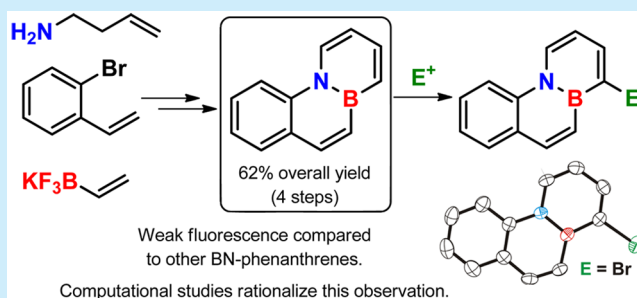


Synthesis, Optical Properties, and Regioselective Functionalization of 4a-Aza-10a-boraphenanthrene

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Supporting Information

ABSTRACT: 4a-Aza-10a-boraphenanthrene has been synthesized in only four steps from commercially available materials with a remarkable overall yield of 62%. In contrast to other BN-isosteres of phenanthrene, this isomer is weakly fluorescent, which has been explained by means of computational studies that found a low energy conical intersection for the nonradiative deactivation of the excited state. Moreover, a completely regioselective functionalization of 4a-aza-10a-boraphenanthrene at C-1 by reaction with activated electrophiles has been achieved.



The synthesis and properties of BN-aromatic compounds have attracted great interest in recent years.¹ Formal replacement of a C=C bond in an aromatic ring by an isoelectronic B–N bond leads to novel aromatic compounds with different properties caused by the presence of a dipole in the molecule.² These unique characteristics provide a great opportunity for the design and production of new materials. Thus, BN-polycyclic aromatic hydrocarbons (PAHs) have been explored as promising components for organic light emitting diodes (OLEDs)³ and organic field effect transistors (OFETs).⁴ Moreover, the potential of BN-aromatic compounds for isosteric replacement of arenes in medicinal chemistry has also been shown.⁵

The growing interest in the properties of BN-polycyclic aromatic compounds has prompted significant advances in this field in the past decade.⁶ Nevertheless, the synthetic strategies are still quite limited and they usually rely on classical electrophilic borylations performed under harsh conditions.⁶ On the other hand, the effects that the replacement of a C=C bond by a B–N bond have on the properties of BN-aromatic compounds are still not fully understood, and therefore, they are not always easy to predict. In this context, the development of new synthetic methodologies for the preparation of novel BN-aromatic compounds would enable a more systematic study of their structure–property relationships and ultimately trigger the rational design of novel BN-polycyclic aromatics with improved properties. In particular, the basic knowledge obtained from the simplest systems would be highly valuable. In this sense, a systematic comparative analysis of different BN isosteres of naphthalene has been recently performed.⁷ Moreover, regarding

phenanthrene **1**, one of the simplest polycyclic aromatic hydrocarbons, three BN-isosteres, namely **2**,⁸ **3**,^{8a} and **4**,⁹ have been prepared and their optical properties evaluated (Figure 1).¹⁰

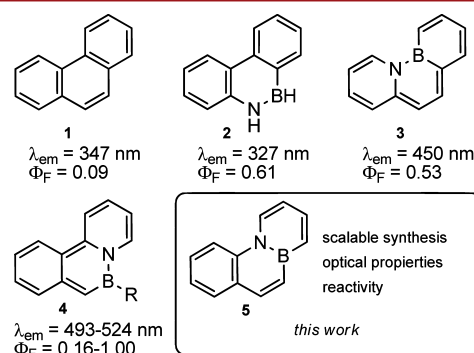


Figure 1. Known BN-phenanthrenes and their fluorescence properties.

The presence of the BN unit in the phenanthrene core has been found to have a marked influence on different properties, especially the optical properties. For instance, the fluorescence emission maxima and quantum efficiency are affected by the position of the B–N bond. However, the reasons for these experimental findings are unclear. Moreover, the reactivity of BN-phenanthrenes remains unexplored.

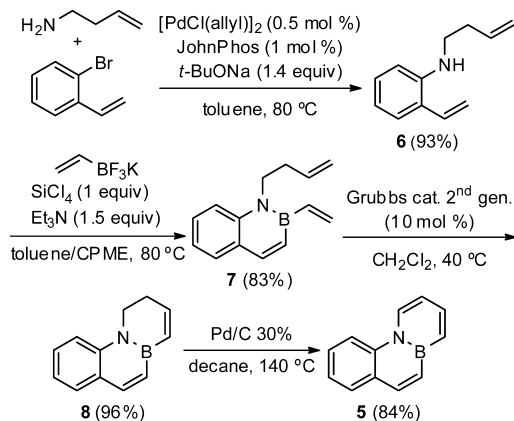
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Herein we report an efficient synthesis of BN-phenanthrene **5** and describe an experimental and theoretical study of its properties in comparison with those of phenanthrene and other known isomers of BN-phenanthrene.

