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Benzobisoxazole Cruciforms as Fluorescent Sensors

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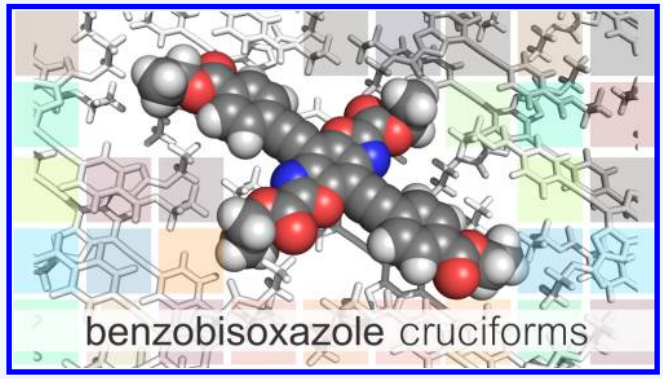
CONSPECTUS: Cross-conjugated molecular cruciforms are intriguing platforms for optoelectronic applications. Their two intersecting π-conjugated arms allow independent modulation of the molecules' HOMO and LUMO levels and guarantee a well-defined optical response to analyte binding. In addition, the rigid cross-conjugated geometries of these molecules allow their organization in two- and three-dimensional space with long-range order, making them convenient precursors for the transition from solution-based to the more practical solid-state- and surface-based devices. Not surprisingly, a number of molecular cruciform classes have been explored because of these appealing properties. These include tetrakis-(arylethynyl)benzenes, tetrastyrylbenzenes, distyrylbis-(arylethynyl)benzenes, tetraalkynylethenes, biphenyl-based "swivel" cruciforms, and benzobisoxazole-based cruciforms.



In this Account, we summarize our group's work on benzobisoxazole molecular cruciforms. The heterocyclic central core of these molecules forces their HOMOs to localize along the vertical bisethynylbenzene axis; the HOMO localization switches to the horizontal benzobisoxazole axis only in cases when that axis bears electron-rich 4-(*N*,*N*-dimethylamino)phenyl substituents and the vertical axis does not. In contrast, the LUMOs are generally delocalized across the entire molecule, and their localization occurs only in cruciforms with donor−acceptor substitution. Such spatially isolated frontier molecular orbitals (FMOs) of the benzobisoxazole cruciforms make their response to protonation very predictable. Benzobisoxazole cruciforms are highly solvatochromic, and their fluorescence quantum yields reach 80% in nonpolar solvents. Solutions of cruciforms in different solvents change emission colors upon addition of carboxylic and boronic acid analytes. These changes are highly sensitive to the analyte structure, and the emission color responses permit qualitative discrimination among structurally closely related species. In self-assembled complexes with boronic acids, benzobisoxazole fluorophores switch their analyte preferences and become responsive to Lewis basic species: phenoxides, amines, ureas, and small organic and inorganic anions. These sensing complexes allow the decoupling of the sensor's two functions: a nonfluorescent boronic acid does the chemistry through the exchange of its labile B−O bonds for other nucleophiles, and it can be optimized for solubility and analyte specificity; the benzobisoxazole fluorophore senses the electronic changes on the boron and reports them to the operator through changes in its emission colors, allowing this sensing element to be kept constant across a broad range of analytes.

We have recently expanded our studies to benzimidazole-based "half-cruciforms", which are L-shaped rigid fluorophores that maintain most of the spatial separation of FMOs observed in benzobisoxazole cruciforms. Unlike benzobisoxazoles, benzimidazoles are acidic on account of their polar N−H bonds, and this feature allows them to respond to a broader range of pH values than their benzobisoxazole counterparts. The deprotonated benzimidazolate anions maintain their fluorescence, which makes them promising candidates for incorporation into solid-state sensing materials known as zeolithic imidazolate frameworks.

INTRODUCTION

Conjugated organic molecules are prominently used as materials for optoelectronic applications[1] since they offer a relatively direct correlation between optical and electronic properties and structure, which can be addressed using a plethora of available synthetic reactions. Even further tunability can be achieved in cross-conjugated molecules, wherein two (or, in principle, more) conjugation currents intersect at a central core. These X-shaped "cruciform" structures offer an opportunity to independently tune the electronic properties of the two arms of the molecule, often through conveniently orthogonal reactivity. When one arm of the cruciform is substituted with electron-donating groups and the other with electron-withdrawing groups, the two frontier molecular orbitals (FMOs) of the molecular cruciforms can be completely separated, such that their highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) are localize along the electron-rich and electron-poor axes, respectively. This spatial isolation of FMOs—recognized first by Bunz[2]—is essential for the use of these systems in sensing, since analyte binding affects the two FMOs to very different extents and invariably leads to changes in the HOMO−LUMO gap and the associated optical properties.

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Several classes of molecular cruciforms have been synthesized and thoroughly examined. These include 1,4-distyryl-2,5-bis(arylethynyl)benzenes,[3] tetrakis(arylethynyl)benzenes,[4] tetrakis(alkynyl)ethenes,[5] tetrastyrylbenzenes,[6] and biphenyl-based "swivel" cruciforms.[7]

In this Account, we summarize the research on the class of cruciform molecules with a heterocyclic benzobisoxazole (BBO) central core. These systems have been studied by our group as well as the group of Nuckolls, who used these molecules as conjugated molecular wires that could be ornamented with solubilizing groups perpendicular to the conjugation circuit,[8] and the group of Jeffries-EL, who focused on the use of BBOs as electron-deficient building blocks for semiconducting polymers.[9] This Account primarily focuses on our work, with several highlights of the research performed by these two other teams.

■ ORBITAL PROPERTIES

Initial computational insight by density functional theory (DFT) at the B3LYP/3-21G level indeed confirmed that the FMOs of the donor−acceptor BBO cruciform **2** (Figure 1, right) are spatially strictly localized: >99% of its HOMO density is positioned along the electron-rich horizontal axis, while the electron-poor vertical axis bears 82% of its LUMO density.[10] The localization of the FMOs is a consequence of both the donor−acceptor substitution and the properties of the [1,2-*d*;4,5-*d*′]-benzobisoxazole parent structure. In the parent benzobisoxazole **1** (Figure 1, left), the LUMO communicates readily with both the horizontal and vertical axes; in the substituted system, the electron-withdrawing pyridines on the vertical axis steer this balance in favor of localizing the LUMO vertically. In contrast, the HOMO−1 orbital of **1** is entirely positioned on the benzobisoxazole, with no density on the triple bonds. While this localization may not be relevant in **1** (whose HOMO is quite delocalized), the substitution of the horizontal axis with electron donors in **2** destabilizes the original HOMO−1, making it the operational HOMO, which is now highly localized.

