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Donor—Acceptor Assisted Alkyne Hydration: A Luminescent Boron-Stabilized Enol

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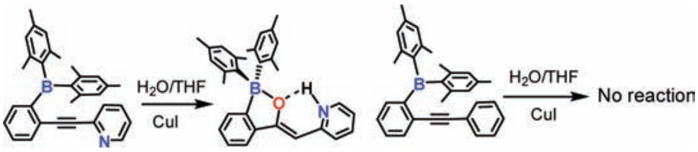
ABSTRACT



An alkyne molecule 2-(2′-BMes$_2$-phenylethynyl)pyridine (1) that contains a Lewis acidic BMes$_2$ group and a Lewis basic pyridyl group has been found to undergo facile hydration under ambient conditions in the presence of CuI, forming a highly emissive and stable enol ester (2). The lack of any hydration reactivity by a control compound 2-(2′-BMes$_2$-phenylethynyl)benzene (3) under the same conditions supports that the cooperativity between the Lewis donor and acceptor groups plays a key role in the formation of 2.

Triarylboron compounds have excellent electron-accepting properties due to the Lewis-acidic boron center.[1] Although ortho-substituted aryl groups are often used to protect the boron center from nucleophilic attack, it has been well established that small anions (e.g., F^- and CN^-) can still access sterically protected triarylboron centers such as BMes$_2$(Ar). As a result, triarylboron compounds can be used as effective sensors for these anions.[2] Gabbaï and co-workers have also shown that OH^- can bind to sterically congested boron centers to form hydroxo adducts.[3] In addition, the copresence of a triarylborane and an appropriate Lewis donor group such as amine or phosphine is known to promote unusual reactivities, including the activation of hydrogen, alkenes, or alkynes.[4] Recently bifunctional aminoboronic acids have been shown to be potential catalysts for direct amide formation and catalytic asymmetric transformation.[5] Furthermore, Yamaguchi and co-workers have demonstrated that alkyne molecules functionalized by a triarylboron group and a phosphine or pyridine can undergo cascade double cyclization, extending π-conjugation of the molecule.[6] During our investigation of triarylboron-functionalized alkyne compounds, we have observed that the presence of an internal Lewis base along with the boryl group can greatly facilitate the alkyne hydration reaction under ambient conditions. Hydration of internal alkynes typically occurs at high temperatures and requires the use of either toxic[7] (e.g., mercury(II) salts) or costly metal catalysts[7] (e.g., platinum or gold). The details on our findings on this unusually facile alkyne hydration are presented herein.

Compound **1**, 2-(2′-BMes$_2$-phenylethynyl)pyridine (Figure 1), was initially obtained in 18% yield by

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(1) For recent reviews see: (a) Hudson, Z. M.; Wang, S. *Acc. Chem. Res.* **2009**, *42*, 1584. (b) Yamaguchi, S.; Wakamiya, A. *Pure Appl. Chem.* **2006**, *78*, 1413. (c) Entwistle, C. D.; Marder, T. B. *Chem. Mater.* **2004**, *16*, 4574. (d) Jäkle, F. *Chem. Rev.*, 2010, *110*, 3985 and references cited therein.

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(5) Georgiou, I.; Ilyashenko, G.; Whiting, A. *Acc. Chem. Res.* **2009**, *42*, 756.

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(7) (a) Alonso, F.; Beletskaya, I. P.; Yus, M. *Chem. Rev.* **2004**, *104*, 3079. (b) Wakatsuki, Y.; Hou, Z.-M.; Tokunaga, M. *Chem. Rec.* **2003**, *3*, 144.

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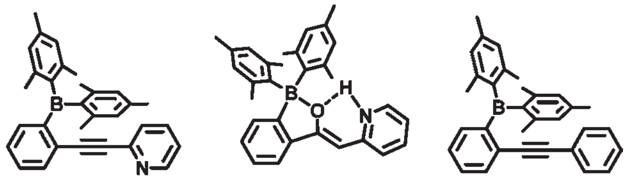

Figure 1. Structure of **1**, **2**, and **3**.

Sonogashira coupling between *o*-(dimesitylboryl)ethynylbenzene and 2-bromopyridine in refluxing wet THF/Et_3N using $Pd(PPh_3)_2Cl_2$ and CuI as catalysts (see the Supporting Information for details). From the same reaction, a yellow precipitate, compound **2**, with bright yellow-green fluorescence was isolated in 22% yield. When freshly dried THF was used in the synthesis, the yield of compound **1** was improved to 35% and no compound **2** was obtained. The control compound, 2-(2′-$BMes_2$-phenylethynyl)benzene (**3**), was obtained by a similar procedure in 45% yield. All three compounds are air stable in solution and in the solid state. They were fully characterized by NMR, HRMS, and single-crystal X-ray diffraction analyses (see the Supporting Information).

