# PCCP

## Accepted Manuscript

Volume 18 | Number 1 | 7 January 2016 | Pages 1–636

PCCP

Physical Chemistry Chemical Physics
www.rsc.org/pccp

ISSN 1463-9076

PERSPECTIVE
Darya Radziuk and Helmuth Möhwald
Ultrasonically treated liquid interfaces for progress in cleaning and separation processes

175 YEARS

ROYAL SOCIETY
OF CHEMISTRY

rsc.li/pccp

# Does Aromaticity Account for an Enhanced Thermodynamic Stability?

## The Case of Monosubstituted Azaborines and the Stereoelectronic

## Chameleonism of NH$_2$ group

Marija Baranac-Stojanović[a]* and Milovan Stojanović[b]

[a] University of Belgrade - Faculty of Chemistry, Studentski trg 12-16, P.O.Box 158, 11000 Belgrade, Serbia

e-mail: mbaranac@chem.bg.ac.rs

[b] University of Belgrade, Institute of Chemistry, Technology and Metallurgy - Center for Chemistry, Njegoševa 12, P.O.Box 473, 11000 Belgrade, Serbia

## Abstract

This work was initiated by the increasing interest in BN/CC isosterism and by the long lasting interest in the concepts of aromaticity and substituent effects. We have theoretically examined aromaticity and stability of monosubstituted BN isosters of benzene, the three isomeric azaborines. The results provide insight into the effect of substitution on two basic molecular properties, which are influenced, here, by the effects of substituent and by the B/N relationship in the ring. The results, along with other examples in the literature, also warn chemists that the general belief that aromaticity accounts for an enhanced thermodynamic stability is not always true. Stability of cyclic, conjugated compounds depends on several effects, and only one of them is aromaticity. In addition, our calculations predict a switching of electronic properties of NH$_2$ group from the usual p-electron donor to the π-electron acceptor when it is moved from B/C atoms to nitrogen atom in all isomers, or C6 in 1,3-azaborine. This is the result of the conformational change that places the $N_{LP}$ in the plane of the ring and the NH bonds in a favourable spatial position to act as acceptors of π-electron density.

## Introduction

Aromaticity is a fundamental and important concept in chemistry. Those cyclic, conjugated, (4n+2)π-electron compounds which show an enhanced thermodynamic stability relative to acyclic structural analogues, tendency toward bond length equalization, which undergo substitution instead of addition reactions and which develop diatropic ring currents in an external magnetic field are said to be aromatic. The concept of aromaticity has attracted great interest from theoretical and experimental chemists who developed various criteria and indices by which one can characterize a compound as aromatic. The mostly used ones are based on molecular structure and bond lengths,[1] electron delocalization,[2] magnetic properties[3] and energy.[4] Though, the often lack of correlation between various measures of aromaticity has led to its description as a multidimensional phenomenon,[5] or even a question whether it can be properly defined.[6]

Relationship between aromaticity and stability, in its original definiton, creates general belief that compound which is more aromatic should be more stable. This may or may not be the case and there are examples when aromaticity and stability do not go hand in hand.[7] An example of different trend between aromaticity and stability is also given by the boron-nitrogen (BN) analogues of benzene, i.e. the three isomeric azaborines (Figure 1). Here, the least stable 1,3-isomer was found to be the most aromatic, while the most stable 1,2-isomer is of intermediate aromaticity.[8] The stability trend was rationalized by the quality of the σ bonds.[8c,e,f] Thus, 1,2-azaborine, having two CC double bonds ($\sigma_{CC}$ = 106 kcal/mol)[9] and one BN bond ($\sigma_{BN}$ = 109.8 kcal/mol)[9] is the most stable. Next comes 1,4-isomer with two CC double bonds, but no BN bond, and the least stable is 1,3-isomer having only one CC double bond and no BN bond. The presence of BN bond, however, was suggested to be the main reason for weaker aromaticity of 1,2-azaborine relative to 1,3-isomer. Thus, the π-electron delocalization within the BN bond disrupts the overall π-electron delocalization, which results in smaller degree of aromaticity.[8c,f] The different trend of stability and aromaticity was rationalized by us[8b] as being due to the inherent charge separation of the π-electronic system of 1,3-isomer (Figure 2) which is responsible for its highest energy. Curiously,

this same effect is also responsible for its largest aromaticity, by acting as a driving force for the strongest π-electron delocalization. Even though 1,2-isomer contains bond between the two atoms with large difference in electronegativity (B and N) and can be expected to be the least aromatic, the 1,4-B/N relationship decreases aromaticity to greater extent. This is because of the mostly one-directional π-electron delocalization in 1,4-isomer, from nitrogen to boron, i.e. the push-pull interaction (Figure 2).[8b]



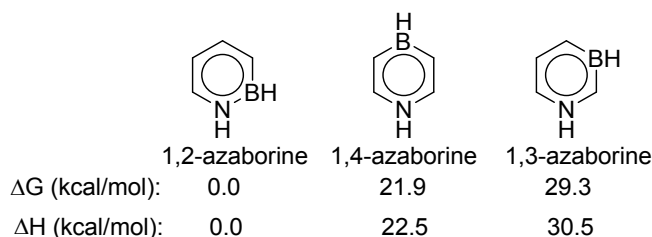|  | 1,2-azaborine | 1,4-azaborine | 1,3-azaborine |
|---|---|---|---|
| ΔG (kcal/mol): | 0.0 | 21.9 | 29.3 |
| ΔH (kcal/mol): | 0.0 | 22.5 | 30.5 |

**Figure 1.** Relative free energies (ΔG, B3LYP/6-311+G(d,p), ref. 8b) and relative energies (ΔH at 298K, G3MP2, ref. 8e) of the three isomeric azaborines.
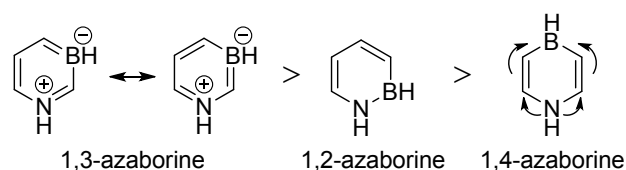


**Figure 2.** Relative aromaticity of the three isomeric azaborines.

Replacement of one CC unit in benzene with the isoelectronic, but polar BN unit endows azaborines with interesting properties so that, in recent years, they have received considerable interest from scientists working in the fields of synthetic, theoretical, material and biological chemistry.[10]

Substituent effects are another important concept in chemistry since they induce changes in electron density and thus affect physico-chemical properties of molecules. In aromatic compounds, substituent effects compete with aromaticity, because substituents′ interaction with π-system decreases degree of π-electron delocalization. The relationship between substituent effects and aromaticity is continuing to be the topic of great interest among chemists. It has been shown that aromaticity of monosubstituted benzene mostly resists substituent effects,[11] while it can be

3

significantly affected by poly-substitution.[12] Monosubstituted heterocycles can show larger substituent effects[13] and also raise a question about relation between aromaticity and stability, which can go in opposite directions.[14]

In this work,[15] we examine the competing influence of substituent effects and azaborine ring effects, affected by the B/N relationship, on aromaticity and stability of all isomeric monosubstituted azaborines. Whereas aromaticity and stability of azaborines themselves were subject of many studies,[8] properties of substituted compounds have not yet been addressed, except for hydroxy-substituted 1,2-azaborine isomer.[16] The latter work showed that substition at boron atom creates more stable, but less aromatic compound than substitution at nitrogen atom. This was explained by an increase in the polarity of B−N bond and by oxygen lone pair delocalization in *B*-substituted isomer which increases its stability but reduces aromaticity, while lone pairs repulsion destabilizes *N*-substituted isomer but increases its aromaticity.[16] Similar effects were previously observed for monosubstituted borazine[14a] and symetrically trisubstituted borazine[17] containing various electron-donating or electron-accepting groups. Understanding of such basic molecular properties and factors governing them should be of value for further exploration and application of BN/CC isosterism in the case of benzene derivatives and also for our better understanding of fundamental concepts in chemistry, such as aromaticity and substituent effects.

The purpose of the work is twofold: to enhance our knowledge on substituted BN isosters of benzene and to show that the general thought that aromaticity accounts for an increased thermodynamic stability is not the best description of the concept, because, as mentioned above and as will be shown in the paper, higher degree of aromaticity does not always bring greater stability. Furthermore, our calculations provide an example of stereoelectronic chameleonic behaviour of $NH_2$ group.

