchange stabilization for largely spread out spin-orbitals.⁶⁷ Additional support for the critical role of DS-TR S_1 state is provided via the computed spin-orbit coupling constants.

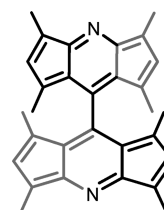
For **bis-4**, **bis-5**, **bis-9**, and **bis-10** (Table S5, Supporting Information) SOCCs dramatically increased for (DS-TR) S_1 - T_1 coupling with respect to monomer (**4** and **5**) S_1 - T_1 SOCCs. On the other hand, (SS) S_1 - T_1 coupling is essentially same as that of monomer (**9** and **10**) S_1 - T_1 . Despite their high system dependence and presence of numerous approximations in the underlying algorithms, computed SOCCs highlight the successful conceptual use of specific electronic structure motifs in estimating ISC possibilities. Chief contributions to such an understanding have been achieved, especially by the work of Shaik.^{59,68} A recent work by Dede et al. highlighting the decisive nature of electronic structure match/mismatch in ISC is noteworthy.⁶⁹ Rigorous treatment of the foundations of singlet \leftrightarrow triplet conversions and numerous examples are available.^{57,61,70} Likewise, the specific electronic structure motif of DS-TR in S_1 states may be used as an electronic structure descriptor to realize $S_1 \rightarrow T_1$ ISC for orthogonal bis-chromophores. Alternatively, the ISC dynamics could be studied with more rigorous approaches that include the nuclear motion in a nonadiabatic hop⁷¹⁻⁷⁴ in order to obtain a more

complete picture. Such a dynamics treatment will be particularly useful as excitation and subsequent deactivation is most likely not comprised of a single path that one specifically probes. A multitude of channels are presumably available for an excited system after a fast Franck-Condon transition. As such, excitation phenomena can realistically be studied with quantum chemical methods that treat multiple states in a time-resolved fashion.^{71,73,75-77} Thus, the results we present do not provide the full details of the excitation and deactivation processes and there is room for refinement. Nevertheless, we were able to provide a working framework, which we experimentally tested, for realizing ISC possibility in bis-BODIPYs.⁷⁸ The conceptual and qualitative nature of DS-TR descriptor is remarkable, and the computational protocol employed can easily be carried, also by a nonspecialist; hence, the concept will be broadly useful.⁷⁹ However, the transferability of the concepts developed above, to other systems of parallel use, is important and was further investigated.

Fine Tuning of S_1 States. We have shown the details of the electronic structures of various bis-BODIPYs and suggested that foundational reasons render the key principle of orthogonality in heavy atom free bis-chromophores nonoperational, in invoking ISC, once π -systems are extended. This sounds disappointing at first; however, it also sheds light on alternative paths for facilitated ISC at longer wavelengths, still heavy atom free. We believe that, starting with modifications on the BODIPY core, new classes of compounds with both decreased HOMO-LUMO gaps and efficient ISC properties could be obtained.⁸⁰ Noting the recent attention on aza-BODIPYs^{64,81,82} and realizing BODIPY as a modified indacene, low-lying electronic states of orthogonal bis-aza-*s*-indacenes, represented in Scheme 5, were studied, and the results are given in Table 3.

The aza-*s*-indacenes **12** and **14**, where the rings are fused through the C8-C8 and N-N bonds, respectively, possess a DS-TR S_1 state. Binding two formally +1 nitrogen atoms would render the synthesis of dication **14** prohibitively difficult, and **13** is an overall +1 system with an SS S_1 state. These findings suggest that DS-TR character is not limited to S_1 states of bis-

Scheme 5



12

Table 3. Orbital Energies Photophysical properties and Nature of S₁ State for Bis-aza-*s*-indacenes^a

species	coupling motif	E _{H-1} (eV)	E _H (eV)	E _L (eV)	E _{L+1} (eV)	ΔE _{L(H-1)} (eV)	ΔE _{(L+1)H} (eV)	S ₁	T ₁ (eV)	S ₁ (eV)	λ (nm)	f
12	8,8'	-5.20	-5.13	-3.12	-3.07	2.08	2.06	DS-TR	0.70	1.35	575	0.272
13	8,N'	-8.17	-7.99	-6.92	-5.97	1.24	2.02	SS	0.66	2.02	588–662	0.241–179
14	N,N'	-11.67	-11.62	-9.86	-9.85	1.82	1.76	DS-TR	0.37	0.74	691	0.145

^aGeometry optimized at UB3LYP/CEP-31G. λ_{ab} values in chloroform. Values of oscillator strength (*f*) below 0.1 are neglected. λ_{ab} and oscillator strength of compounds 12–14 at the TD-B3LYP/CEP-31G level using PCM with chloroform as the solvent.