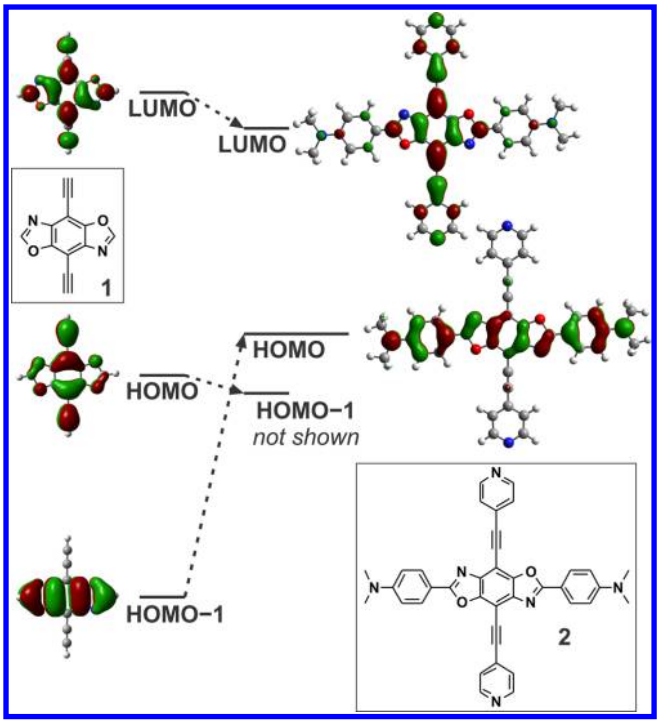

Figure 1. Selected molecular orbitals of the parent bis(ethynyl)-benzobisoxazole **1** and the donor−acceptor-substituted cruciform **2**. The spatial isolation of the FMOs in **2** is a consequence of both the core heterocyclic structure and the donor−acceptor substitution.

What happens in systems which are not donor−acceptor-substituted? We have examined this case both synthetically and computationally by preparing and calculating FMOs for a series of nine BBO cruciforms in which the substitution on both the vertical and horizontal axes was varied pairwise among the electron-rich 4-(*N*,*N*-dimethylamino)phenyl, electron-neutral phenyl, and electron-poor 4-pyridyl groups. As an illustration, the FMOs of the tetraphenyl-substituted parent cruciform **3** are shown in Figure 2. Its HOMO is very similar to the HOMO of the parent molecule **1** in that they both communicate with the vertical axis but not with the horizontal one. In contrast, the LUMO of **3** is spread out over the entire molecule. While in this case the FMOs are not completely separated, the HOMO has significantly more of its density localized along the vertical axis than the LUMO does (and, accordingly, significantly less along the horizontal axis). Analyte binding to either of the two axes should still affect the two FMOs disproportionately. This phenomenon illustrates one important feature of the central BBO core: it can induce spatial separation of the FMOs without the explicit requirement of donor−acceptor substitution.

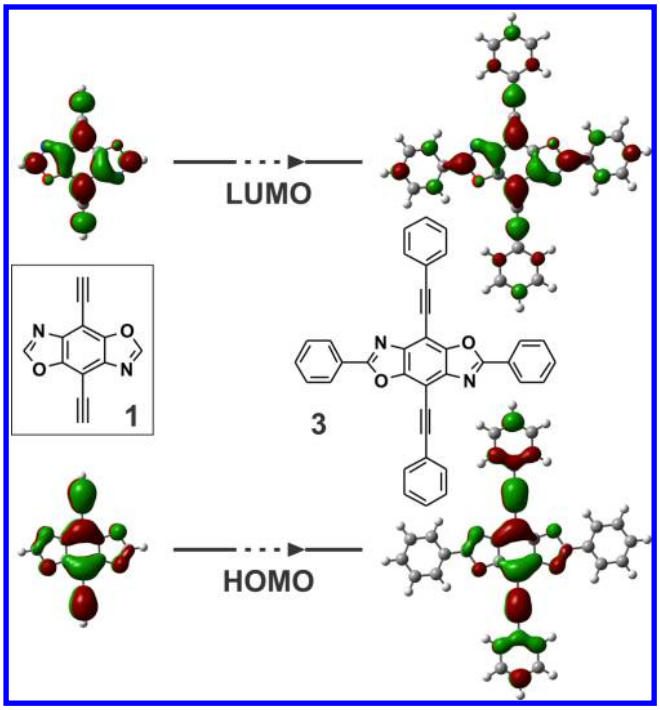

Figure 2. FMOs of the parent bis(ethynyl)benzobisoxazole **1** and the tetraphenyl-substituted BBO cruciform **3**. The HOMO of **3** is still localized, but its LUMO appears more broadly delocalized across the molecule.

Jeffries-EL and co-workers have performed analogous computational studies on aryl- and heteroaryl-substituted BBO cruciforms[11] with the aim of examining their HOMO−LUMO gaps for applications in the area of electronic materials. Using a combination of DFT calculations and ultraviolet photoelectron spectroscopy (which can measure absolute HOMO levels), they have shown that substitution can be