## Methods and Computational Details

In order to examine substituent effects on aromaticity and stability of the three isomeric azaborines, we chose two substituents: nitro group, as a representative of electron-accepting groups, and amino group, as a representative of electron-donating groups.

### Evaluation of Degree of Aromaticity

Degree of aromaticity was quantified by means of indices which belong to the four kinds of manifestation of the phenomenon: bond length equalization, electron delocalization, magnetic shielding and energetic stabilization.

The harmonic oscillator model of aromaticity (HOMA) index[1] was used to assess a degree of bond length equalization and bond lengths' closeness to an optimal bond length of an aromatic compound. It is defined as in Eq. 1, where $\alpha$ represents an empirical constant taken to give HOMA = 1 for systems in which all bonds are equal to an optimal bond length ($R_{opt}$) and HOMA = 0 for nonaromatic system. An individual bond length is given by $R_{i,j}$ is related with the type of the bond and $n$ is the number of bonds taken into summation. The following $\alpha/R_{opt}$ (Å) have been used for HOMA calculations: 118.618/1.4386 (BC), 72.03/1.402 (BN), 257.7/1.388 (CC) and 93.52/1.334 (CN).[1a]

$$\text{HOMA} = 1 - \frac{\alpha_j}{n}\sum_{i}^{n} (R_{opt,j} - R_{j,i})^2 \qquad (1)$$

A degree of electron delocalization was estimated on the basis of two indices, *para*-delocalization index (PDI) and aromatic fluctuation index (FLU). The PDI represents an average of delocalization indices between *para*-related atoms in a six-membered ring (Eq. 2, $\delta$ = delocalization index) and is based on the idea that delocalization of electron density in benzene is greater between *para*-related carbons than between *meta*-related carbons.[2,18] The PDI increases with increasing aromaticity.

$$PDI = \frac{\delta(1,4) + \delta(2,5) + \delta(3,6)}{3} \qquad (2)$$

The FLU index (Eq. 3, $N$ = the number of atoms in a ring) is the measure of the fluctuation of electronic charge between adjacent atoms in a given ring.

$$FLU = \frac{1}{N} \sum_{i=1}^{N} \left[ \left( \frac{V(A_i)}{V(A_{i-1})} \right)^{\alpha} \left( \frac{\delta(A_i, A_{i-1}) - \delta_{ref}(A_i, A_{i-1})}{\delta_{ref}(A_i, A_{i-1})} \right) \right]^2 \qquad (3)$$

The $V(A)$ is defined as in Eq. 4 and $\alpha$ is a function to ensure that the first term is always greater or equal to 1 (Eq. 5).

$$V(A_i) = \sum_{A_j \neq A_j} \delta_{ref}(A_i, A_j) \qquad (4)$$

$$\alpha = \begin{cases} 1 & V(A_i) > V(A_{i-1}) \\ -1 & V(A_i) \leq V(A_{i-1}) \end{cases} \qquad (5)$$

The FLU values are close to zero in aromatic compounds and increase upon going to nonaromatic and antiaromatic molecules.[2,19] The following reference values for delocalization indices were used for the FLU calculations: 1.42 e (BC), 1.26 e (BN), 1.468 e (CC) and 1.566 e (CN).[20]

As a magnetic index of aromaticity, we used the nucleus independent chemical shift (NICS).[3c,21] Calculated NICS value represents the magnitude of (de)shielding at a point in the vicinity of the molecule. To characterize (anti)aromaticity it is used with the negative sign and is calculated at the center of the ring or at a chosen distance above/below it. Thus, negative NICS values (magnetically shielded) indicate presence of diatropic ring currents and aromaticity, while positive NICS values (magnetically deshielded) denote paratropic ring currents and antiaromaticity. We used two of its variants. They are the $NICS(1)_{zz}$ and the $NICS(0)_{\pi zz}$. The first one corresponds to the out-of-plane component of magnetic shielding calculated 1 Å above the center of the ring and the second one involves only the $\pi$-electron contribution to the out-of-plane component of magnetic shielding calculated at the center of the ring. The latter is considered as the most refined NICS index.[21a] The center of the ring is the geometric center calculated as an average of coordinates of heavy atoms making up the ring. Negative NICS values indicate diatropic currents and aromaticity,

positive values denote paratropic currents and antiaromaticity, and values close to zero correspond to nonaromatic system.

The extra cyclic resonance energy (ECRE), which measures extra stabilization of a molecule due to cyclic electron delocalization, was used as an energetic criterion of aromaticity.[4a] It was calculated as a difference between vertical resonance energy (VRE) of cyclic molecule and acyclic reference systems. The VRE represents the resonance energy (difference in energy between localized and delocalized state of a molecule) evaluated at an optimal geometry of delocalized state. For the reference systems, we used three appropriately substituted *cis*-1,3-butadiene molecules which had the same number and the same kind of π-electron conjugations as in cyclic molecules. The *cis*-conformation was chosen because butadiene fragments in cyclic systems have *cis* arrangement. When cyclic compound had the $C_s$ or $C_{2v}$ symmetry, reference systems were taken in their $C_s$ symmetry forms, which, in many cases corresponded to transition state structure with one imaginary frequency, or to the second order saddle point with two imaginary frequences. When cyclic compound had the $C_1$ symmetry, or $C_2$ in the case of 1,4-isomer with B−NO₂ group, substituent conformation was kept the same in cyclic molecule and acyclic reference. In cases when azaborine ring was not fully planar, the same dihedral angles were used in acyclic reference molecules while other parameters were fully optimized. In the case of reference systems having the $C_1$ symmetry, the σ/π separation was good, except in two cases (see Table S3 in the ESI). Positive ECRE values mean stabilization of a cyclic molecule relative to acyclic reference molecules and negative ones denote destabilization. Details of ECRE calculations are provided in Table S3.

**Examination of Relative Stability**

To get insight into the factors which determine stability of examined compounds we performed an isomerization energy decomposition analysis (IEDA).[7b,22] Since boron-substituted compounds were found to be the most stable for each substituent (NO₂ and NH₂) and for each azaborine isomer, an isomerization process was performed by moving substituent from boron atom

to another site in the molecule. The related energy change is isomerization energy ($\Delta E_{iso}$). This energy can be separated into two main energy parts: change in deformation energy ($\Delta\Delta E_{def}$) and change in interaction energy ($\Delta\Delta E_{int}$), as given by Eq. 6.

$$\Delta E_{iso} = \Delta\Delta E_{def} + \Delta\Delta E_{int} \qquad (6)$$

The $\Delta\Delta E_{def}$ term involves energy change due to structural changes of substituent and azaborine ring that occur upon isomerization and energy needed to transfer hydrogen atom from carbon or nitrogen atom to boron atom. Thus, this energy term involves differences in CH, NH and BH bond energies. The $\Delta\Delta E_{int}$ term is related to changes in substituent-ring bond strenght occurring upon isomerization. This energy depends on the relative strength ($\Delta\Delta E$ value) of classical electrostatic interactions ($\Delta E_{elstat}$), quantum-mechanical orbital interactions ($\Delta E_{Pauli}$ and $\Delta E_{oi}$) and dispersion interactions ($\Delta E_{disp}$) in the isomers considered (Eq. 7).

$$\Delta\Delta E_{int} = \Delta\Delta E_{elstat} + \Delta\Delta E_{Pauli} + \Delta\Delta E_{oi} + \Delta\Delta E_{disp} \qquad (7)$$

The $\Delta E_{elstat}$ term involves attractive (electron-nucleus) and repulsive (electron-electron and nucleus-nucleus) electrostatic interactions, where the former prevail in a molecule. Thus, electrostatic energy can be more or less attractive upon going from one isomer to another. The $\Delta E_{Pauli}$ involves repulsive (destabilizing) interactions occuring between the same spin electrons of substituent and the ring. The stabilizing $\Delta E_{oi}$ energy involves the strength of the substituent-ring σ bond, donor-acceptor interactions between substituent and the ring, and polarization (empty-occupied orbital mixing in substituent due to the presence of ring, and vice versa). The $\Delta E_{disp}$ is associated with stabilizing dispersion forces.

In order to perform energy decomposition analysis (EDA) we formed a molecule from two radical fragments, the ring and the substituent (Scheme 1). These fragments had opposite spin so that they could form a bond.

