1,2-BN Cyclohexane: Synthesis, Structure, Dynamics, and Reactivity

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S *Supporting Information*

ABSTRACT: BN/CC isosterism has emerged as a viable strategy to increase the structural diversity of carbon-based compounds. We present the first synthesis and characterization of the parent 1,2-BN cyclohexane, the BN-isostere of cyclohexane. 1,2-BN cyclohexane is an air- and water-stable compound that cleanly forms a trimer with release of dihydrogen when thermally activated. We also demonstrate that 1,2-BN cyclohexane has a lower activation barrier for ring inversion than cyclohexane due to BN/CC isosterism.

Scheme 1. BN/CC Isosterism of Cyclohexane

The expansion of structural diversity beyond that achieved by Nature is one of the main goals of synthetic chemists. BN/CC isosterism (i.e., replacement of a carbon–carbon bond with a boron–nitrogen bond) has emerged as a viable strategy to increase the chemical space of useful materials and molecules.[1] At the macroscopic level, BN/CC isosterism has led to the development of BN analogues of carbon allotropes (e.g., diamond,[2] graphite,[3] and nanotubes[4]). At the molecular level, this approach has produced conjugated materials with distinct optoelectronic properties,[5] and potential applications in the biomedical field are emerging.[6] Our group has been interested in the development of aromatic systems partially substituted with boron and nitrogen.[7] To this end, we have recently prepared 1,2-dihydro-1,2-azaborine (Scheme 1, top), which is the parent BN isostere of the quintessential aromatic compound, benzene.[8] The corresponding saturated heterocycle, i.e., 1,2-BN cyclohexane (Scheme 1, bottom), is isoelectronic and isostructural to cyclohexane, a molecule of fundamental importance in conformational analysis, and the structural foundation of the concept of A-values.[9] The cyclohexyl motif is also prevalent in biologically active molecules.[10] In contrast to the covalent bonding between the C–C bond in cyclohexane, the N–B bonding in 1,2-BN cyclohexane is of a dative nature. Thus, 1,2-BN cyclohexane is a cyclic member of the family of amine borane complexes. Ammonia borane (NH_3–BH_3; AB), the parent compound of this family, and its acyclic derivatives have recently received significant attention as potential hydrogen storage materials due to favorable attributes such as high storage capacity and facile H_2 release.[11] Cyclic amine boranes have not been extensively investigated in hydrogen storage applications, arguably due to the lack of synthetic access.[12] Despite 1,2-BN cyclohexane's simple structure and its fundamental importance, the isolation of this molecule has remained elusive. In this communication, we present the first synthesis and characterization of the parent 1,2-BN cyclohexane. We show that the replacement of CC with BN in cyclohexane leads to a lower activation barrier of ring inversion. Furthermore, we demonstrate that 1,2-BN cyclohexane is
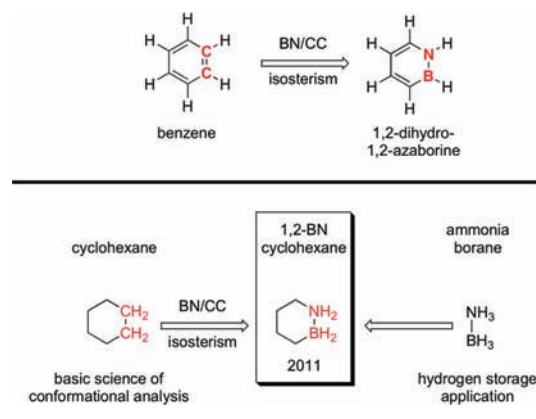
an air- and moisture-stable compound that cleanly releases hydrogen to form a trimer when thermally activated.