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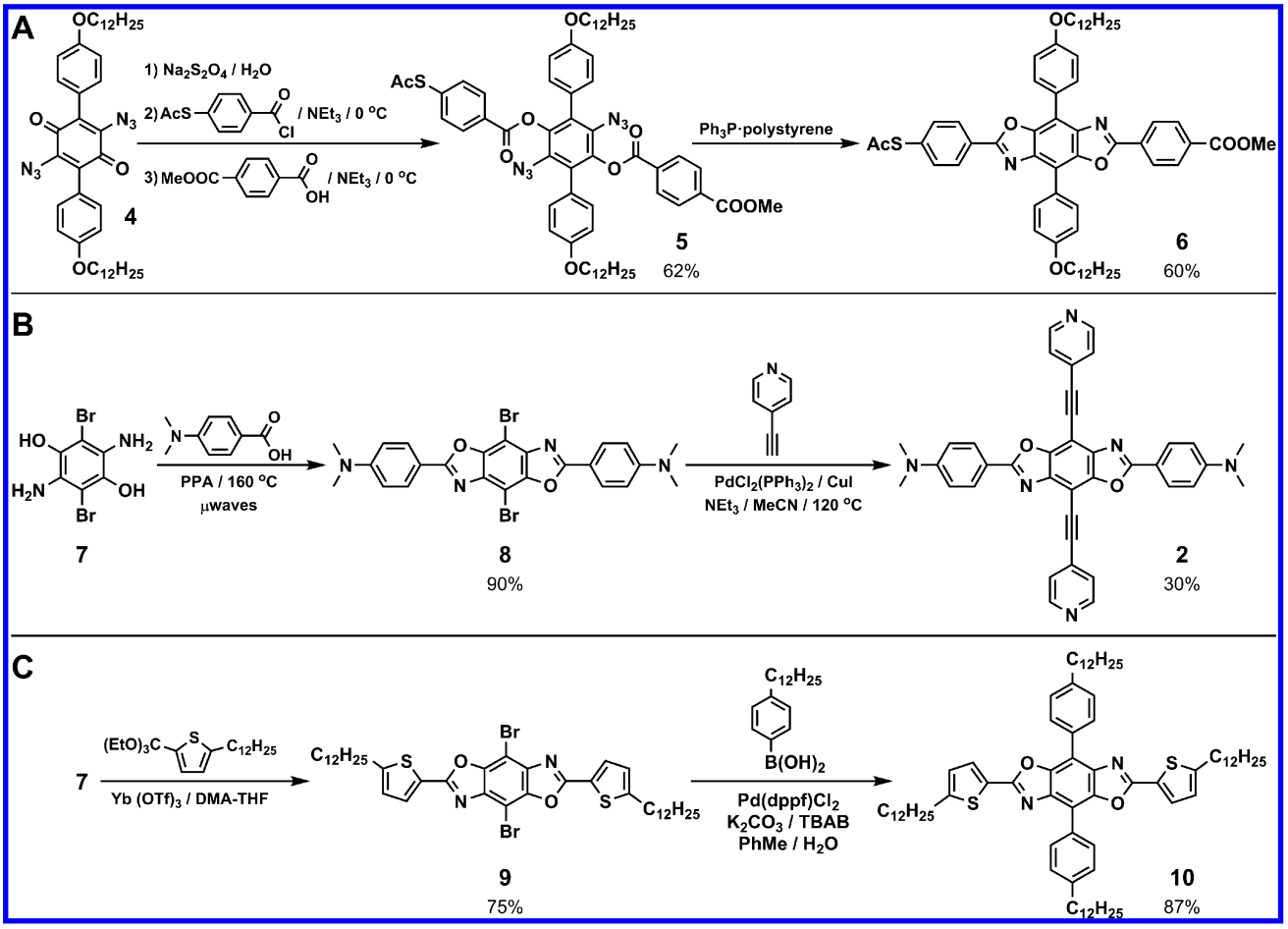
Scheme 1. Synthetic Strategies Used To Access BBO Cruciforms



used to modify the BBO cruciforms' HOMO–LUMO gaps across a 0.5 eV range.

SYNTHESIS OF BENZOBISOXAZOLE CRUCIFORMS

Three general synthetic routes to cross-conjugated BBOs have been developed, allowing the installation of a wide variety of alkyl, aryl, heteroaryl, and arylethynyl groups in each of the four substitution positions available on the BBO nucleus. For clarity, Scheme 1 illustrates each route with just a single example; among them, these three routes have yielded close to 50 different cruciform systems. In 2003, Nuckolls and co-workers developed a versatile synthesis of aryl-substituted BBO cruciforms.[12] Starting with azide-substituted benzoquinone **4** (Scheme 1A, accessible in five steps from 4-bromophenol), reduction with $Na_2S_2O_4$ and subsequent acylation produced diester **5**. By judicious choice of the reaction conditions, differentially substituted esters could be prepared, which was essential for the subsequent attachment of these cruciforms to surfaces. Final Staudinger cyclization produced cruciform **6**. This route was mild enough to allow incorporation of fragile functionalities such as acetate-protected thiols into BBO cruciforms. Our procedure for the preparation of donor–acceptor-substituted BBO cruciforms (Scheme 1B) started from 2,5-diamino-3,6-dibromobenzene-1,4-diol (**7**).[13] The horizontal axis of the cruciforms was installed using microwave-assisted acyl condensation with the parent carboxylic acids in the presence of polyphosphoric acid (PPA).[10] Subsequent Sonogashira coupling was performed on **8** to introduce the vertical axis in the final cruciform **2**. While this protocol used harsher conditions than the one described by Nuckolls, the installed functional groups were not overly sensitive, and all of the reactions yielded the desired cruciform products. For other BBO cruciforms, the yields of the final Sonogashira coupling varied widely (9–96%). Occasional low yields could be attributed to the low solubility of dibromo intermediate **8** (and analogues), possible coordination of metal catalysts with nitrogen-containing intermediates, and the electronic mismatch between terminal alkyne and aryl bromide coupling patterns. Jeffries-EL utilized orthoesters as condensation partners for **7** (Scheme 1C).[14] Subsequent Suzuki coupling of **9** with a phenylboronic acid yielded aryl/heteroaryl cruciform **10**.[12] Compound **9** and its analogues were also reacted with terminal alkynes through Sonogashira coupling[15] and thiophenyltin reagents by Stille cross-coupling[12] to deliver cruciforms substituted with alkynyl and heteroaryl groups along the vertical axis (not shown).