The synthetic route used for the preparation of BN-phenanthrene **5** is depicted in Scheme 1. The first step consisted

Scheme 1. Synthesis of BN-Phenanthrene 5



of the preparation of 2-aminostyrene derivative **6** by Buchwald–Hartwig amination between commercially available *o*-bromostyrene and 3-butenylamine. Substrate **6** was efficiently cyclized with vinyl trifluoroborate under slightly modified conditions from the procedure reported by Molander et al.¹¹ to yield BN-naphthalene derivative **7**. Subsequent ring closing metathesis using second generation Grubbs' catalyst afforded **8**, which was finally oxidized to BN-phenanthrene **5**.

It is worth noting that other methods previously used for the oxidation of dihydroazaborines did not give satisfactory results for the aromatization of **8**. For example, the use of DDQ led to low conversions even when a 10-fold excess of oxidant was used.¹² Moreover, only starting material was recovered on heating at 60 °C with Pd/C in cyclohexene,¹³ whereas at 140 °C reduction of **8** to a BN-tetrahydrophenanthrene mainly occurred instead of the expected oxidation.¹⁴ Remarkably, compound **5** was obtained in 84% yield by heating **8** in decane at 140 °C in the presence of Pd/C.¹⁵ This is the most efficient methodology reported to date for the oxidation of a dihydroazaborine, and it could therefore find further applications in the synthesis of other BN-analogs of aromatic compounds. Overall, BN-phenanthrene **5** was obtained in a remarkable 62% global yield in four steps from commercially available materials.

The absorption spectrum of **5** in CH₂Cl₂ (Figure S1) shows a maximum at 258 nm, and the overall appearance of the spectrum clearly resembles that of **1**. In contrast, other BN-phenanthrenes feature maxima at 326 (**2**) or 446 (**3**) nm. A weak emission at 352 nm ($\Phi_f = 0.01$) is also very similar to that of the parent phenanthrene **1**. However, the Stokes shift is clearly larger (94 nm for **5**, 54 nm for **1**). This finding implies a small hypsochromic shift with regard to phenanthrene **1**, as observed for BN-phenanthrene isomer **2** and in sharp contrast with the large bathochromic shift observed for isomers **3** and **4**. Moreover, in all isomers of BN-phenanthrene studied previously the introduction of the BN unit led to increased fluorescence quantum yields with regard to the all-carbon analog but a decrease was observed for BN-phenanthrene **5**. Computational studies were carried out to rationalize these observations and gain greater insight into the structure–property relationships of BN-polycyclic aromatic

hydrocarbons, which could be helpful in the design of novel materials with improved performance. The critical points along the potential energy surface (PES) for **5** were computed at the CASPT2//CASSCF level of theory using a (14,14) active space and the ANO-L-VDZ basis set (see Supporting Information (SI) for details). For the sake of comparison, the critical points for **2** and **3**, isomers with high reported Φ_F , were also computed.^{8a} The results are shown in Figure 2.

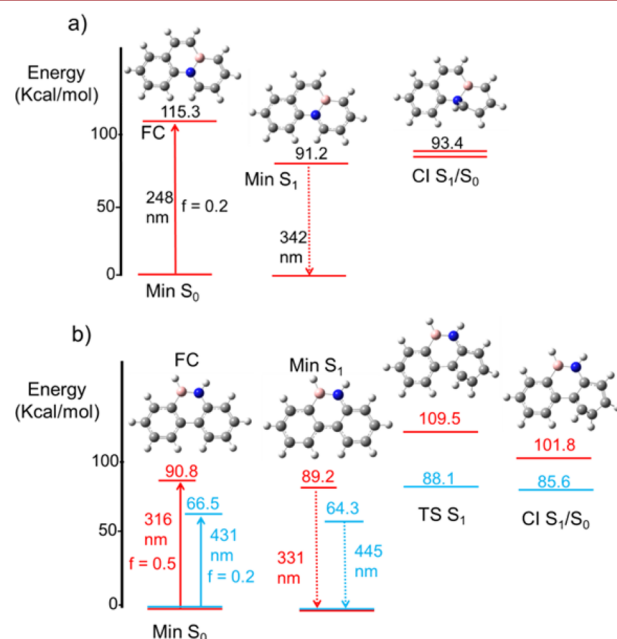


Figure 2. Computed critical points along the potential energy surface for **5** (top), **2** (bottom, red), and **3** (bottom, blue, geometries not shown).