<div align="center">

**azaborine** ⌐  +  ⌐ **substituent** ⟶ **substituted azaborine**

</div>

**Scheme 1.** Formation of substituted azaborines from two radical fragments.

8

The deformation energy of each fragment was calculated as an energy change upon going from its equilibrium geometry to the one it had in a molecule, while deformation energy of each molecule ($\Delta E_{def}$) was obtained by summing up these two energies (Eq. 8). Since the equilibrium azaborine radical had unpaired electron at boron atom, the $\Delta E_{def}$ also involves hydrogen transfer energy.

$$\Delta E_{def} = \Delta E_{def}(azaborine) + \Delta E_{def}(substituent) \qquad (8)$$

The interaction energy of each molecule ($\Delta E_{int}$) was partitioned into various energy components (Eq. 7) by using the localized molecular orbital energy decomposition analysis (LMOEDA) of Su and Li.[23]

When azaborine ring isomerization energy was examined, molecule was studied as being composed of six radical fragments, where NH(R) and BH(R) were taken in their triplet electronic state and four CH(R) fragments were taken in their quartet electronic state. Isomerization was carried out by exchanging positions of these fragments so that they corresponded to those in the three azaborine isomers.

**Computational Details**

All calculations were done at the B3LYP/6-311+G(d,p) level of theory.[24] The Gaussian 09[25] was used for geometry optimization, frequency calculations and NICS calculations, which were performed with the GIAO method.[26] Only energy minimum structures, with no imaginary frequences, are discussed in the manuscript. Stability test, performed for substituted 1,3-azaborines, confirmed that the molecules are closed-shell singlet species at the theory level employed. All high energy isomers were also optimized in their triplet states, which were higher in energy than the closed-shell singlet state. For NICS(0)$_{\pi zz}$ calculations, the natural chemical shielding analysis (NCS)[27] of NBO 3.1 implemented in Gaussian 09, was used. The NCS separates total shielding into contribution from natural localized molecular orbitals (NLMOs), so that we could extract contributions from $\pi$-orbitals only. Resonance energies for ECRE calculations were calculated by NBO deletion analysis[28] of NBO 6.0 version,[29] linked to Gaussian 09. Six $\pi$-electron delocalizations

were switched off in cyclic molecule and two in each acyclic reference system. When cyclic/acyclic molecules had less than three/two $\pi$-bonds in NBO analysis, the $\pi$-bonds were generated by using the ″choose″ keyword of NBO analysis. The final ECRE values are based on the relative weights of two resonance structures of cyclic compounds, which were calculated by means of the natural resonance theory analysis (NRT)[28] of NBO 6.0, with the use of ″nrtstr″ keyword. The HOMA, PDI and FLU indices were calculated by using the Multiwfn program.[30] The EDA was performed by employing the LMOEDA,[23] implemented in the Gamess program.[31]

## Results and Discussion

### Molecular structures and NH$_2$ as stereoelectronic chameleon

The carbon analogue of the studied nitro derivatives, nitrobenzene, has a planar structure and all nitro-substituted azaborines are planar, too, except 4-nitro-1,3-azaborine, which very sligthly deviates from planarity, and 4-nitro-1,4-azaborine which was optimized with $C_2$ symmetry and dihedral angle of 63° between the substituent and the ring. However, the energy difference between these two energy minimum structures and planar transition state structures was very small (< 0.5 kcal/mol).

Another carbon analogue of the studied molecules, aniline, possesses slightly pyramidalized nitrogen atom. The extent of pyramidalization can be varied by substituents and it correlates well with the electron-accepting ability of the ring.[32] However, attachment of amino group at azaborine ring gives the NH$_2$ potential to behave as stereoelectronic chameleon.[33] When placed at the electron-deficient boron atom, the NH$_2$ is the strong p-electron donor and all *B*-substituted azaborines are planar. This can be ascribed to an enhanced resonance between nitrogen lone pair ($N_{LP}$) and boron atom.[34] However, when the NH$_2$ group is moved at the electron rich nitrogen atom the $N_{LP} \rightarrow \pi^*$ interaction is significantly reduced. This effect, along with an increased steric repulsion between the $N_{LP}$ and the electron rich part of the $\pi$-system of the ring induces a conformational change, which results in the in-plane orientation of the $N_{LP}$ (Figure 3). The resulting conformation is stabilized by

the $\pi \rightarrow \sigma^*_{NH}$ hyperconjugation, which is increased in this case due to the increased $\pi$-electron density at nitrogen atom, and the overall result is the transformation of the strong p-donor into the $\pi$-acceptor, the effect named as stereoelectronic chameleonism.[33] The data in Figure 3 show that the difference in energy between conformation with the $N_{LP}$ oriented perpendicularly to the ring plane and the in-plane conformation is the largest for 1,4-azaborine and the smallest for 1,3-azaborine. This is consistent with the strength of the $\pi$-electron delocalization, which is the strongest in 1,3-isomer and the weakest in 1,4-isomer.
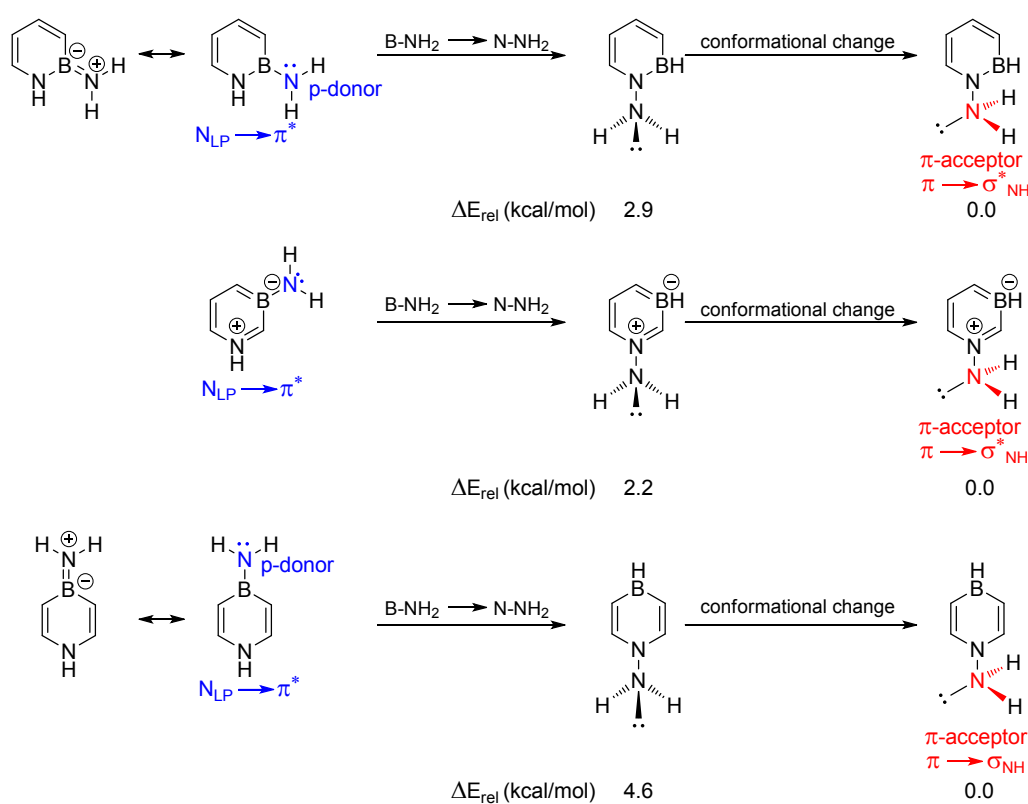


**Figure 3.** The $NH_2$ as stereoelectronic chameleon when moved from boron atom to nitrogen atom within the azaborine ring.