SOLID-STATE ORGANIZATION

The tunable optoelectronic properties, well-defined rigid structures, and modular syntheses of molecular cruciforms make these materials appealing candidates for incorporation into solid-state devices. Benzobisoxazole cruciforms are particularly interesting in this regard, as they offer a 90° angle between the four available valences, which is unusual for organic molecules. Nuckolls employed this feature to install solubilizing groups perpendicular to the benzobisoxazole

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conjugation axis in their 2006 study,[16] which used benzobisoxazoles as conducting wires to connect single-walled carbon nanotubes. The same group further demonstrated that upright monolayers of benzobisoxazole cruciforms (assembled on gold via Au−S linkages) can be subjected to mild chemical reactions such as imine formation from aldehydes without the loss of structural integrity of the self-assembled cruciform monolayer.[17]

One of our long-term goals is the incorporation of BBO cruciforms into solid-state sensing devices based on the crystallographically ordered porous materials known as metal−organic frameworks (MOFs)[18] and covalent organic frameworks (COFs).[19] We thus embarked on a systematic investigation of solid-state structures of eight benzobisoxazole cruciforms using X-ray crystallography.[20] Their crystal structures revealed the expected cross-conjugated geometry, with the most significant deviations coming from distortion of the triple bonds from linearity. Within this set of cruciforms, three distinct organizational structural motifs can be observed (Figure 3). Five cruciforms having carbonyl groups attached to either of their axes organize into two-dimensional sheets, within which individual cruciform molecules adopt a nearly planar conformation. These two-dimensional layers then are $[\pi\cdots\pi]$-stacked into the three-dimensional crystal. This structural organization is exemplified by cruciform **11** (Figure 3A), which bears 4-formylphenyl groups along the vertical and 4-(*N*,*N*-dimethylamino)phenyl groups along the horizontal axis.

The two examined cruciforms that lack carbonyl groups but are ornamented with 4-(*N*,*N*-dimethylamino)phenyl groups organize into one-dimensional tapes, which then propagate into two-dimensional "walls" of cruciforms. In compound **12** (Figure 3B), the molecular structure is significantly deplanarized, as the 4-(*N*,*N*-dimethylamino)phenyl moieties are distorted from the central BBO plane into an almost perpendicular arrangement. These groups then engage in $[\pi\cdots\pi]$ stacking with their counterparts in adjacent molecules, resulting in an infinite tape.

Finally, the parent cruciform **3**, in which the horizontal and vertical axes bear no functional groups, organizes into a unique structure wherein molecules of **3** stack in an offset arrangement into infinite columns, with an interplanar distance of 3.44 Å between two adjacent molecules (Figure 3C). These columns alternate in the direction of their tilt, surrounding a threefold rotation axis. Through its phenyl rings on the vertical axis, each cruciform is shared between two of these six-column assemblies, forming the complete three-dimensional structure.

In all of the examined systems, the closest observed contacts are found between C−H bonds and electronegative O and N atoms or between C−H bonds and the carbons of the triple bond.

Nuckolls crystallographically examined the parent cruciform substituted along the vertical axis with aryl groups.[18a] Its structure proved to be quite different from those of our alkynyl-substituted systems: the molecule is deplanarized, and the BBO core is sterically blocked by the four adjacent phenyl rings, meaning that it is not available for short contacts with the neighboring cruciforms.

SPECTROSCOPIC PROPERTIES

All of the benzobisoxazole cruciforms we prepared are solids, ranging in color from light yellow to brown. They are highly fluorescent in virtually all of the solvents we examined, as well as in the solid state. The fluorescence quantum yields (ϕ_{fl}) of

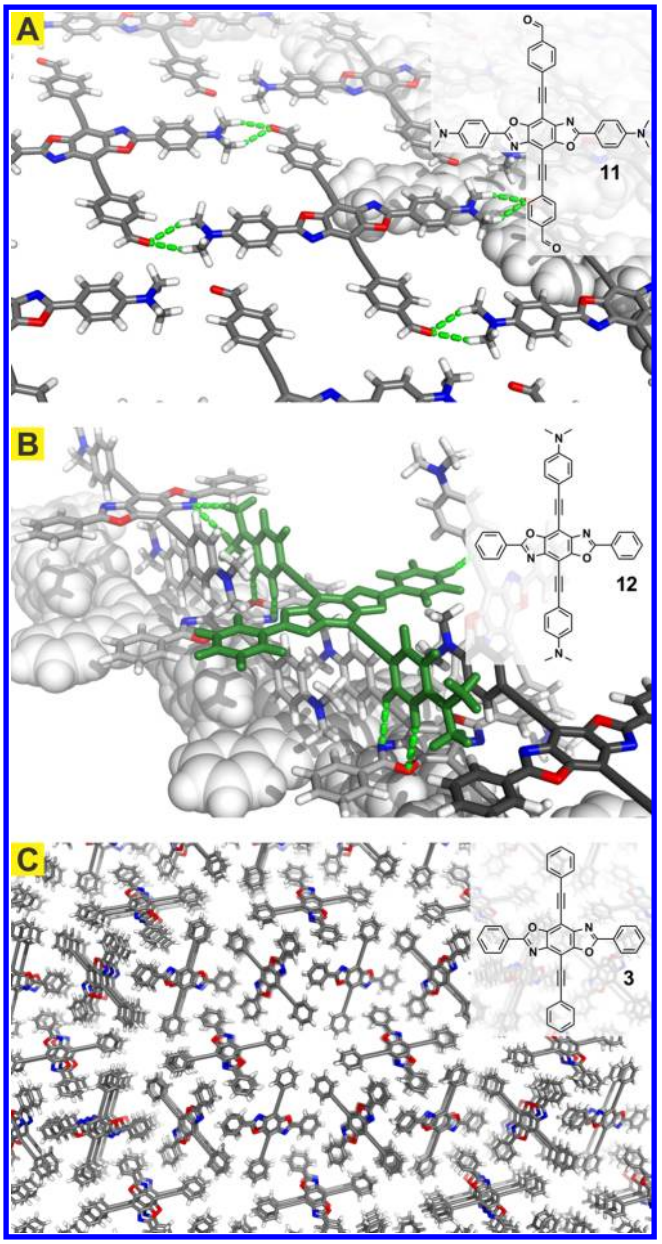

Figure 3. Crystal structures of BBO cruciforms illustrating the three structural motifs observed in cruciforms substituted with alkynyl groups along their vertical axis: (A) two-dimensional sheets; (B) one-dimensional tapes; (C) infinite columns surrounding a threefold axis. In (A) and (B), short contacts are highlighted in green. Adapted with permission from ref 20a. Copyright 2012 Royal Society of Chemistry.