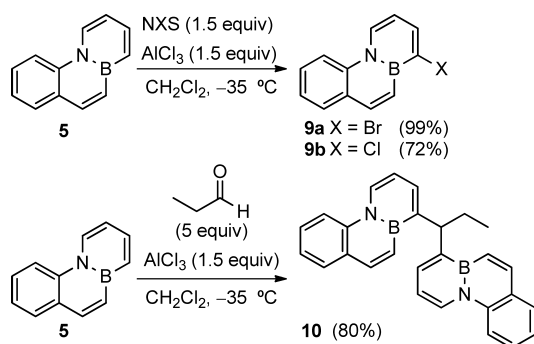
A detailed computational analysis of the factors that control the emission of BN-phenanthrenes is beyond the scope of this paper, but several conclusions can be drawn from the data shown in Figure 2. Both **2**, **3**, and **5** share planar minima in both the ground and the first excited states. However, one difference arises from the relative stabilization of the excited state minimum. In **2** and **3** the S_1 minimum is only a few kcal/mol below the Franck–Condon (FC) region. This situation is consistent with the very small Stokes shift.^{8a} In contrast, for **5** the minimum in S_1 is more stable by ca. 24 kcal/mol. In all cases, a conical intersection (CI) point was located. These CIs cause the ground state recovery once the associated energy barrier is surmounted. The geometries of both CIs are very similar because the excitation is mainly located in only one aromatic ring. This allows the other two rings to maintain conjugation and planarity, thus yielding a CI that is relatively low in energy. For **2** and **3** a transition state (TS) structure connects the excited state minimum and the CI point. These TSs and CIs are very close both structurally and energetically. The presence of the TS generates an energy barrier that the molecules need to overcome in order to move to the CI and populate the ground state through a nonradiative mechanism. For **5**, the ground state can be recovered once the energy barrier due to the relative energy of the CI is surmounted. As a competitive radiative mechanism, the S_1 minimum could decay to the ground state through fluorescence emission. Analysis of the CIs allows the different Φ_F values to be explained. For **2** and **3** the CIs (and related TSs) are very high in energy and this leads to a high energy barrier (more than 20 kcal/mol), whereas in **5** the CI

is far more stable leading to a small energy barrier. Thus, ground state recovery through the CI (nonradiative) is very efficient in **5**, with the associated very low Φ_F . Accordingly, any structural modification that causes an increase in the CI energy should also lead to a higher Φ_F as the barrier for nonradiative decay will increase. This aspect will be explored in the second generation of BN-phenanthrenes.

The photostability of **5** was also evaluated. Solutions of **5** in different solvents (acetonitrile, acetone, chloroform, methanol) were irradiated using a medium-pressure Hg lamp with a Pyrex filter ($\lambda > 290$ nm). In all cases, only minor decomposition products were detected by ^1H NMR spectroscopy after 1–2 h of irradiation.

The reactivity of BN-phenanthrene **5** was evaluated in order to gain insight into the properties of this compound and to develop new possibilities for obtaining functionalized derivatives. It is worth noting that postfunctionalization is emerging as a useful way to obtain families of BN-aromatic polycyclic compounds with modulated properties. In particular, halogenation of a few particular substrates, generally followed by cross-coupling reactions, have been reported.^{3b,16–18} In this sense, regioselective bromination of **5** was achieved by treatment with 1.5 equiv of *N*-bromosuccinimide in the presence of AlCl_3 in CH_2Cl_2 at -35°C (Scheme 2). Under these conditions, **9a**¹⁹ was isolated in

Scheme 2. Regioselective Reaction of BN-Phenanthrene **5 with Electrophiles**



excellent yield and traces of other regioisomers or dibrominated products were not observed. It is worth noting that under the same conditions phenanthrene **1**, the fully carbonated analog of **5**, yielded a mixture of starting material and different brominated products, which highlights the tremendous influence of the presence of the B–N bond on the behavior of these aromatic compounds. Chlorination of **5** to **9b** was also efficiently achieved with *N*-chlorosuccinimide. Moreover, the use of propanal as an electrophile under otherwise analogous conditions provided a high yield of **10**, which incorporates two units of BN-phenanthrene **5**. Formation of the alcohol arising from addition of a single BN-phenanthrene unit was not observed, despite the use of excess aldehyde.

