Chemical Science

ROYAL SOCIETY OF CHEMISTRY

EDGE ARTICLE

View Article Online
View Journal | View Issue

Cite this: *Chem. Sci.*, 2024, **15**, 13923

All publication charges for this article have been paid for by the Royal Society of Chemistry

Received 13th May 2024
Accepted 18th July 2024

DOI: 10.1039/d4sc03109a

rsc.li/chemical-science

Triborane (B_3H_7)-mediated regioselective substitution reactions of pyridine derivatives†

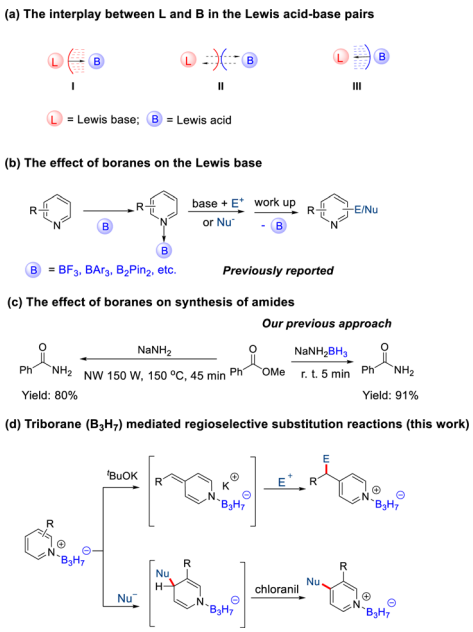
Zi-Heng Fan,[a] Jia-Xin Kang,[a] Sihan Jia,[a] Qiao-Jing Pan,[a] Lei Cao,[a] Xi-Meng Chen,[a] Cong-Qiao Xu,[b] Yan-Na Ma *[c] and Xuenian Chen *[ac]

There exists an interplay between borane and a Lewis base in their adducts. However, studies on these adducts so far have mainly focused on the different reactions of B–H bonds with limited attention given to the influence of borane on the chemistry of the Lewis base, except for BF_3 and BAr_3. Herein, we have synthesized novel borane adducts with pyridine derivatives, Py·B_3H_7, in which the coordination of B_3H_7 efficiently achieved the intra-molecular charge transfer. The strong B–N bond in these adducts resulted in the formation of stable dearomatic intermediates of pyridine derivatives, confirmed by ^{1}H and ^{11}B NMR spectroscopy, from which different reactions have transpired to realize C(sp^3)–H and C(sp^2)–H functionalization under mild conditions. The B_3H_7 pyridine derivatives are stable and do not dissociate or decompose during the reaction process. The high stability of the B–N bond makes this method a good option for boron-containing drugs with potential for use in boron neutron capture therapy (BNCT).

Introduction

Simple boranes, such as BH_3 and BF_3, denoted as **B**, cannot exist stably due to the electron deficiency of the boron atom. Usually they form a Lewis acid–base adduct **L**·**B** with a Lewis base (**L** = THF, Me_2S, NH_3, Me_3N, *etc.*) through a dative bond. There is no doubt that the interplay between the Lewis acid and base exists in these adducts (Scheme 1a). However, while the influence of **L** on the properties and reactivity of **B** has been extensively explored (Scheme 1a **I**)[1] and the steric interrelationship results in frustrated Lewis pair (FLP) complexes that are also well-known (Scheme 1a **II**),[2] the influence of boranes (**B**) on a Lewis base (**L**) has been relatively underexplored (Scheme 1a **III**).

Most studies on the influence of boranes (**B**) on a Lewis base (**L**) have mainly focused on the impacts of BF_3, BAr_3, and B_2pin_2 on pyridine derivatives. BF_3 mediated C-2 or C-4 selective functionalization,[3] C-2 methyl group deprotonation,[4] and asymmetric synthesis of pyridine derivatives[5] have been extensively studied. BAr_3 and B_2pin_2 mediated C-3 alkylation,[6] trifluoromethylthiolation,[7] allylation,[8] and cyanation[9] of pyridine have become hot research fields recently (Scheme 1b). In contrast, the effects of the boron hydrogen complexes, such as BH_3, on the Lewis base have rarely been reported because of their strong reducing ability[10] and weak Lewis acidity. Recent studies from our group have found that $NaNH_2BH_3$ could directly react with esters to form amides,[11] which did not work for $NaNH_2$ (Scheme 1c).[12] This result suggested that BH_3 could change the reactivity of the Lewis base of adducts.



Scheme 1 Properties and reactions of borane Lewis base adducts.

[a]*School of Chemistry and Chemical Engineering, Henan Key Laboratory of Boron Chemistry and Advanced Materials, Henan Normal University, Xinxiang, Henan 453007, China*

[b]*Department of Chemistry, Southern University of Science and Technology, Shenzhen 518055, China*

[c]*College of Chemistry, Zhengzhou University, Zhengzhou, Henan 450001, China. E-mail: mayanna@zzu.edu.cn; xuenian_chen@zzu.edu.cn*

† Electronic supplementary information (ESI) available. CCDC 2308054 (**1a**) and 2308050 (**4aa**). For ESI and crystallographic data in CIF or other electronic format see DOI: https://doi.org/10.1039/d4sc03109a

Multinuclear boranes are usually used as reducing agents in organic synthesis.[13] Recently, multinuclear boranes, such as carborane, $[B_{10}H_{10}]^{2-}$, $[B_6H_6]^{2-}$, and $[HCB_{11}Cl_{11}]^-$ have also been used as borylation reagents[14] or catalysts.[15] However, there has been hardly any research into the influence of the Lewis acid properties of multinuclear boranes on reactions.