In carbon substituted azaborines (Figure 4), nitrogen atom of amino group is more or less pyramidalized, whereas the spatial position of $N_{LP}$ is almost perpendicular to the azaborine ring (difference between $\angle$ HNCC and $\angle$ HNCC(B) is less than 10°) when substituent is attached at the carbon atom which is *ortho*-related to boron atom (3-amino-1,2-azaborine, 3-amino-1,4-azaborine and 4-amino-1,3-azaborine) or *meta*-related to boron atom (4-amino-1,2-azaborine and 5-amino-

1,3-azaborine). A strong interaction between $NH_2$ group and $\pi$-system of the ring is theoretically predicted for 4-amino-1,3-azaborine in which the sum of bond angles around nitrogen atom amounts 357°. In all these compounds, the $NH_2$ behaves as p-electron donor. The *ortho-* or *meta-* relation to boron atom and, at the same time, *ortho*-relation to nitrogen atom (6-amino-1,2-azaborine, 2-amino-1,4-azaborine and 2-amino-1,3-azaborine) creates an angle of less than 90° between the $N_{LP}$ and the ring (difference between $\angle$ HNCN and $\angle$ HNCC(B) is more than 20°). This can be ascribed to the decreased $N_{LP} \rightarrow \pi^*$ electronic interaction and to the molecular tendency to reduce $N_{LP}/\pi$ repulsion, which both go larger near the electronegative nitrogen atom. The *meta-* relation to nitrogen atom (and *para*-relation to boron atom, 5-amino-1,2-azaborine) has the same result, which can be atributted to nitrogen resonance effect increasing the $\pi$-electron density at that site. The *ortho*-relation to nitrogen and *para*-relation to boron results in an almost in-plane orientation of $N_{LP}$ and azaborine ring (6-amino-1,3-azaborine), that is, in this case the $NH_2$ would turn into the electron-accepting group.
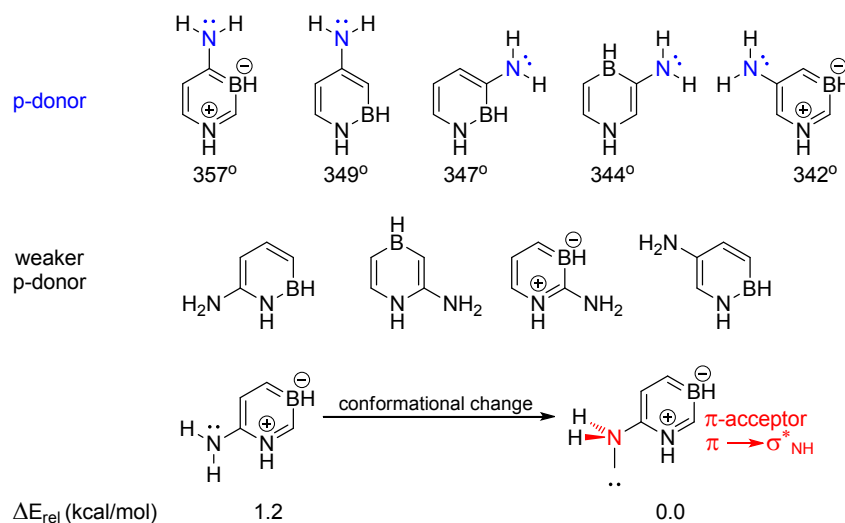


**Figure 4.** The stereoelectronic properties of $NH_2$ when attached at carbon atoms of azaborine ring and the sum of bond angles around nitrogen atom for the p-donor $NH_2$ group.

On the basis of the presented results, our calculations predict that it could be possible to control the stereoelectronic properties of amino group by changing its position within the azaborine ring and this is expected to affect chemical reactivity of amino-substituted azaborines.

### Energetic Stability

Figure 5 shows the structures of all compounds with their relative energies. Values in black show how energy changes when substituent changes its position within the azaborine ring. Values in red represent relative energies of boron-substituted compounds (three isomeric nitro derivatives and three isomeric amino derivatives). Values in green are related to carbon-substituted compounds and represent relative energies of the ten isomeric nitro derivaties and relative energies of the ten isomeric amino derivatives. Values in blue are relative energies of nitrogen-substituted compounds (three isomeric nitro derivatives and three isomeric amino derivatives). Analysis of these energies gives an insight into the effect of azaborine ring isomerization on molecular energy, while substituent remains attached at the same type of atom. Values in violet are energies of all nitro-substituted compounds, or all amino-substituted compounds relative to the most stable isomer, which is, for both series, B-substituted 1,2-azaborine. This analysis takes into account both effects, change of substituent position and ring isomerization.

For all three azaborine isomers, substitution at boron atom creates the most stable system and substitution at nitrogen atom results in the least stable compound, irrespective of electronic properties of substituents ($\Delta G_{(N-R)}$ = 42.1-47.7/48.6-55.9 kcal/mol for R = $NO_2$/$NH_2$, black values in Figure 5). Energies of carbon-substituted molecules are between the $B$- and $N$-substituted ones and are by $\Delta G$ = 18.6-23.6/18.0-31.1 kcal/mol above the most stable $B$-substituted isomer when R = $NO_2$/$NH_2$. The IEDA results (Table S1 in the ESI) show that in the case of B$-NO_2 \rightarrow$ N$-NO_2$ isomerization the most important effect which is responsible for energy rise is better electrostatic stabilization of B$-NO_2$ vs N$-NO_2$ isomers (entries 1, 10, 11, 23, 32, 33, 45, 50 and 51). This is understandable, since boron atom carries partial positive charge and nitrogen atom carries partial negative charge, while nitro group is partially negatively charged, much more so in B$-NO_2$ (around $-0.4$) than in N$-NO_2$ isomers ($-0.07$ or less). In the case of amino substituent, the $B$-substituted isomer in each series is better stabilized by orbital interactions, due to $N_{LP} \rightarrow$ B electron donation, which is the most important effect responsible for energy rise upon B$-NH_2 \rightarrow$ N$-NH_2$

isomerization. The second important effect is, again, better electrostatic stabilization of B–NH$_2$ vs

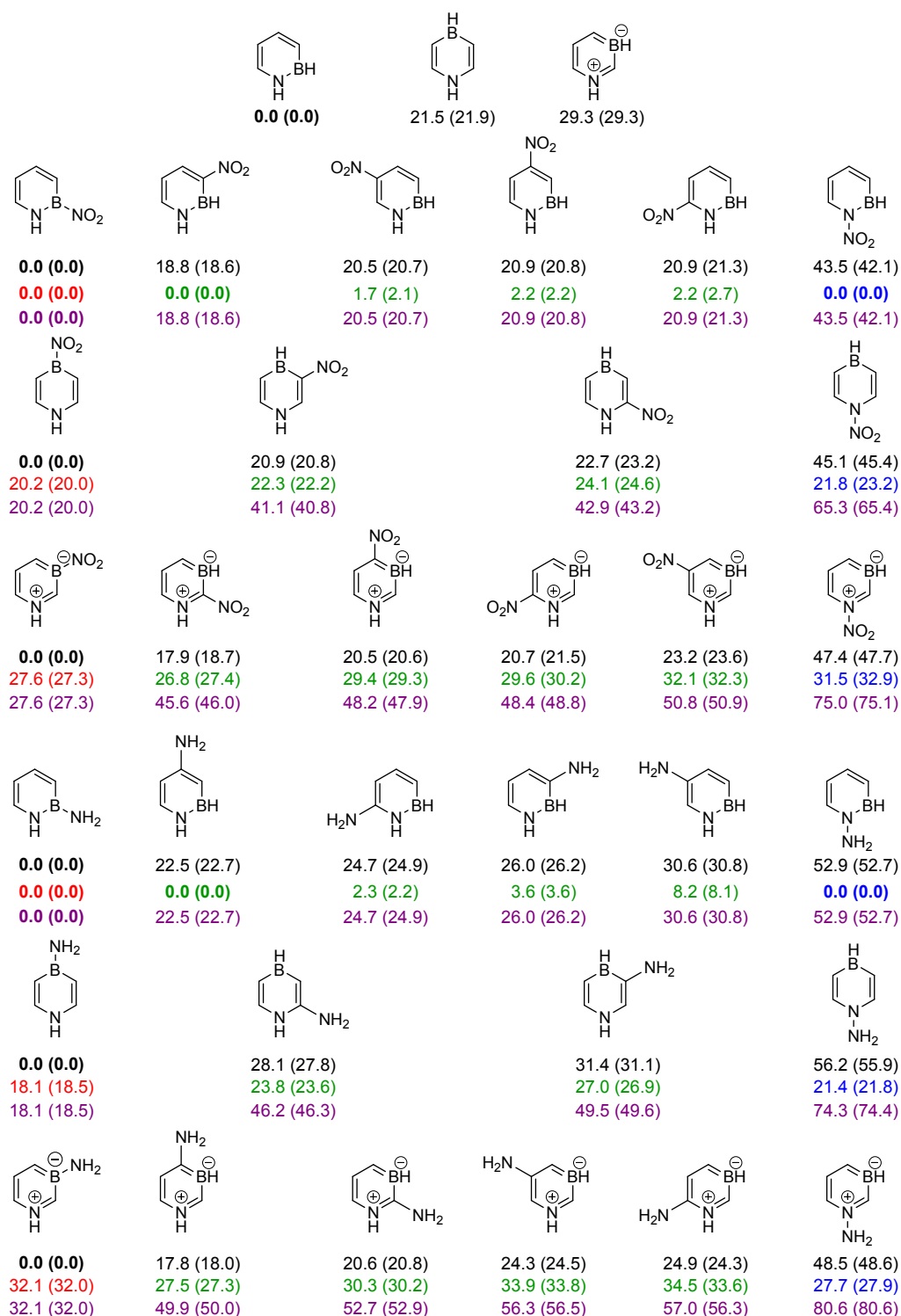N–NH$_2$ isomers (Table S1, entries 12, 21, 22, 34, 43, 44, 52, 57, and 58).