Both **1** and **2** crystallize in the monoclinic space group $P2_1/c$ while compound **3** crystallizes in the triclinic $P\overline{1}$ space group. The structures of **1** and **3** are shown in Figure 2 for comparison. The B−C bond lengths in both molecules span the range of 1.55(1) to 1.58(1) Å, which are typical of triarylboron compounds. In **1**, one mesityl is parallel and directly above the pyridylalkyne group with a dihedral angle of 16.4° and short separation distances (e.g., 3.00, 3.48 Å). Such π-stacking interaction may be faciliated by the attraction between the electron-rich mesityl ring and the electron-deficient pyridylalkynyl group. In contrast, the mesityl ring in **3** is nearly perpendicular to the phenylakynyl group with a dihedral angle of 106.4°. This conformation of **3** may be attributed to the dimer formation via intermolecular C−H (methyl)$\cdots\pi$ (alkynylphenyl) interactions in the solid state (see the Supporting Information).

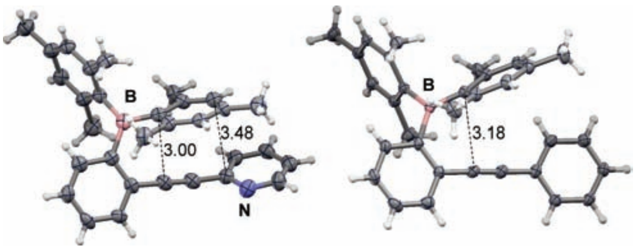

Figure 2. Crystal structures of **1** (left) and **3** (right) with 35% thermal ellipsoids.

Compound **2** is stable in solution and the solid state under air with an unusual structure. It has a rare C,O-chelate around the four-coordinate boron atom. The B−C bonds are much longer (1.617(7) to 1.632(7) Å) than those of **1** and **3**, but similar to those of previously reported four-coordinate $BMes_2$ compounds.[8] The B−O bond is 1.609(6) Å, somewhat longer than those observed in noncongested four-coordinate boron compounds (e.g., $BPh_2(q)$, q = 8-hydroxyquinolato).[9] The alkyne bond has been transformed to an olefin bond with a typical double bond distance, 1.352(6) Å, and an *E*-geometry with respect to the pyridyl and phenyl groups. A proton bound to the py nitrogen atom was located and refined successfully in X-ray analysis. This proton forms a hydrogen bond with the oxygen atom (N−H = 0.98(3) Å, O$\cdots$H = 1.98(3) Å), holding the py ring in plane with the phenyl ring. The C−O bond length is 1.322(7) Å, typical of conjugated C−O bonds.[10] Thus, based on the crystal structure, compound **2** can be described as a zwitterionic $BMes_2$ enolate (Figure 3). Between the *enol* and *keto* tautomers, the *keto* form is usually much more stable, thus more commonly observed than the enol tautomer.[11] Clearly, binding to the $BMes_2$ unit by the oxygen atom stabilizes the otherwise unstable *enol* tautomer.

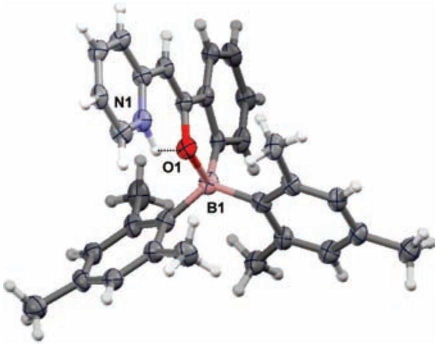

Figure 3. Crystal structure of **2** with 35% thermal ellipsoids.

Compound **2** has a distinct yellow color in solution due to an intense and broad absorption band between 360 and 470 nm (λ_{max} = 435 nm, ε = 27 000 M^{-1} cm^{-1}) in the absorption spectrum (Figure 4) that can be attributed to a π to π^* transition on the backbone with a small charge transfer contribution from the mesityl to the π^* orbital of the chelate backbone, based on TD-DFT calculation results (see the Supporting Information). In contrast, **1** and **3** are colorless with little absorption in the visible region.

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[8] (a) Baik, C.; Hudson, Z. M.; Amarne, H.; Wang, S. *J. Am. Chem. Soc.* **2009**, *131*, 14549. (b) Amarne, H.; Baik, C.; Murphy, S. K.; Wang, S. *Chem.—Eur. J.* **2010**, *16*, 4750.