BODIPYs and may be broadly useful.⁸³ Moreover, synthetic details to obtain stable 1,3,5,7-tetra-*tert*-butyl-4-(aza- and phospho-)-*s*-indacenes^{84–87} were reported⁸⁵ where the absorption compared to the BODIPY core is ca. 75 nm red-shifted. Thus, via comprehending the key features of the monomer chromophore cores that dictate the formation of DS-TR S₁ states in the orthogonal dimer, fine-tuning of S₁ states that will both retain DS configurations and afford lower HOMO–LUMO gaps looks attainable. We emphasize that synthetic limitations may render the search impractical but these results are a clear demonstration of existence of fruitful research directions that could be achieved by modifications in the chromophore cores. Attempts to design and synthesize dimeric π-systems that may act as potential photosensitizers with improved properties is under way in our laboratories.

CONCLUSION

We performed detailed multireference quantum chemical analyses on several electronic states of orthogonal bis-BODIPYs. Essentially isolated monomeric states in the dimers dictated formation of a pair of (near) degenerate S₀ frontier orbitals, which yielded four SOMOs in the S₁ state. Domination of S₁ wave function by doubly substituted configurations was utilized as an electronic structure descriptor in assessing ISC efficiency. Formation of DS-TR S₁ states was not only tied to orthogonality but also to a certain degree of truncation in the π-framework of the substituents. Bis-BODIPYs with extended π-systems possess destabilized DS-TR states, as exchange coupling among unpaired electrons of same spin is significant only at small distances. An increase in S₁–T₁ SOCC from monomer to dimer correlates with presence of the DS-TR motif in S₁ state of dimer. Comparisons with iodine-incorporated bis-BODIPYs revealed that facile ¹O₂ production by orthogonal bis-BODIPYs without heavy atoms is via the specific electronic structure fingerprint, DS configurations, that are closely related to zwitterionic configurations which are well-known to effectively couple with triplets. Spectroscopic properties of a newly synthesized near-IR absorbing bis-BODIPY are in excellent agreement with the results of CASSCF calculations. Shifting the absorption wavelength to the red region is achieved with π-extension of bis-BODIPYs; however, ISC properties are adversely affected for such dimers. Modifications in the chromophore cores are likely to be a more promising research direction. We conclude that DS-TR is a valuable descriptor in assessing the ISC performance of S₁ states for heavy-atom-free bis-chromophores. Calculated DS-TR motif present in the S₁ wave function correlates with, if not explains, the ability of the orthogonal bis-BODIPY systems to photosensitize ¹O₂. Quantitatively more reliable quantum chemical/dynamical calculations can provide more insight into the behavior of the excited states. Principles to design DS-TR S₁ states in other bis-chromophores are yet to be established.

EXPERIMENTAL SECTION

Synthesis of Bis-8,2'-distyryl-BODIPY Derivative, bis-10a.

Compound 3 (0.121 mmol, 60.0 mg) and 4-methoxybenzaldehyde (0.728 mmol, 99.2 mg) were added to a 100 mL round-bottomed flask containing 50 mL of benzene, and to this solution were added piperidine (0.6 mL) and acetic acid (0.6 mL). The mixture was heated under reflux using a Dean–Stark trap, and the reaction was monitored by TLC (CHCl₃). When all of the starting material had been consumed, the mixture was cooled to room temperature and solvent was evaporated. Water (100 mL) was added to the residue, and the product was extracted into the chloroform (3 × 100 mL). The organic phase dried over Na₂SO₄ and evaporated, and the residue was purified by silica gel column chromatography using CHCl₃ as the eluent. Product was separated as a blue solid in 30% yield (35 mg, 0.0363 mmol). ¹H NMR (400 MHz, CDCl₃): δ_H 7.68 (3H, d, *J* = 18.8 Hz), 7.65–7.55 (m, 8H), 7.40 (d, 2H, *J* = 8.9 Hz), 7.35 (d, 1H, *J* = 15.2 Hz), 7.22 (d, 2H, *J* = 15.2 Hz), 7.10 (s, 1H), 7.02–6.93 (m, 6H), 6.86–6.77 (m, 3H), 6.66 (s, 2H), 3.95–3.85 (9H, m), 3.80 (3H, s), 2.37 (s, 3H), 2.16 (s, 3H), 1.85 (s, 6H). ¹³C NMR (100 MHz, CDCl₃): δ_C 160.4, 153.0, 141.5, 141.3, 138.0, 137.2, 136.5, 136.1, 129.6, 129.5, 129.4, 129.3, 129.2, 129.1, 117.6, 117.3, 116.9, 116.5, 116.2, 114.5, 114.3, 114.2, 55.4, 55.3, 14.2, 11.5, 9.6 ppm. MS HRMS (TOF-ESI): *m/z* calcd for C₅₈H₅₃B₂F₄N₄O₄⁺ 967.41891 [M + H]⁺, found 967.41898 [M + H]⁺, Δ = 0.1 ppm. Extinction coefficient (ε): 125300 cm⁻¹ mol⁻¹ L in CHCl₃.

ASSOCIATED CONTENT

Supporting Information

Additional computational and experimental data, absolute energies, Cartesian coordinates, and complete ref 45. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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