**Figure 5.** Relative energies (including ZPE) and relative free energies (in parentheses) of azaborines and their

monosubstituted derivatives. For substituted compounds, values in black show the effect of substituent position on

energy of a single azaborine isomer, values in red, green and blue show the effect of the azaborine ring isomerization on

molecular energy, while substituent remains attached at the same kind of atom (B, C, or N), values in violet include both effects and represent energies of all nitro or amino derivatives relative to the most stable one.

In 1,2- and 1,4-azaborine series, transfer of nitro group from boron to carbon atom decreases electrostatic stabilization, as well, but to lesser extent than the transfer to nitrogen atom (Table S1, entries 1-9 and 45-49). This effect is partly responsible for weaker stability of C–NO$_2$ vs B–NO$_2$ isomers. Another one involves an increase in the Pauli repulsion and can be ascribed to repulsive effects between $\pi$-electrons of the nitro group and $\pi$-electrons of the azaborine ring, which are more intense when NO$_2$ resides at carbon atom than at electron-deficient boron atom. These repulsive effects are more pronounced in 1,2-azaborine series which is a consequnce of somewhar shorter C–NO$_2$ bonds (1.46-1.47 Å in 1,2-isomers and 1.48-1.49 Å in 1,4-isomers). It is interesting that the C–NO$_2$ bond in 4-nitro-1,2-azaborine is long (1.505 Å) so that there is no increase in Pauli repulsion upon B–NO$_2$ → C–NO$_2$ isomerization (entries 1, 6 and 7). Small, or negative changes in repulsive effects upon transfer of NO$_2$ from boron to nitrogen atom can also be explained by long N–NO$_2$ bonds, while it should be kept in mind that molecules often increase bond lengths just to decrease destabilization due to the Pauli repulsion. In the case of amino-substituted 1,2- and 1,4-azaborines, decrease in stabilizing orbital interactions and somewhat smaller decrease in electrostatic stabilization occuring when B–NH$_2$ isomerizes into C–NH$_2$ are the main sources of energy rise, that is the smaller stability of carbon-substituted amino derivatives (entries 12-20 and 52-56).

The absence of uniformity of change in electrostatic, Pauli and stabilizing orbital interactions when R is transferred from boron to carbon atom in 1,3-azaborine series can be attributed to charge separation of the $\pi$-system of 1,3-isomer, though a diradical character of this molecule was also suggested.[35] For NO$_2$ group, the dominant effect leading to molecular destabilization upon B-NO$_2$ → C-NO$_2$ isomerization is increase in Pauli repulsion (Table S1, entries 23-31). There is a decrease in electrostatic stabilization only for 4-NO$_2$ and 5-NO$_2$ isomers (entries

23, 26, 27, 30 and 31), almost equal in magnitude as $\Delta\Delta E_{Pauli}$ for the latter (entry 31). The other two isomers become slightly better stabilized by $\Delta E_{elstat}$. For $NH_2$ substituent, the reduced orbital interactions and to lesser extent decreased electrostatic stabilization are mainly reponsible for the weaker stability of the three $C-NH_2$ isomers vs $B-NH_2$ isomer (entries 34, 37-42), but there is a reversal of effects for 4-amino-1,3-azaborine which is destabilized by Pauli interactions, but better stabilized by $\Delta E_{elstat}$ and $\Delta E_{oi}$ (entries 34-36). This is a consequence of the strong substituent-ring interaction, which shortens the C–N bond to only 1.37 Å. Shorter bonds have larger Pauli repulsion, but better orbital and electrostatic interactions.

Data in Figure 5 show that azaborine ring effects are dominant effects that determine relative stability when substituent is attached at the same kind of atom (values in red/green/blue for boron/carbon/nitrogen atoms). Thus, when substituent is placed at boron or at nitrogen atom, 1,2-azaborine ring isomerization into 1,4-azaborine, and further isomerization into 1,3-azaborine increases the energy by very similar values as in the case of unsubstituted azaborine ring isomerizations. The stability trend 1,2-azaborine > 1,4-azaborine > 1,3-azaborine is the same for C-substituted compounds, only difference in energy between the ring isomers becomes smaller, particularly between the least stable 1,4-azaborine isomer and the most stable 1,3-azaborine isomer (2.7 kcal/mol and 0.4 kcal/mol for $NO_2$ and $NH_2$ derivatives, respectively). This decrease in energy difference can be attributed to stabilization of separated charges of 1,3-isomeric ring by substitent, which decreases $\Delta\Delta E_{def}$ component (the EDA data in Table S2, entries 1-6 for $NO_2$ and 7-12 for $NH_2$).

The, above mentioned, stability trend of azaborine isomers can be affected by substituent effects when comparing all nitro-derivatives, or all amino-derivatives (Figure 5, values in violet). Firstly, 1,2-azaborine having substituent at boron atom is the most stable for both nitro-substituted and amino-substituted series. Substituent effects (slightly) destabilize C-substituted 1,2-azaborines relative to *B*-substituted 1,4-azaborines, so that the latter is slightly more stable than 5-nitro-1,2-azaborine and more stable than any of C-$NH_2$ 1,2-azaborine isomers. This reversal of stability trend

of 1,2 and 1,4 azaborine isomers originates from smaller *B*-substituted 1,2-azaborine $\rightarrow$ *B*-substituted 1,4-azaborine isomerization energy compared with that of parent compounds and can be attributed to the smaller Pauli repulsion increase upon isomerization when boron atom contains substitutent (Table S2 in the ESI, entries 13-21). The increased Pauli repulsion in 1,4-isomer relative to 1,2-isomer can be ascribed to repulsive effects between nitrogen lone pair and neighbouring $\pi$-electrons (only one such interaction in 1,2-azaborine). The data in Table S2 suggest that substitution at B atom mostly affects (increases) $\Delta E_{Pauli}$ in 1,2-isomer, thus reducing $\Delta\Delta E_{Pauli}$ upon isomerization. This can be ascribed to increased $\pi$-electron density at B atom, which is due to the direct $N_{LP} \rightarrow$ B electron donation ($NH_2$), or $\pi$-electron withdrawal toward B atom because of its increased $-I$ effect when substituted with $NO_2$ group. The *B*-substituted 1,3-azaborines come next, according to their stability (after C-R 1,2-azaborines), and are more stable that C-substituted 1,4-azaborines. Since B-R 1,4-azaborine $\rightarrow$ B-R 1,3-azaborine isomerization energy is similar to that of parent compounds when R = $NO_2$, or is larger when R = $NH_2$, the greater stability of *B*-substituted 1,3-system relative to C-substituted 1,4-system (by ~13 kcal/mol) should be attributed to better electrostatic stabilization and lower Pauli repulsion for B-substitution when R = $NO_2$, or better electrostatic and orbital stabilization for B-substitution when R = $NH_2$. More favourable electrostatic energy of C-substitution compared with N-substitution (R = $NO_2$), or more favourable electrostatic and orbital interactions (R = $NH_2$) are the main reasons for lower energy of C-R 1,4-isomers relative to N-R 1,2-isomers (Table S1, entries 48 and 50 for R =$NO_2$, 55 and 57 for R =$NH_2$), since N-R 1,2-azaborine $\rightarrow$ 1,4-isomerization energy is similar to that of parent azaborines. Finally, carbon substitution stabilizes 1,3-azaborine ring system relative to *N*-substituted 1,4-azaborine ring system because of better electrostatic and orbital interaction energy (Table S1, entries 30 and 32 for R =$NO_2$, 41 and 43 for R =$NH_2$). The least stable compound for each series of substituents is N-R 1,3-azaborine isomer.

## Aromaticity

Correlation between indices, which were used to quantify aromaticity, range from poor to good (Table S4 in the ESI) and this can be expected because they characterize various manifestations of aromaticity phenomenon, as is widely discussed in the literature. Nevertheless, the calculated indices are indication of similarities and differences between aromaticity degree of the studied compounds and the following conclusions are based on examination of all kinds of indices.