BBO cruciforms vary dramatically with solvent.[21] Compound **2**, for example, has a ϕ_{fl} of 18% in ethanol but 81% in nonpolar dichloromethane. Jeffries-EL similarly observed high ϕ_{fl} values (28−81%) for a number of aryl- and heteroaryl-substituted cruciforms.[12] In addition, all of the examined BBO systems are solvatochromic, with their emission shifting steadily toward the red with increasing solvent polarity. The series of nine cruciforms showed emission ranging from 402 to 615 nm, covering much of the visible region.

RESPONSE TO ANALYTES

BBO cruciforms reversibly respond to protonation by dramatic changes in their UV/vis absorption and fluorescence emission properties; these changes can be rationalized using the orbital

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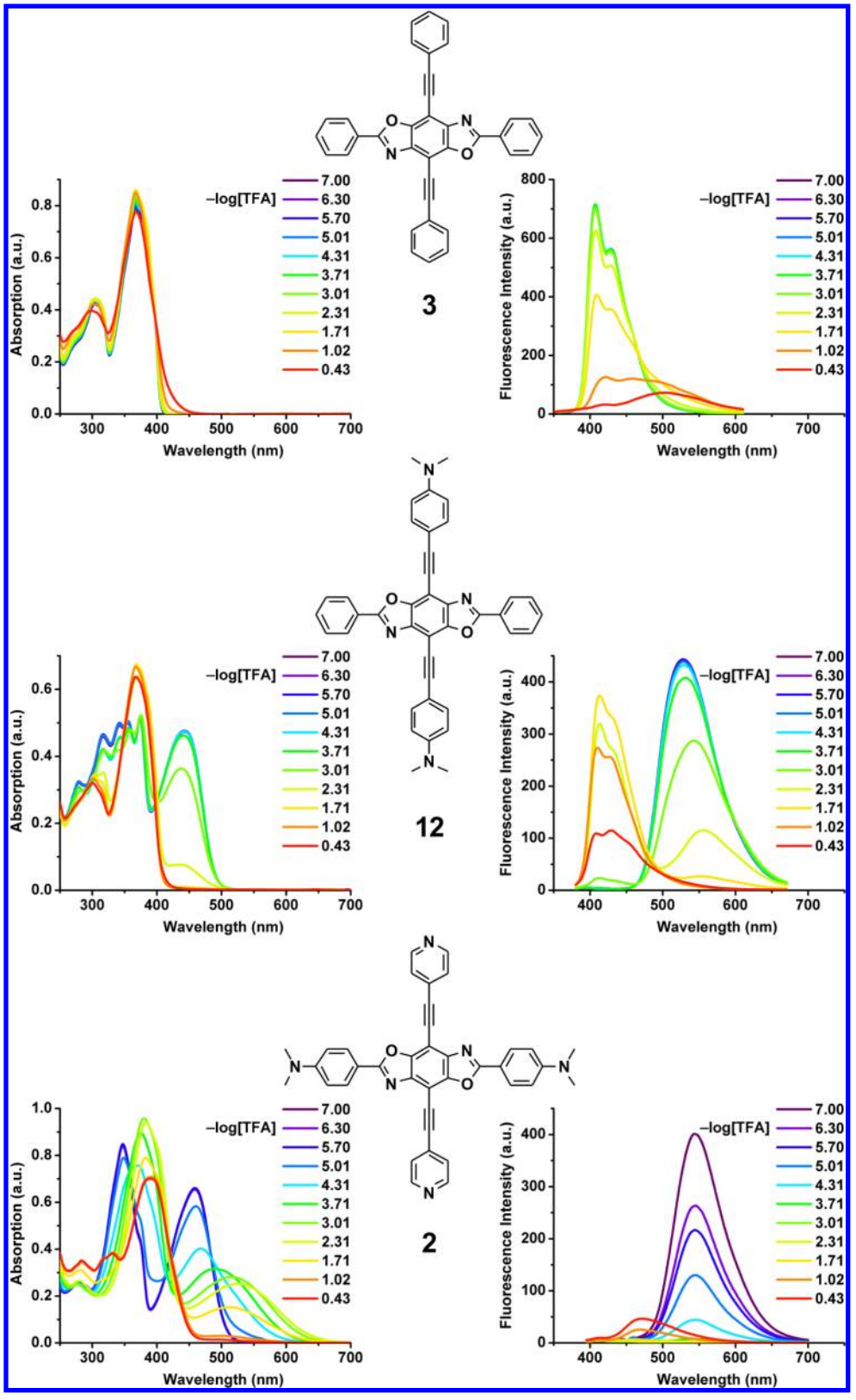

Figure 4. Changes in the absorption and fluorescence emission spectra of solutions of BBO cruciforms **3** (top), **12** (middle), and **2** (bottom) in CH_2Cl_2 in response to protonation with trifluoroacetic acid. All of the spectroscopic changes are reversible.

pictures presented in Figures 1 and 2. To highlight the main observed trends, we will use cruciforms **3** (with no basic groups along its periphery), **12** (with basic groups only along the vertical axis), and **2** (with groups of different basicity along its horizontal and vertical axes). The absorption and emission spectra of cruciform **3** change very little with the addition of acid (Figure 4, top row); the reason is simply the absence of suitable protonation sites. At high acid concentrations, central

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oxazole rings become protonated, as is evident in the sudden changes in the emission spectrum; however, this final protonation is difficult to explain in terms of FMO (de)-stabilization, as both the HOMO and LUMO have significant densities in the central heterocycle.

Cruciform **12** is substituted with electron donors along its vertical axis: its HOMO is localized along the vertical axis (86%), while the more delocalized LUMO still has more of its density (38% more) along the horizontal axis. Thus, protonation of the dimethylamino groups disproportionately stabilizes the HOMO, leading to blue shifts in the absorption and emission spectra (Figure 4, middle row). As is the case with **3**, high acid concentrations lead to some quenching in the emission spectrum, a phenomenon that we attribute to partial protonation of the benzobisoxazole core under such conditions.

The most complex case is presented by the donor−acceptor cruciform **2** (Figure 4, bottom row). Here, initial protonation occurs on the more basic pyridines, stabilizing the LUMO and causing a red shift in absorption. The quenching of the emission suggests that this initial protonated species is nonfluorescent. With continued acidification, *N*,*N*-dimethylamino sites in **2** are also protonated, stabilizing the HOMO and resulting in a blue shift, which is observed in both the absorption and fluorescence emission spectra. Similar two-step optical responses were previously observed in distyrylbis(arylethynyl)benzenes[22] and tetrakis(arylethynyl)benzenes[4a] both upon protonation and upon exposure to Lewis acidic metal ions.