A retrosynthetic analysis suggests that an amine-directed hydroboration reaction of homoallylamine might furnish the desired target 1,2-BN cyclohexane in a straightforward fashion (Scheme 2, top).[13] However, despite an extensive screening of reaction conditions, this direct synthetic route was not successful in our hands. The intractable mixtures that we observed might be due to the tendency of hydroboration of homoallylic amines to form regioisomeric products (e.g., five- and six-membered heterocycles) and the propensity of amine boranes to lose H_2 and undergo subsequent oligomerization and/or polymerization.[14] Similarly, removal of the *N-t*-Bu group in compound **A**[12] (Scheme 2) also proved difficult. To avoid the complications associated with H_2 loss in the hydroboration process, we envisioned that hydroboration of a tertiary homoallylic amine in which two of the *N*-substituents are protecting groups could lead to a cleaner process. Gratifyingly, we determined that the use of the bistrimethylsilyl-substituted homoallylamine **1** ultimately led to the successful isolation of the desired 1,2-BN cyclohexane (Scheme 2, bottom). Treatment of **1** with $BH_3 \bullet THF$ under elevated temperature furnished an intermediate consistent with heterocycle **2** (^{11}B NMR: δ 45 ppm (d, $^1J_{BH}$ = 117 Hz)). Without its isolation, **2** was reacted with KH to give cyclic amido borane **3**, which we have characterized by single crystal X-ray diffraction analysis (*vide infra*). Removal of the *N*-TMS protecting group in **3** was accomplished using HF•pyridine to produce the target 1,2-BN cyclohexane in excellent yield.

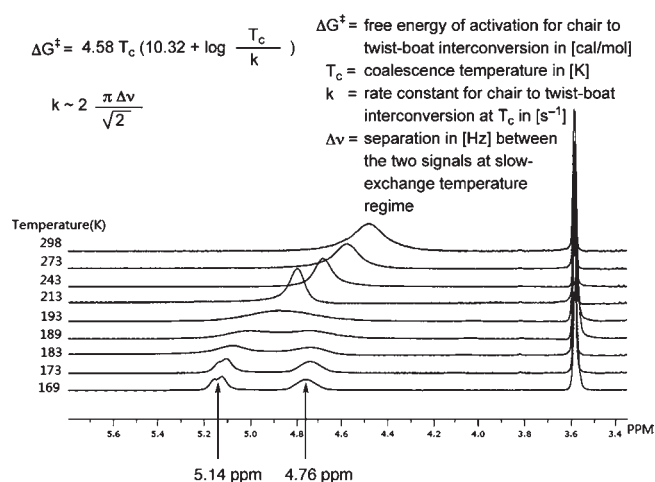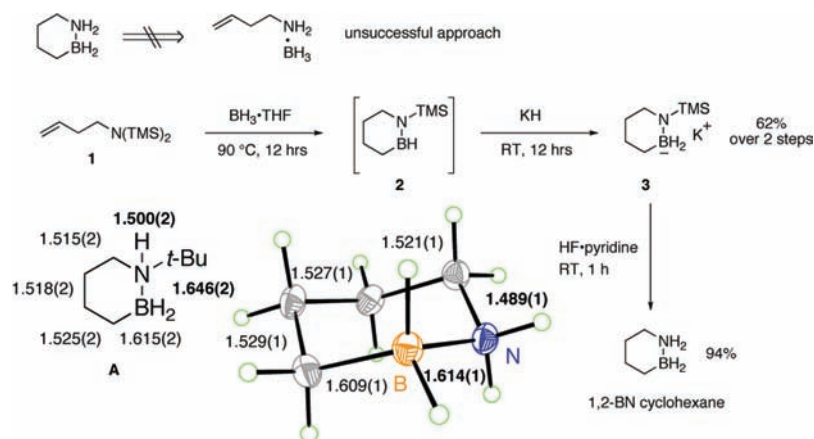**Scheme 2. Synthesis of 1,2-BN Cyclohexane**

Figure 1. 300 MHz ^{1}H NMR signals of the NH_2 protons of 1,2-BN cyclohexane (in THF-d_8) recorded at different temperatures.

We were able to obtain a single crystal X-ray structure of 1,2-BN cyclohexane and thus unambiguously confirm its identity. The structure shows that it adopts a chair conformation in the solid state (Scheme 2). All hydrogen atoms were found on the residual density map.[15] Compared to the N-tBu-substituted analogue **A**,[12] the parent compound exhibits a slightly shorter N−B (1.614(1) Å vs 1.646(2) Å) and N−C (1.489(1) Å vs 1.500(2) Å) bond lengths. This might be due to the steric influence exerted by the N-tBu group in heterocycle **A**.