Firstly, we discuss how moving of NO$_2$ group across the azaborine ring influences aromaticity. Data in Figure 6 indicate that differences in degree of aromaticity between *B/C*-substituted 1,2- and 1,4-isomers and parent compounds are small, only *B*-substituted 1,2-azaborine appears to be slightly more aromatic. Substitution at nitrogen atom, however, affects aromaticity to larger extent: *N*-substituted isomers are less aromatic and substituent effect is more pronounced in the least aromatic 1,4-isomer. In this case, the electron-accepting NO$_2$ group has the largest interaction with the π-electronic system of the ring, thus decresing its aromaticity, because the π-electron density is larger at nitrogen atom. In the case of B-NO$_2$ substitution, interaction of substituent with the π-system is the weakest, while boron atom becomes more electron-withdrawing due to –I effect of the substituent and, consequently, aromaticity of 1,2-isomer slightly increases. In 1,3-azaborine, substituent effects are small at any position and this is in accord with the largest π-electron delocalization in this isomer. The B-NO$_2$ isomer mostly retains aromaticity of its parent compound, whereas the others are only slightly less aromatic. This slight decrease in aromaticity makes nitro-substituted 1,3-azaborine isomers and B-NO$_2$-1,2-isomer to be similarly aromatic. The N-NO$_2$ 1,2-azaborine and B/C-NO$_2$ 1,4-azaborines also have comparable degree of aromaticity, and no reversal of aromaticity order of the three isomeric BN rings has been observed upon introduction of electron-withdrawing nitro group. All BN compounds are (slighty) less aromatic than their carbon analogue, nitrobenzene.

| | | | | | |
|---|---|---|---|---|---|
| NICS(1)$_{zz}$ | -29.25 | -27.51 | -24.85[a] | -20.31 | -25.16 | -19.64 |
| NICS(0)$_{\pi zz}$ | -35.77 | -33.93 | -34.73 | -25.42 | -31.15 | -24.38 |
| HOMA | 0.990 | 0.994 | 0.976 | 0.782 | 0.807 | 0.632 |
| PDI | 0.1074 | 0.0969 | 0.0950 | 0.0838 | 0.0848 | 0.0660 |
| FLU | 0.0000 | 0.0012 | 0.0019 | 0.0113 | 0.0081 | 0.0219 |
| ECRE | 93.99 | 85.72 | 85.50 | 55.69 | 76.66 | 33.51 |

| | | | | | |
|---|---|---|---|---|---|
| NICS(1)$_{zz}$ | -21.50 | -18.83 | -18.11 | -19.84 | -19.19 | -16.15 |
| NICS(0)$_{\pi zz}$ | -27.00 | -23.57 | -22.89 | -24.84 | -24.10 | -20.34 |
| HOMA | 0.876 | 0.812 | 0.788 | 0.764 | 0.766 | 0.706 |
| PDI | 0.0828 | 0.0776 | 0.0714 | 0.0823 | 0.0729 | 0.0740 |
| FLU | 0.0093 | 0.0141 | 0.0130 | 0.0141 | 0.0143 | 0.0210 |
| ECRE | 79.27 | 68.45 | 59.78 | 23.39 | 42.27 | 32.25 |

| | | | | | |
|---|---|---|---|---|---|
| NICS(1)$_{zz}$ | -11.77 | -15.58[a] | -16.37[a] | -18.62[a] | -18.94[a] | -20.60 |
| NICS(0)$_{\pi zz}$ | -18.06 | -22.58 | -23.49 | -26.45 | -26.56 | -25.99 |
| HOMA | 0.646 | 0.776 | 0.835 | 0.743 | 0.756 | 0.811 |
| PDI | 0.0699 | 0.0693 | 0.0754 | 0.0743 | 0.0813 | 0.0835 |
| FLU | 0.0204 | 0.0112 | 0.0108 | 0.0180 | 0.0149 | 0.0117 |
| ECRE | 25.64 | 29.25 | 76.17 | 40.37 | 27.57 | 81.12 |

| | | | | |
|---|---|---|---|---|
| NICS(1)$_{zz}$ | -19.76 | -18.20 | -19.21 | -14.33 |
| NICS(0)$_{\pi zz}$ | -25.30 | -22.44 | -23.85 | -18.31 |
| HOMA | 0.749 | 0.630 | 0.626 | 0.523 |
| PDI | 0.0649 | 0.0611 | 0.0617 | 0.0511 |
| FLU | 0.0218 | 0.0269 | 0.0238 | 0.0374 |
| ECRE | 32.72 | 36.24 | 35.29 | 14.53 |

| | | | | |
|---|---|---|---|---|
| NICS(1)$_{zz}$ | -11.00 | -15.69[a] | -19.19[a] | -19.28 |
| NICS(0)$_{\pi zz}$ | -16.04 | -21.29[b] | -26.35[b] | -24.38 |
| HOMA | 0.449 | 0.633 | 0.677 | 0.641 |
| PDI | 0.0496 | 0.0594 | 0.0630 | 0.0641 |
| FLU | 0.0363 | 0.0251 | 0.0220 | 0.0258 |
| ECRE | 12.65 | 37.62 | -56.20 | 37.87 |

| | | | | | |
|---|---|---|---|---|---|
| NICS(1)$_{zz}$ | -25.36 | -22.22 | -23.63[a] | -21.82 | -24.27 | -23.11 |
| NICS(0)$_{\pi zz}$ | -31.42 | -27.59 | -29.32 | -27.27 | -29.94 | -28.55 |
| HOMA | 0.889 | 0.771 | 0.796 | 0.767 | 0.807 | 0.809 |
| PDI | 0.0825 | 0.0739 | 0.0822 | 0.0679 | 0.0811 | 0.0784 |
| FLU | 0.0095 | 0.0184 | 0.0146 | 0.0159 | 0.0101 | 0.0132 |
| ECRE | 93.06 | 37.38 | 85.74 | -17.20 | 69.90 | 60.14 |

| | | | | | |
|---|---|---|---|---|---|
| NICS(1)$_{zz}$ | -17.80 | -20.38[a] | -21.03[a] | -21.60[a] | -24.54[a] | -24.51 |
| NICS(0)$_{\pi zz}$ | -26.71 | -29.95 | -29.09[b] | -29.43[b] | -31.04 | -30.58 |
| HOMA | 0.697 | 0.761 | 0.757 | 0.811 | 0.810 | 0.811 |
| PDI | 0.0726 | 0.0685 | 0.0762 | 0.0785 | 0.0821 | 0.0829 |
| FLU | 0.0169 | 0.0148 | 0.0169 | 0.0093 | 0.0104 | 0.0112 |
| ECRE | 58.04 | 0.94 | 30.65 | 56.21 | 83.69 | 83.66 |

[a] Average of the two sides of the ring. [b] Not clear σ/π separation.

**Figure 6.** Calculated aromaticity indices for studied compounds.

19

In the case of amino substituent, theory predicts similar aromatic character of all three N$-$NH$_2$ derivatives and the parent unsubstituted azaborines. This is attributable to the substituent conformation which prevents the N$_{LP}$/$\pi$ interaction. Similar conformation of 6-amino-1,3-azaborine results in high degree of aromaticity, as well. Delocalization of the $\pi$-electron density into the two $\sigma^*_{N-H}$ appears to have a minor effect on the degree of aromaticity. Even though the N$_{LP}$ is almost parallel with the ring p-orbitals of 3-amino-1,4-azaborine, their interaction should be weak due to the increased $\pi$-electron density at the carbon carrying the substituent, coming from nitrogen resonance effect, so that this molecule also possesses similar degree of aromaticity as the parent molecule. Other carbon-substituted compounds are characterized by slightly lower aromaticity which shows small variations with substituent conformation, whereas the three B$-$NH$_2$ isomers are clearly the least aromatic. This is a consequence of the strong N$_{LP}$/$\pi$ interaction at the site of electron-deficient boron atom. The established aromaticity trend 1,3-azaborine > 1,2-azaborine > 1,4-azaborine is affected by amino-substitution only for B-NH$_2$-1,3-azaborine and N-NH$_2$-1,2-azaborine, when the former becomes slightly less aromatic than the latter, while N$-$NH$_2$ 1,2-isomer appears to be similarly aromatic as C$-$NH$_2$ 1,3-isomers and aromaticity of B$-$NH$_2$ 1,3-azaborine, C$-$NH$_2$ 1,2-isomers and N(C)$-$NH$_2$ 1,4-isomers becomes close to each other. The carbon analogue, aniline, is (slightly) more aromatic than any of its BN isosters.

The presented results show that azaborine ring effects mostly win the substituent effects by retaining the original aromaticity order 1,3-azaborine > 1,2-azaborine > 1,4-azaborine, except for B-NH$_2$ substitution of 1,3-isomer and N-NH$_2$-1,2-azaborine, when reversal of aromaticity order has been observed. Though, it should be noted that substitution decreases differences in aromaticity degree between isomeric azaborines and sometimes makes different isomers to have similar aromaticity.