As mentioned before, cruciform **2** is highly solvatochromic: its solutions in five common solvents have widely different emission colors. Upon exposure to 12 aromatic carboxylic acids with closely related pH values and quite similar structures, these emission colors change, but no two carboxylic acids induce the same changes across all five solvents (Figure 5).[23] This effect could therefore be used to qualitatively discriminate among structurally closely related carboxylic acid analytes without the need to perform rigorous spectroscopic titrations. Bunz and co-workers demonstrated that similar distinction could be achieved using a battery of three distyrylbis(arylethynyl)benzenes[24] and have subsequently shown that photographic information—such as one presented in Figure 5—can be directly correlated to emission spectra.[25] The origins of this ability to distinguish minute structural differences are still unclear, but we hypothesize that at least three factors are at play: (a) because of the somewhat different acidities of carboxylic acid analytes, they do not all equally shift the spectra of **2** at the same concentration; (b) electron-poor analytes act as efficient quenchers of **2**'s fluorescence, and this quenching is likely solvent-dependent; and (c) some analytes, such as salicylic acids, show inherent fluorescence, which is superimposed on that of the BBO fluorophore. The simultaneous operation of these three (and possibly other) effects makes it very unlikely that all of them will exactly match for two analytes in all five solvents, thus making discrimination possible under the controlled conditions used in these experiments.

In addition to carboxylic acids, aryl- and alkylboronic acids are also capable of inducing substantial shifts in the emission colors of cruciform **2**. The ability to discriminate is much more vivid compared with the carboxylic acid example discussed above. The precise nature of the assembly formed between **2** and a boronic acid is still not clear. While hydrogen-bonded assemblies between pyridines and boronic acids have ample precedent,[26] direct N−B coordination bonds cannot be fully excluded.

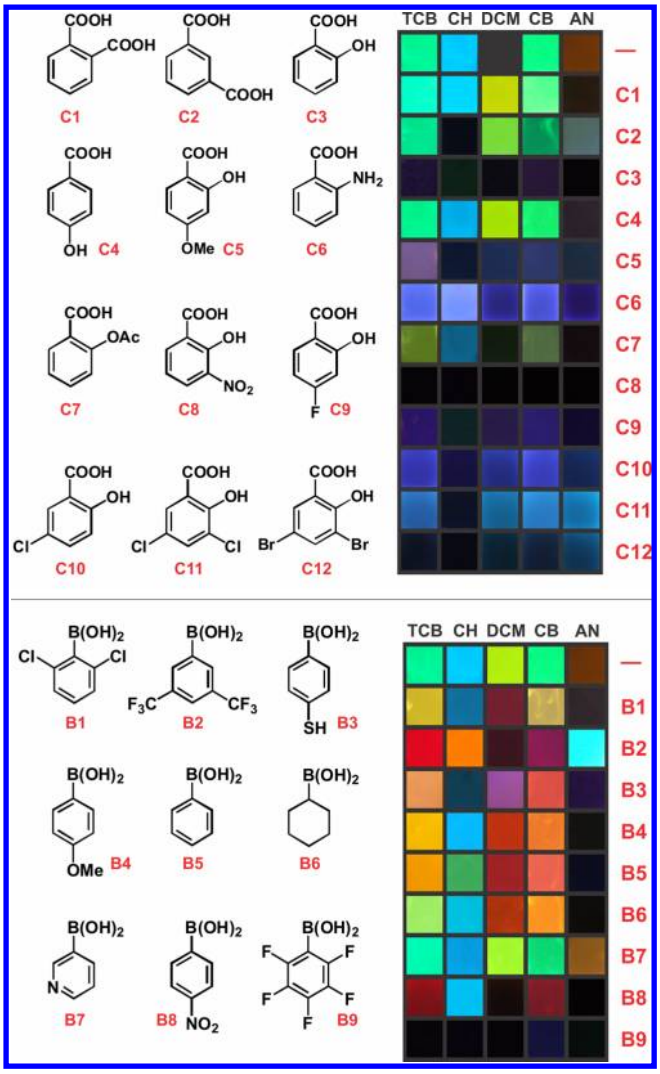

Figure 5. Optical responses of BBO cruciform **2** to the addition of carboxylic acids **C1**−**C12** (top) and boronic acids **B1**−**B9** (bottom) to its solutions in five different solvents [from left to right: 1,2,4-trichlorobenzene (TCB), cyclohexane (CH), dichloromethane (DCM), chlorobenzene (CB), acetonitrile (AN)]. Shown are cutouts of photographs of the emission colors ($\lambda_{excitation}$ = 365 nm; shutter speed = 0.5 s).

Boronic acids have themselves been used as sensors for sugars and small organic and inorganic anions.[27] In order to achieve fluorescence-based sensing of sugars, for example, one must prepare a fluorescent boronic acid, which often involves a nontrivial synthesis. We hypothesized that self-assembled complexes of boronic acids with cruciform **2** could be used as hybrid sensors in which the chemical reaction is performed by the boronic acid but reporting of that chemical reaction occurs using the cruciform fluorophore. Such a modular approach allows independent optimization of the two partners: the boronic acid can be modified to, e.g., ensure better solubility, selectivity, or steric match with analytes, while one and the same cruciform can be used to detect a broad range of analytes.