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[10] Bond lengths in crystalline organic compounds. In *CRC Handbook of Chemistry and Physics*, 91st ed.; CRC Press: Boca Raton, FL, 2010; pp 9−10 .

[11] March, J. *Advanced Organic Chemistry: Reactions, Mechanisms, and Structures*, 4th ed.; John Wiley & Sons: New York, 1992; p 762.

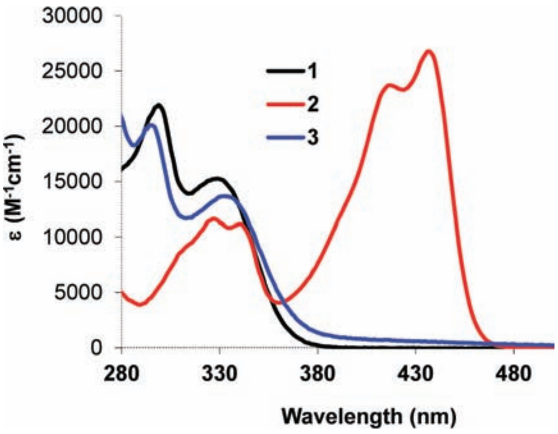
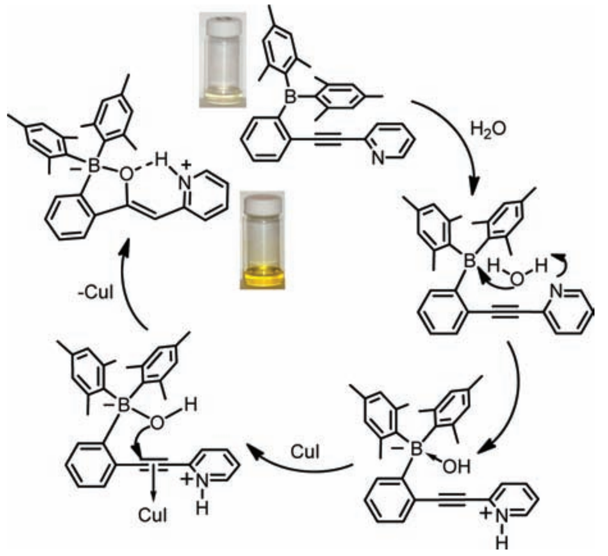


Figure 4. Absorption spectra of compounds **1**−**3** in CH_2Cl_2.

The formation of **2** from the synthesis of compound **1** clearly involved adventitious water molecules in the reaction solvent since when dry THF was used, no compound **2** was observed and the yield of **1** was doubled. To determine if compound **1** is a precursor for **2**, several control reactions were performed and monitored by ^{1}H NMR spectroscopy (see the Supporting Information). In each of the control reactions, H_2O and **1** were mixed in a 10:1 molar ratio in THF under nitrogen at ambient temperature with varied amounts of CuI, $Pd(PPh_3)_2Cl_2$, and Et_3N. On the basis of the results of these studies, we concluded that the Pd(II) catalyst and amine are not required for the formation of **2**. The presence of a catalytic amount of CuI (10%) is, however, necessary to enable the transformation of **1** to **2** as the reaction does not occur in the presence of Et_3N/H_2O only. In fact, the conversion of **1** to **2** occurs within minutes of the addition of CuI and is readily observable due to a distinct solution color change from colorless to bright yellow. The proposed catalytic cycle for the hydration of **1** and the formation of **2** is shown in Scheme 1. In this cycle, OH^- is generated from deprotonation of water by the pyridine group on **1** and coordinates to the boron site. This step is consistent with the well-known binding ability of sterically congested boron to hydroxide,[3] and it is likely promoted by the synergistic effect of the Lewis basic pyridine nitrogen acting in concert with Lewis acidic boron. Coordination of CuI activates the triple bond and allows the facile addition of the bound hydroxo group. Finally, replacement of CuI by a proton leads to the regeneration of CuI and the formation of **2**.