As a guide for experimental chemists, regarding aromaticity, the following can be used. To create a molecule having aromaticity degree comparable to that of the most aromatic 1,3-azaborine, electron-accepting group (NO$_2$) can be introduced at B atom, or electron-donating group (NH$_2$) can

be introduced at N, or C6 of the same isomer. Introduction of $NO_2$ at any other position of 1,3-azaborine, or at B atom of 1,2-azaborine, as well as introduction of $NH_2$ at C atoms of 1,3-azaborine, or at N atom of 1,2-azaborine very slightly reduces aromaticity. Further, also slight, reduction in aromaticity can be achieved by introducing $NH_2$ at B atom of 1,3-azaborine, $NH_2$ and $NO_2$ at C and C/N atoms, respectively, of 1,2-azaborine and $NO_2$ at B/C atoms or $NH_2$ at C/N atoms of 1,4-azaborine isomer. Additional decrease in aromaticity degree comes from B-$NH_2$ substitution of 1,2-azaborine and N-$NO_2$ substitution of 1,4-azaborine and, finally, the least aromatic system can be created by introducing $NH_2$ substituent at B atom of 1,4-isomer.

**Aromaticity and stability**

Comparison of degree of aromaticity and thermodynamic stability of nitro-subtituted compounds shows that molecules having similar degree of aromaticity differ significantly in their relative energy (Figure 5) and this clearly renders aromaticity as just one of several effects that influences thermodynamic stability. Decrease of stability goes along with decrease in aromaticity only when $NO_2$ is moved to nitrogen atom in 1,2- and 1,4-series, but the main reason for substantially higher energy of N-$NO_2$ derivatives is not change in aromaticity, which is not large (Figure 6), but decrease in electrostatic stabilization. In the case of electron-donating $NH_2$ group, aromaticity and stability show opposite trend: (slight) decrease in aromaticity is followed by an increase in thermodynamic stability and both, primarily, come from the same effect, substituent-ring orbital interactions. While such kind of interactions interferes with the six $\pi$-electron delocalization (aromatic stabilization), it thermodynamically stabilizes molecule and together with electrostatic energy component dominates over the aromatic stabilization of thermodynamically less stable isomers. This is one more confirmation that aromaticity does not always account for an increased thermodynamic stability and, thus, should be taken along with other effects to interpret increased or decreased molecular stability.

# Conclusions

In this work we have theoretically examined how substitution of azaborine ring affects energetic stability and aromaticity. In the last section, we discuss them together and show that greater aromaticity does not always mean more stable system. The main conclusions can be summarized as follows.

## Geometry and stereoelectronic chameleonism

Electron-withdrawing group ($NO_2$) orients itself in the plane of azaborine ring, so that its interaction with the ring $\pi$-system is maximal. The electronic properties of amino group depend on its position within the azaborine ring and, thus, can be controlled. When attached at boron atom, or at C4 of 1,3-azaborine, the $NH_2$ acts as a strong electron-donor, with the lone pair orbital perpendicularly oriented with resepect to the ring plane. However, when placed at nitrogen atom, or at C6 of 1,3-azaborine, it aligns the lone pair orbital with the plane of the ring, while the N–H bonds adopt a favourable orientation to act as $\sigma^*$-acceptors. This conformational shift can be considered to be induced by the enhanced steric repulsion between the lone pair and the increased $\pi$-electron density at nitrogen atom and by a decreased magnitude of the $N_{LP} \rightarrow \pi^*$ conjugation, while the resulting conformation is stabilized by $\pi \rightarrow \sigma^*_{NH}$ interactions. At other positions, the $NH_2$ should behave as electron-donor, but with the weaker magnitude of $N_{LP} \rightarrow \pi^*$ interaction, because the $N_{LP}$ is tilted from the $\pi$-parallel orientation.

## Stability

Substituent-ring interactions determine stability trend when substituent is moved accross the ring. In each azaborine series, the most stable is B-R isomer and the least stable is N-R isomer, irrespective of electronic properties of substituent. An increase in energy that follows moving of substituent from B to C or N atoms mainly comes from decrease in electrostatic stabilizing energy ($NO_2$ and $NH_2$) and increase in Pauli repulsion ($NO_2$) or decrease in stabilizing orbital interactions ($NH_2$). Some deviations of this trend were observed for charge-separated 1,3-azaborine isomer.

Azaborine ring effects, influenced by the B/N relationship, are dominant in determining relative stability when comparing compounds in which substituent is attached at the same kind of atom. In this case, stability trend 1,2 > 1,4 > 1,3 is the same for substituted and parent molecules. However, substituent effects can diminish energy difference between carbon-substituted azaborine isomers. When comparing all nitro-derivatives, or all amino-derivatives, substituent effects can change stability order established for parent molecules.

**Aromaticity**

The electron-withdrawing $NO_2$ group has a little effect on aromaticity of the most delocalized 1,3-azaborine isomer and *B*/C-substituted 1,2- and 1,4-isomers. However, it decreases aromaticity when placed at nitrogen atom of 1,2- and 1,4-isomers by more strongly interacting with the ring $\pi$-system.

The electron-donating $NH_2$ group also affects aromaticity degree slightly, except when it is placed at boron atom. At that site, it most strongly interacts with the $\pi$-system, thus decreasing aromaticity.

The aromaticity order of the parent molecules 1,2 > 1,4 > 1,3 is mostly retained by substitution except for *B*-$NH_2$ 1,3-azaborine which is less aromatic than *N*-$NH_2$-1,2-azaborine. However, substitution reduces differences in aromaticity between azaborine isomers and can make different isomers to have similar aromaticity.

**Aromaticity and stability**

Large differences in energies of isomers with similar degree of aromaticity and, particularly, the opposite trend of these two properties, found for some isomeric species, along with other similar examples in the literature, show that more aromatic does not always mean more stable. Stabilization (energy lowering) due to cyclic delocalization of electrons, named as aromaticity, is just one of several, often more pronounced effects that influence molecular stability.

## Acknowledgements

## Conflicts of Interest

There are no conflicts to declare.

## References and Notes

1. a) T. M. Krygowski, H. Szatylowicz, O. A. Stasyuk, J. Dominikowska and M. Palusiak, *Chem. Rev.*, 2014, **114**, 6383-6422; b) T. M. Krygowski and M. K. Cyrański, *Chem. Rev.*, 2001, **101**, 1385-1420.

2. a) F. Feixas, E. Matito, J. Poater and M. Solà, *Chem. Soc. Rev.*, 2015, **44**, 6434-6451; b) J. Poater, M. Duran, M. Solà and B. Silvi, *Chem. Rev.*, 2005, **105**, 3911-3947.

3. a) R. Gershoni-Poranne and A. Stanger, *Chem. Soc. Rev.*, 2015, **44**, 6597-6615; b) R. Islas, T. Heine and G. Merino, *Acc. Chem. Res.*, 2012, **45**, 215-228; c) Z. Chen. C. S. Wannere, C. Corminboeuf, R. Puchta and P. von R. Schleyer, *Chem. Rev.*, 2005, **105**, 3842-3888; d) P. Lazzeretti, *Chem. Phys. Phys. Chem.*, 2004, **6**, 217-223; e) R. H. Mitchell, *Chem. Rev.*, 2001, **101**, 1301-1316.

4. a) Y. Mo and P. v. R. Schleyer, *Chem. Eur. J.*, 2006, **12**, 2009-2020; b) M. K. Cyrański, *Chem. Rev.*, 2005, **105**, 3773-3811.

5.  M. K. Cyrański, T. M. Krygowski, A. R. Katritzky and P. v. R. Schleyer, *J. Org. Chem.*, 2002, **67**, 1333-1338.

6. a) J. Grunenberg, *Int. J. Quantum Chem.*, 2017, **117**, e25359. b) A. Stanger, *Chem. Comm.* 2009, 1939-1947.

7. a) O. A. Stasyuk, H. Szatylowicz and T. M. Krygowski, *Org. Biomol. Chem.*, 2014, **12**, 6476-6483; b) M. El-Hamdi, W. Tiznado, J. Poater and M. Solá, *J. Org. Chem.*, 2011, **76**,

8913-8921; c) Y. Wang, J. I.-C. Wu, Q. Li and P. v. R. Schleyer, *Org. Lett.*, 2010, **12***, 4824-4827; d) M. Mandado, N. Otero and R. A. Mosquera, *Tetrahedron*, 2006, **62**, 12204-12210.