We have demonstrated this approach in practice using phenols (Figure 6, left two panels),[24] amines (Figure 6, right two panels), and small organic and inorganic anions[28] as model analytes. Specifically, mixing of a 10^{-6} M solution of cruciform

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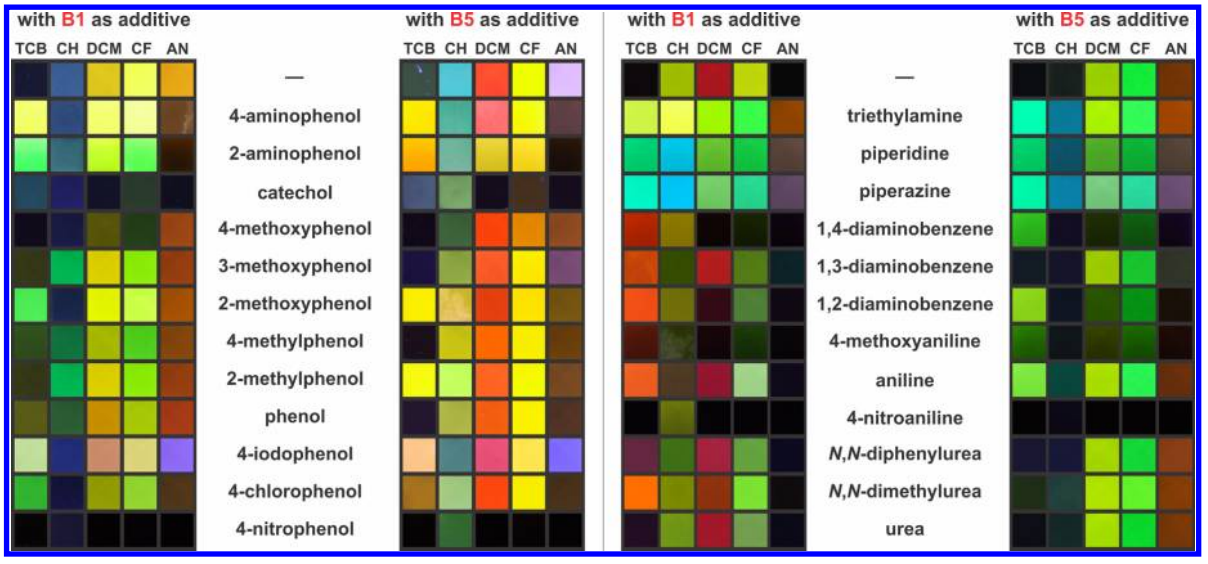

Figure 6. Vicarious sensing of phenol (left two panels) and amine (right two panels) analytes using self-assembled complexes of BBO cruciform **2** with nonfluorescent phenylboronic acid (**B1**) or 2,6-dichlorophenylboronic acid (**B5**). Solvents used were (from left to right) 1,2,4-trichlorobenzene, cyclohexane, dichloromethane, chloroform, and acetonitrile. Shown are cutouts of photographs of the emission colors ($\lambda_{excitation}$ = 365 nm; shutter speed = 0.5 s).

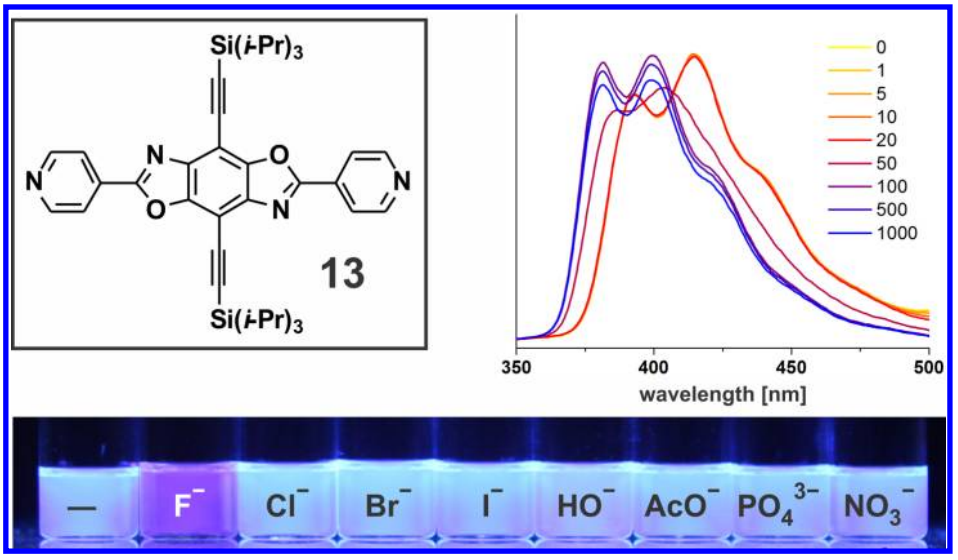

Figure 7. Fluoride addition to the solution of silylated BBO cruciform **13** (top left) in THF causes desilylation of **13** to give the terminal alkyne. This change shifts the fluorescence emission maximum toward the blue region with as little as 50 equiv of fluoride (numbers at the top right indicate equivalents of fluoride). The response is fluoride-specific and visible with the naked eye (bottom).

2 with two nonfluorescent boronic acids (a 1:20,000 ratio was needed, because the complex-formation equilibria are unfavorable) resulted in self-assembled complexes whose structures were tentatively assigned as **2**·2ArB$(OH)_2$ and whose emission colors are clearly distinct from that of pure BBO **2**. Subsequent exposure of each of these entities to analytes of interest (approximately 2 equiv of analyte relative to the boronic acid) resulted in another color change. These color changes again were never the same for two different analytes across all 10 of the performed experiments. Very small structural differences—such as those between 2-methoxy, 3-methoxy, and 4-methoxyphenols—could be identified, proving that these hybrid sensors are remarkably responsive to minute variations in analyte structure.

With amine analytes, an interesting leveling effect was observed. Cruciform **2** is itself an amine, and its pyridine rings are presumed to be the closest points of interaction with the boronic acid. Amines more basic than **2** would therefore be expected to expel it out of its complex with the boronic acid, resulting in the recovery of the emission colors of the pure cruciform **2**. Discrimination between such basic amines should be very unlikely because they would all produce the same emissive species. Indeed, this was experimentally confirmed: triethylamine, piperidine, and piperazine, all of which are stronger bases than pyridine, resulted in emission responses that were similar to each other. On the other hand, less basic aniline and urea analytes could be readily distinguished.