The crystal structure of **9a** was determined by X-ray diffraction analysis. The results confirmed the position in which the bromo-substituent had been incorporated (Figure S9).²⁰ The B–N bond length in **9a** (1.455(5) Å) is in the range of other previously reported delocalized B–N bonds in BN-aromatic compounds²¹ and, therefore, in agreement with the aromatic character of **9a**. The crystal packing reveals a herringbone pattern based on π – π interactions (Figure S10a), similar to the disposition reported for 1-bromopyrene.²² The adjacent molecules connected by π – π

interactions are separated by a perpendicular distance of 3.43 Å, and they are aligned parallel with respect to the B–N bond (Figure S10b). However, the neighboring molecules of **9a**, which are associated by hydrophobic interactions in the herringbone motif, show an antiparallel orientation for the B–N bond (Figure S10b).

The regioselectivity of the electrophilic aromatic substitution of **5** can be explained, qualitatively speaking, in terms of the relative stability of each possible intermediate formed after the attack of the E^+ species (i.e., the arenium cation). More specifically, the resonance stabilization is higher in the C1 attack position, where all of the possible resonance forms preserve the aromaticity of the ring marked in green in Figure 3. In contrast, the attack of E^+ on any other position involves fewer resonance forms and/or the loss of aromaticity in this all-carbon aromatic ring (see Figure 3).

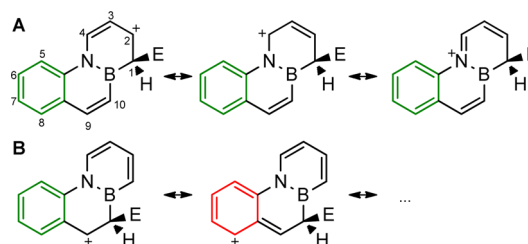
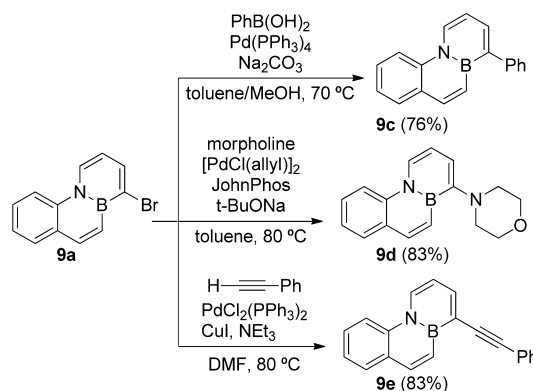


Figure 3. (A) Resonance forms for the most stable attack of E^+ on C1. The resonance forms preserve the aromaticity of the phenyl ring marked in green. (B) Example of nonstabilized intermediate: the attack on C10 produces just one resonance form that maintains the aromaticity of the phenyl ring (green), while the rest of the resonance forms lead to loss of the aromaticity (marked in red).

In an effort to account for this qualitative explanation, the regioselectivity of the bromination reaction was studied by means of DFT calculations (see SI for methods) involving a systematic study of all possible bromination positions. The relative energies of each intermediate are consistent with the qualitative description based on the resonance forms. In fact, equilibrium populations at room temperature are predicted to be ca. 100% for C1 attack, ca. 0.01% for C9, and virtually negligible for the rest of the positions.

Interestingly, **9a** is suitable for further functionalization by palladium-catalyzed cross-coupling reactions under standard conditions. These reactions afforded good yields of a variety of BN-phenanthrenes, **9c**,¹⁹ **9d**,¹⁹ and **9e**, with different substituents at C1 in a straightforward manner (Scheme 3).

Scheme 3. Synthesis of 1-Substituted BN-Phenanthrenes **9**



In conclusion, the design and development of an efficient synthesis of 4a-aza-10a-boraphenanthrene **5** has allowed the preparation of this compound in gram scale, thus enabling a full characterization of this quite simple but so far underexplored BN-PAH. Moreover, this synthetic strategy could potentially be applied for the synthesis of more complex BN-PAHs by selecting appropriate starting materials. Evaluation of the optical properties of **5** confirmed the previously observed dramatic effect of the position of the B–N unit in BN-phenanthrenes. The low intensity of the fluorescence emission displayed by **5** can be attributed to the presence of a very low energy CI point for ground state recovery.

Reaction of **5** with activated electrophiles proceeds with complete regioselectivity at C1, which is in full agreement with the prediction made by DFT calculations. Understanding the reactivity of simple BN-aromatic compounds in an effort to predict the behavior of more complex systems is fundamental for future designs of novel BN-PAHs based on appealing postfunctionalization processes. Of particular interest is the introduction of a bromo-substituent, which allows straightforward derivatization based on palladium-catalyzed cross-coupling reactions. Further studies on the reactivity of BN-phenanthrene **5** are currently ongoing in our laboratories.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.7b01435.

Experimental and computational details, X-ray crystallographic data for **9a**, and NMR spectra for all new compounds (PDF)

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Notes

The authors declare no competing financial interest.

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