In order to understand the effects of BN/CC isosterism on the conformational dynamics of cyclohexane, we performed a temperature-dependent ^{1}H NMR analysis of 1,2-BN cyclohexane in direct comparison to cyclohexane. Figure 1 shows that, in THF-d_8, the NH_2 protons of 1,2-BN cyclohexane appear as a broad singlet at 298 K. At 169 K however, the interconversion between the two NH_2 protons via a ring flip (presumably involving a twist-boat intermediate) is sufficiently slow on the NMR time scale so that the axial NH proton is distinct from the equatorial one. Based on the data and the equations shown in Figure 1, we estimate that the free energy of activation for 1,2-BN cyclohexane $\Delta G^{\ddagger}_{(1,2\text{-BN cyclohexane})}$ to be 8.8 ± 0.2 kcal/mol (T_c = 193 K, $\Delta \nu$ = 114 Hz).[16] In direct comparison, we performed the same study with cyclohexane in THF-d_8 and determined that the
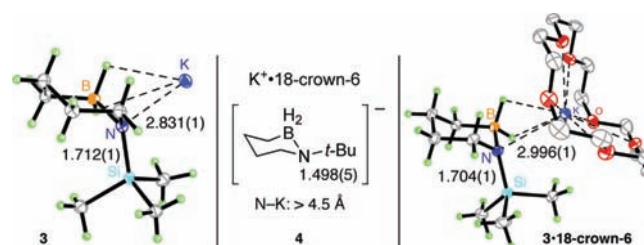

Figure 2. Structural analysis of complexes **3**, **4**, and **3•18-crown-6**.

corresponding $\Delta G^{\ddagger}_{(\text{cyclohexane})}$ is 10.5 ± 0.2 kcal/mol (T_c = 232 K, $\Delta \nu$ = 136 Hz).[17] Our free energy of activation for the cyclohexane ring flip is very similar to the previously determined value of 10.1 kcal/mol measured with a 60 MHz spectrometer in carbon disulfide.[18] The NMR studies demonstrate that 1,2-BN cyclohexane has a lower coalescence temperature than its carbonaceous counterpart (193 vs 232 K) and consequently also a significantly lower activation barrier for the ring flip (8.8 vs 10.5 kcal/mol). These observations are consistent with (1) the longer B−N bond distance in 1,2-BN cyclohexane (1.614(1) Å) compared to the shorter C−C bond distance in cyclohexane (1.51−1.53(1) Å)[19] and (2) the shallow potential energy curve for the B−N stretch,[20] which might reduce the strain and steric interaction associated with the conversion from the ground-state chair conformation to the half-chairlike transition state.

Complex **3** (see Scheme 2) is the potassium salt of a cyclic member of the family of metal amido boranes. Metal amido boranes have recently received increased attention as a potential alternative to amine boranes in hydrogen storage applications.[21] We have structurally characterized complex **3** via single crystal X-ray diffraction. Interestingly, the N-trimethylsilyl substituent (N-TMS) is located at the axial position in the solid state (Figure 2, left ORTEP). This is in stark contrast to the corresponding N-t-Bu derivative **4** in which the N-t-Bu group prefers the equatorial position (Figure 2, middle structure).[12] Compound **4** contains 18-crown-6 as a ligand for potassium. In order to provide a more direct comparison, we independently prepared the 18-crown-6 complex of **3** (i.e., **3•18-crown-6**; see Supporting Information for synthetic details). Figure 2 (right ORTEP) illustrates that irrespective of the presence of 18-crown-6, the N-TMS group prefers to be in the axial position in the solid

state. The relatively long N–Si bond in **3** (1.712(1) Å) and **3•18-crown-6** (1.704(1) Å) compared to the N–C bond in **4** (1.498(5) Å) and the lower A-value for the TMS vs the *t*-Bu group (2.5 vs >4.5, respectively)[9a] might be partly responsible for this conformational preference. There is a strong covalent character in the bonding between N and K in **3** and **3•18-crown-6** in which the K is found in the equatorial position (Figure 2). The N–K bond distances in **3** and **3•18-crown-6** are 2.831(1) and 2.996(1) Å, respectively, and are just slightly longer than the sum of the covalent radii of K and N (2.67 Å)[22] but significantly shorter than the sum of the van der Waals radii of K and N (4.30 Å).[23] On the other hand, the bonding between the N and K in compound **4** can be regarded as purely ionic (N–K distance > 4.5 Å).[12] This stark contrast in N–K bonding might be another contributing factor for the observed conformational preferences in these cyclic amido borane complexes. Noteworthy is also the difference in hybridization of the nitrogen atom in compounds **3** and **3•18-crown-6** vs complex **4**. Whereas the nitrogen atom in **4** adopts more of a pyramidal configuration (sum of the bond angles around N = 340.1°), a planarization of the N atom in **3** and **3•18-crown-6** is observed (sum of the bond angles around N are 351.6° and 351.3° for **3** and **3•18-crown-6**, respectively).[24]