BBO and other cruciforms have been used as dynamic covalent and coordination-based sensors for a variety of species. However, this reversible analyte binding occasionally results in low detection sensitivities, in cases where the association constants are unfavorable. We therefore explored the possibility

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of using irreversible reactions of BBO cruciforms as a method to lower the detection limits for specific substrates that engage in those reactions. Specifically targeted was fluoride anion, which can selectively and quickly deprotect bulky silyl groups on alkynes because of the high driving force provided by the strong Si−F bond (135 kcal mol^{-1}). With this aim in mind, we designed and synthesized BBO cruciform **13** decorated with two tris(isopropyl)silyl (TIPS) groups[29] (Figure 7, top left). Fluoride addition causes rapid cleavage of the C−Si bond, resulting in the formation of a terminal alkyne and a corresponding shift of the fluorescence emission maximum by −15 nm. This behavior can be rationalized by a broadening of the HOMO−LUMO gap, which in turn is explained by the dominant stabilization of the HOMO upon desilylation by fluoride anion.[30] With this dosimeter, fluoride can be detected at concentrations as low as 50 μM. As expected, cruciform **13** responds only to fluoride[31] and not to other basic anions such as hydroxide and acetate, which would have deprotected smaller trialkylsilyl groups (Figure 7, bottom).

BENZIMIDAZOLE HALF-CRUCIFORMS

Encouraged by the rich optical behavior of benzobisoxazole cross-conjugated fluorophores, we expanded our interests to other fluorophore geometries and chemical identities. Switching from basic benzobisoxazoles to amphoteric benzimidazoles afforded new sensors that are capable of acting as both acids and bases. We also sought to explore what happens when a cruciform is "cut in half", to form an L-shaped compound. Figure 8 (top) illustrates the synthesis of a typical L-shaped benzimidazole fluorophore. Starting with 3-bromo-*o*-phenylenediamine (**14**),[32] oxidative condensation with an aldehyde[33] installs the horizontal axis, and subsequent Sonogashira coupling of an alkyne creates the vertical axis. Just as in the benzobisoxazole series, this synthetic route is highly modular, and nine different half-cruciforms were synthesized. Donor−acceptor system **15** maintains spatially segregated FMOs, although to a degree somewhat attenuated relative to the benzobisoxazole relatives (Figure 8, center). Most significantly, benzimidazole **15** clearly responds to bases through changes in both UV/vis absorption and fluorescence (Figure 8, bottom, two spectra on the left); since there is only one N−H proton available for removal, a clear isosbestic point is observed. The spectroscopic data obtained during a titration with acid (Figure 8, bottom, two spectra on the right) are not as easily rationalized: while the absorption maxima appear to be moving toward the red with addition of acid, the emission maxima move toward the blue. A possible explanation of this phenomenon could invoke the relatively close basicities of the imidazole, pyridine, and dimethylaniline groups in **15**.

Benzimidazole fluorophores hold additional potential as they can be deprotonated into benzimidazolate anions, which are good ligands to metals. This feature could be used in the development of porous coordinated materials, such as extended zeolitic imidazolate frameworks (ZIFs),[34] which could act as robust solid-state fluorescent sensors.

CONCLUSIONS

The rigid benzobisoxazole and benzimidazole cruciforms described in this Account are small and relatively simple molecules whose well-controlled orbital properties make them useful as sensors for a wide variety of species. Their behavior is not unique; in fact, our work and that of other groups has

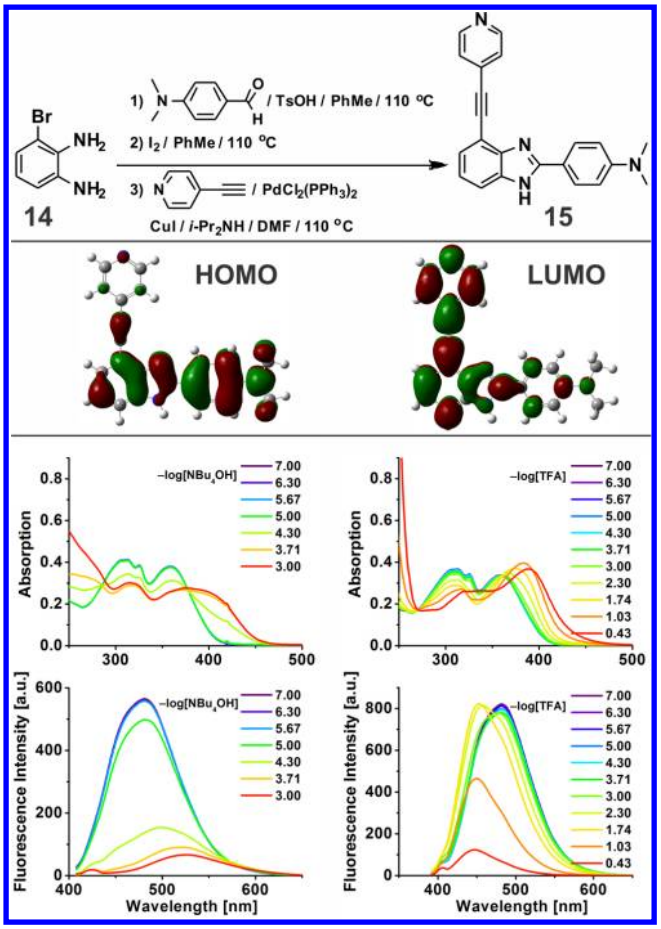

Figure 8. Synthesis of the exemplary benzimidazole half-cruciform **15** (top). Benzimidazole half-cruciforms are also characterized by spatially isolated FMOs (center). Their UV/vis absorption and fluorescence responses to bases (bottom left) are highly predictable, while their responses to acids (bottom right) are complicated by the comparable basicities of the benzimidazole, pyridine, and dimethylamino nuclei. THF was used as the solvent in all of the titration experiments.

shown that virtually any cross-conjugated geometry could be induced to have spatially isolated FMOs. The availability of such a broad and highly modular class of sensors bodes well for their use in the development of sensing arrays similar to "chemical noses".[35] Their potential in this area could be further enhanced with the development of chemical dynamic cruciform sensors (or mixtures of sensors), which could respond to analytes by the in situ creation of a sensor that both binds its analyte well and responds to it with a strong emission change.[36] Another new frontier in the study of cruciform fluorophores would be their incorporation into functional solid-state materials with high surface accessibility, such as MOFs or COFs, which would capitalize on their rigidity and predictable optical response. From a fundamental perspective, an interesting direction could be the exploration of cross-hyperconjugated systems, such as those suggested by Ottosson,[37] where the central unit is a formally saturated fragment based on either a carbon or silicon atom. Our group is working on several of these directions.

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Notes

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