Although metal-catalyzed hydration of alkynes was known previously,[7] CuI-catalyzed hydration of internal alkynes under ambient temperature is rare. The only related example is a Cu(I)-catalyzed intramolecular cyclization reaction.[12] The facile hydration of **1** to form **2** is believed to be the consequence of cooperative action by the $BMes_2$ group and the pyridyl group. This is confirmed by the fact that the boron center in both compounds has a similar electrophilicity as evidenced by their similar reduction potential ($E_{1/2}^{red}$ = −2.22 V for **1** and 2.29 V for **3**, vs $FeCp_2^{+/0}$) and similar affinity to fluoride ions (see the Supporting Information), but no hydration reaction occurred at all for compound **3** when subjected to the same reaction conditions as monitored by NMR (see the

Scheme 1. A Proposed Mechanism for the Conversion of **1** to **2**



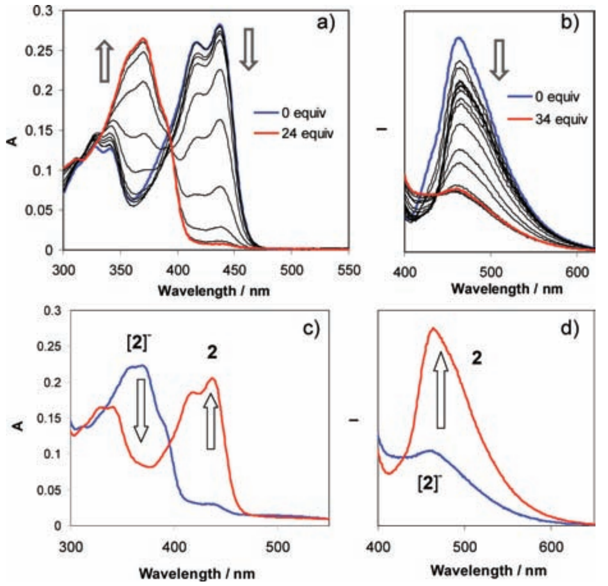


Figure 5. (Top) Titration of **2** in CH_2Cl_2 (1.0×10^{-5} M) by $NaOMe/CH_3OH$: (a) UV−vis spectral change, (b) fluorescence spectral change. (Bottom) UV−vis (c) and fluorescence (d) spectral change after the addition of 2 equiv of HBF_4 (vs the amount of NaOMe added) to the NaOMe titrated solution of **2**. The full titration spectra can be found in the Supporting Information.

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Supporting Information). The pyridyl in **1** likely acts as an internal base that helps to trap the OH^- anion, enhances its nucleophilicity, and stabilizes the transition state/intermediate in the hydration process via the formation of an internal H-bond with OH^-.

The formation of **2** is related to the double-cyclization phenomenon reported recently by Yamaguchi and coworkers where a six-membered N,O-chelate borole species was generated by hydration of a bis(pyridyl)acetylene with two internally coordinated bromobenzoborole groups.[13] Although this reaction mechanism was not well understood, it was suggested that the high Lewis acidity and reactivity of the bromobenzoborole group may have played a key role in the observed transformation.[13]

To determine the role of the H-bond in stabilizing the boron enol ester structure in **2**, we examined the response of **2** toward base. Titration experiments in both absorption and fluorescence modes using NaOMe/CH_3OH were performed. The addition of base caused a change in solution color from yellow to colorless. As shown in Figure 5, the fluorescence intensity of **2** decreases gradually with increasing concentrations of NaOMe; the absorption peak at λ_{max} = 435 nm is quenched and replaced with a new absorption band at 350 nm. This can be attributed to the formation of the anionic boron enol ester $[\mathbf{2}]^-$ that destabilizes both π and π^* energy levels localized on the pyridyl−vinyl−phenyl backbone such that this $\pi \rightarrow \pi^*$ transition becomes the lowest energy with a much bigger energy gap compared to that of **2**. This is supported by the TD-DFT calculation results that show an increase of about 0.90 eV in the HOMO−LUMO gap from **2** to its anion (see the SI). The addition of 2 equiv of HBF_4 to the NaOMe-titrated solution of **2** restores the yellow color, and the absorption and fluorescence spectra (Figure 5), supporting that the anion $[\mathbf{2}]^-$ is a stable species in solution. Thus, the stability of **2** can be mostly attributed to chelation to the boron center. However, we have observed that the addition of a large excess of HBF_4 causes irreversible spectral changes to **2**, indicating that compound **2** is not stable under acidic conditions.

In summary, a $BMes_2$- and pyridyl-functionalized acetylene has been found to undergo a facile hydration reaction in the presence of CuI. The cooperativity between the Lewis acidic and basic groups has been demontrated to play a key role in promoting the hydration process and in stabilizing the enol structure of the product.

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Supporting Information Available. Synthetic details, NMR spectra, TD-DFT data, fluoride titration UV−vis spectra of **1** and **3**, UV−vis and fluorescence titration spectra of $[\mathbf{2}]^-$ by HBF_4, and complete X-ray crystallographic data. This material is available free of charge via the Internet at http://pubs.acs.org.

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