We are particularly interested in the physical and reactivity differences between 1,2-BN cyclohexane and its carbonaceous counterpart, cyclohexane. To this end, we determined that 1,2-BN cyclohexane is a crystalline solid with a melting point of 62–63 °C. In contrast, cyclohexane is a liquid with a melting point of 4–7 °C. Neat 1,2-BN cyclohexane does not appear to decompose during melt/freeze cycles. ^{11}B and ^{1}H NMR analysis indicates that 1,2-BN cyclohexane does not decompose when exposed to air and moisture in the solid state and in benzene solution for 2 days under ambient conditions.[25]

In contrast to 1,2-dihydro-1,2-azaborine (Scheme 1), the B–H bond of which has been shown not to exhibit strong hydridic character,[8a] we determined that B–H in 1,2-BN cyclohexane is hydridic in nature. When 1,2-BN cyclohexane is treated with 1 equiv of HCl, heterocycle **5** is formed in high yield (eq 1). Similarly, treatment of 1,2-BN cyclohexane with 2 equiv of HCl furnishes compound **6** in 90% yield (eq 2).

(1)

(2)
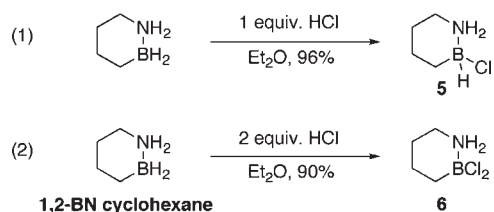
1,2-BN cyclohexane   **6**

Given the hydridic character of the BH₂ bonds in 1,2-BN cyclohexane (which is similar to NH₃–BH₃), we investigated the potential of 1,2-BN cyclohexane to release H₂ under thermal activation. We determined that when 1,2-BN cyclohexane is heated as a solution in toluene for 2 h, trimer **7** is formed quantitatively with concomitant release of 6 equiv of H₂ per trimer (Scheme 3).[26] In contrast to AB, which has been shown to produce a mixture of intractable oligomers/polymers upon H₂ release,[27] the trimerization of 1,2-BN cyclohexane is a well-defined, clean, and high-yielding process. With a molecular weight of 85, 1,2-BN cyclohexane carries 4.7 wt % H₂ when considering just the trimerization process. The hydrogen storage capacity could be potentially doubled if the H₂ release from BN was coupled with dehydrogenation

Scheme 3. Trimerization of 1,2-BN Cyclohexane
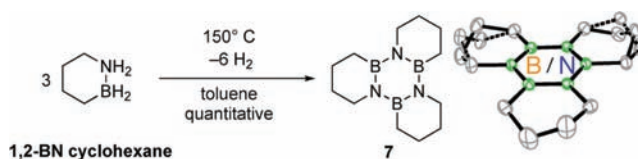
from the carbon positions as well, which would lead to a material with a capacity of 9.4 wt % H₂.

In summary, we synthesized and characterized 1,2-BN cyclohexane, the parent BN isostere of cyclohexane that had thus far eluded isolation. Conformational analysis by VT-NMR showed that the energy barrier for the ring flip of 1,2-BN cyclohexane is 1.7 kcal/mol less than that of cyclohexane as a result of BN/CC isosterism. We also demonstrated that 1,2-BN cyclohexane is an air- and moisture-stable compound that trimerizes in quantitative yield with release of hydrogen upon thermal activation. Thus, 1,2-BN cyclohexane can serve as a viable hydrogen storage platform that features a well-defined and high-yielding H₂ desorption process. Although the demonstrated 4.7 wt % H₂ storage capacity is relatively low, 1,2-BN cyclohexane has the theoretical potential to reach a 9.4 wt % capacity. Current efforts are geared toward achieving this goal.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information. Experimental procedures, spectroscopic data, complete ref 10a, and crystallographic data (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

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