8.  a) A. G. Papadopoulos, N. D. Charistos, K. Kyriakidou and M. P. Sigalas, *J. Phys. Chem. A*, 2015, **119**, 10091-10100; b) M. Baranac-Stojanović, *Chem. Eur. J.*, 2014, **20**, 16558-16565; c) S. Xu, T. C. Mikulas, L. N. Zakharov, D. A. Dixon and S.-Y. Liu, *Angew. Chem. Int. Ed.*, 2013, **52**, 7527-7531; d) D. Ghosh, G. Periyasamy and S. K. Pati, *Phys. Chem. Chem. Phys.*, 2011, **13**, 20627-20636; e) M. H. Matus, S.-Y. Liu and D. A. Dixon, *J. Phys. Chem. A*, 2010, **114**, 2644-2654; f) M. Kranz and T. Clark, *J. Org. Chem.*, 1992, **57**, 5492-5500.

9.  D. J. Grant and D. A. Dixon, *J. Phys. Chem. A*, 2006, **110**, 12955-12962.

10. For review articles, see: a) Z. X. Giustra and S.-Y. Liu, *J. Am. Chem. Soc.*, 2018, **140**, 1184-1194; b) G. Bélanger-Chabot, H. Braunschweig and D. K. Roy, *Eur. J. Inorg. Chem.*, 2017, 4353-4368; c) P. G. Campbell, A. J. V. Marwitz and S.-Y. Liu, *Angew. Chem. Int. Ed.*, 2012, **51**, 6074-6092; d) M. J. D. Bosdet and W. E. Piers, *Can. J. Chem.*, 2009, **87**, 8-29.

11. a) T. Siodla, H. Szatylowicz, K. S. Varaksin and T. M. Krygowski, *RSC Adv.*, 2016, **6**, 96527-96530; b) T. M. Krygowski and B. T. Stępień, *Chem. Rev.*, 2005, **105**, 3482-3512; c) T. M. Krygowski, K. Ejsmont, B. T. Stepień, M. K. Cyrański, J. Poater and M. Solà, *J. Org. Chem.*, 2004, **69**, 6634-6640.

12. I. V. Omelchenko, O. V. Shishkin, L. Gorb, F. C. Hill and J. Leszczynksi, *Struct. Chem.*, 2012, **23**, 1585-1597.

13. C. Curutchet, J. Poater, M. Solà and J. Elguero, *J. Phys. Chem. A*, 2011, **115**, 8571-8577.

14. a) A. K. Srivastava, S. K. Pandey and N. Misra, *Theor. Chem. Acc.*, 2016, **135**, 158. b) I. V. Omelchenko, O. V. Shishkin, L. Gorb, F. C. Hill and J. Leszczynksi, *Struct. Chem.*, 2013, **24**, 725-733.

15. A part of this work was presented at the conference: M. Baranac-Stojanović, M. Stojanović, Aromaticity2018, Riviera Maya, Mexico, 2018, November 28-December 1. Book of Abstracts, p. 65.

16. A. K. Srivastava, S. K. Pandey and N. Misra, *Mol. Phys.*, 2016, **114**, 1763-1770.

17. M. Baranac-Stojanović and M. Stojanović, *RSC Adv.*, 2013, **3**, 24108-24117.

18. J. Poater, X. Fradera, M. Duran and M. Solà, *Chem. Eur. J.*, 2003, **9**, 400-406.

19. E. Matito, M. Duran and M. Solà, *J. Chem. Phys.*, 2005, **122**, 014109.

20. Except for the BC bond, these are the default values of Multiwfn program (ref. 29) and were obtained for borabenzene, borazine, benzene and pyridine calculated at the HF/6-31G(d) level of theory.

21. a) H. Fallah-Bagher-Shaidaei, C. S. Wannere, C. Corminboeuf, R. Puchta and P. v. R. Schleyer, *Org. Lett.*, 2006, **8**, 863-866.

22. For selected examples of IEDA used to study the origin of stability trend of various species, see a) E. Ravell, S. Jalife, J. Barroso, M. Orozco-Ic, G. Hernández-Juárez, F. Ortiz-Chi, S. Pan, J. L. Cabellos and G. Merino, *Chem. Asian J.,* 2018, **13**, 1467-1473; b) M. Baranac-Stojanović, *Eur. J. Org. Chem.,* 2017, 5163-5169; c) M. Contreras, E. Osorio, F. Ferraro, G. Puga, K. J. Donald, J. G. Harrison, G. Merino and W. Tiznado**,** *Chem. Eur. J.,* 2013, **19**, 2305-2310; d) J. Poater, R. Visser, M. Solà and F. M. Bickelhaupt, *J. Org. Chem.,* 2007, **72**, 1134-1142, and ref. 8b.

23. P. Su and H. Li, *J. Chem. Phys.*, 2009, **131**, 014102. The original labeling in that paper was changed as following, $\Delta E_{es} \rightarrow \Delta E_{elstat}$ and $\Delta E_{pol} \rightarrow \Delta E_{oi}$, while the separately given exchange ($\Delta E_{ex}$) and repulsion energy ($\Delta E_{rep}$) were summed up to represent the Pauli repulsion, labeled as $\Delta E_{Pauli}$.

24. a) A. D. Becke, *J. Chem. Phys.*, 1993, **98**, 5648–5652; b) C. Lee, W. Yang and R. G. Parr, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1988, **37**, 785–789; c) J. B. Foresman and A. Frisch in *Exploring Chemistry with Electronic Structure Methods*, Gaussian, Inc., 1996.

25. M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K.

Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, T. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, O. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski and D. J. Fox, *Gaussian 09 (Revision D.01)*, Gaussian, Inc., Wallingford CT, 2013.

26. a) R. Ditchfeld, *Mol. Phys.*, 1974, **27**, 789-807; (b) K. Wolinski, J. F. Hinton and P. Pulay, *J. Am. Chem. Soc.*, 1990, **112**, 8251-8260.

27. J. A. Bohmann, F. Wienhold and T. C. Farrar, *J. Chem. Phys.*, 1997, **107**, 1173–1184.

28. a) E. D. Glendening, C. R. Landis and F. Weinhold, Natural Bond Orbital Methods. *WIREs Comput. Mol. Sci.*, 2012, **2**, 1-42; b) F. Weinhold and C. R. Landis, in *Discovering Chemistry with Natural Bond Orbitals*, John Wiley & Sons, Inc., 2012.

29. E. D. Glendening, J. K. Badenhoop, A. E. Reed, J. E. Carpenter, J. A. Bohmann, C. M. Morales, C. R. Landis and F. Weinhold, NBO 6.0, Theoretical Chemistry Institute, University of Wisconsin, Madison, WI, 2013.

30. T. Lu and F. Chen, *J. Comput. Chem.*, 2012, **33**, 580-592.

31. M. W. Schmidt, K. K. Baldridge, J. A. Boatz, S. T. Elbert, M. S. Gordon, J. H. Jensen, S. Koseki, N. Matsunaga, K. A. Nguyen, S. J. Su, T. L. Windus, M. Dupuis and J. A. Montgomery, Jr., *J. Comput. Chem.*, 1993, **14**, 1347-1363; Gamess 2013-R1 version was used in this work.

32. I. V. Alabugin, M. Manoharan, M. Buck and R. J. Clark, *J. Mol. Struct. Theochem*, 2007, **813**, 21-27.

33. a) P. W. Peterson, N. Shevchenko and I. V. Alabugin, *Org. Lett.*, 2013, **15**, 2238-2241; b) S.

Z. Vatsadze, Y. D. Loginova, G. dos Passos Gomes and I. V. Alabugin, *Chem. Eur. J.*, 2017,
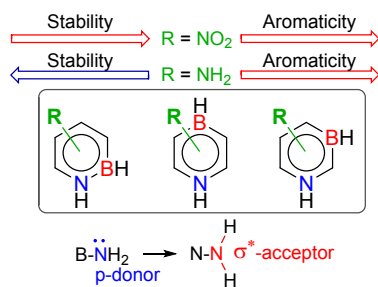
**23**, 3225-3245.

34. I. V. Alabugin, S. Bresch and M. Manoharan, *J. Phys. Chem. A*, 2014, **118**, 3663-3677.

35. T. Zheng, N. Ananth and R. Hoffmann, *J. Am. Chem. Soc.*, 2014, **136**, 12638-12647.

# TOC Graphic



The relationship between aromaticity and thermodynamic stability, and the stereoelectronic chameleonism of amino group are analysed and discussed in the case of monosubstituted azaborines.