We have systematically studied the syntheses and properties of octahydridotriborate ($B_3H_8^-$) and its neutral derivatives ($L{\cdot}B_3H_7$), indicating that B_3H_7 as a Lewis acid possesses remarkable features.[16] Compared with BH_3, B_3H_7 exhibits greater stability, weaker reducing ability, and a higher ability to coordinate with metals.[17] Compared with BF_3, B_3H_7 has relatively low acidity. In addition, B_3H_7 has a steric effect and σ aromaticity. All these properties may enable the B_3H_7 group to mediate different organic reactions (Scheme 1d).

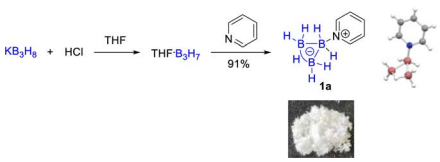
Results and discussion

Synthesis and properties of $Py{\cdot}B_3H_7$

To explore the effects of B_3H_7 on a Lewis base, we selected pyridine, which is widely used in pharmaceutical chemistry, functional materials, and natural products as a Lewis base.[18] We synthesized $Py{\cdot}B_3H_7$ through a reaction of pyridine with $THF{\cdot}B_3H_7$, formed *in situ* by reacting KB_3H_8 with $HCl{\cdot}Et_2O$. The $Py{\cdot}B_3H_7$ adduct **1a** was obtained as a white solid in 91% yield (Scheme 2). This novel compound showed excellent stability towards both acid and base in aqueous solutions at room temperature (see ESI, Fig. S1†), offering an opportunity to examine their reactivity. The results indicated that a rapid dearomatic reaction of pyridine derivatives occurred, which then further reacted with electrophiles or oxidants to provide the rearomatic products (Scheme 1d).

B_3H_7 mediated dearomatic reaction of Py derivatives

A direct dearomatic reaction of pyridine is impossible under mild conditions. The dearomatic intermediates of BF_3 coordinated pyridine derivatives are potential products in most situations.[19] We found that the B_3H_7 mediated dearomatic reaction of 4-methylpyridine rapidly proceeded by reacting with KO^tBu to form 4-methylene dihydropyridine at low temperatures. This intermediate was identified spectrally (Fig. 1e) but not isolated, which indicated that B_3H_7 could stabilize the dihydropyridine derivatives. To explore the universality of such an effect, we conducted a reaction of the B_3H_7 mediated addition of Grignard reagents to pyridines bearing an electron-withdrawing substituent. Similarly, the dihydropyridine intermediates were stable under these conditions, which could also be characterized by ^{11}B, ^1H, and $^1H\{^{11}B\}$ NMR spectra (ESI, Fig. S7–S9†).



Scheme 2 Synthesis of the pyridine B_3H_7 adduct.

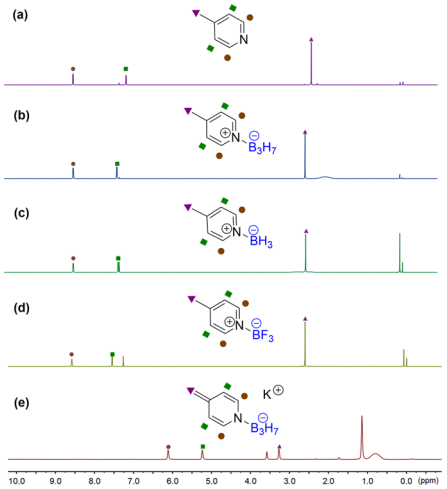


Fig. 1 ^1H NMR in $CDCl_3$ of (a) 4-methylpyridine, (b) **1b**, (c) **1c**, (d) **1d**, and (e) 4-methylene dihydropyridine **3a** in THF-d_8 at −78 °C.

These observations differ from the BF_3 mediated similar reactions of pyridine derivatives under the same conditions where no dihydropyridine derivative intermediates were detected. We further set up control experiments to explore the different influences of BH_3, BF_3, and B_3H_7 on pyridine in their adducts. The ^1H NMR spectra of 4-methylpyridine of the corresponding B_3H_7 adduct **1b**, BH_3 adduct **1c**, and BF_3 adduct **1d** showed that the chemical shifts of the protons at the C3 and C5 position and the methyl downfield-shifted in the adducts in comparison with 4-methylpyridine.

The impact of the BF_3 group was the most significant and those of the BH_3 and B_3H_7 groups were almost the same, but the B_3H_7 group was slightly larger than that of BH_3 (Fig. 1a–d). Therefore, we speculated that the impacts of these three Lewis acids on their coordinated Lewis base should be BF_3 > B_3H_7 > BH_3.

Surprisingly, the $^{11}B\{^1H\}$ NMR signals of the B_3H_7 coordinated 4-methylene dihydropyridine anion **3a** and ethyl 4-isopropyl 3-carboxylate dihydropyridine complex **3b** changed significantly in comparison with those of their parent complexes. The top boron atom connected with the nitrogen atom shifted to a lower field and the two base boron atoms to a higher field (Fig. 2), in contrast to the general B-signals of the B_3H_7 adducts.[13a] Furthermore, the signal shifts in **3a** and **3b** are different (Fig. 2b and d). The exploration of the reason for such a difference is underway in our laboratory.

B_3H_7 mediated the nucleophilic substitution reaction of 4-alkylpyridine

Based on the formation of the dearomatic intermediates, we further explored the B_3H_7 mediated nucleophilic substitution reactions of pyridine derivatives by selecting the 4-ethylpyridine B_3H_7 adduct **1e** as the model substrate, reacting with methyl iodide (Table S4†). After systematically screening reactions with different bases in various solvents, we found that the methylation product **4a** was obtained at an 88% yield in CH_3CN when a mild base KO^tBu was used (entry 1 in Table S4†). In contrast,

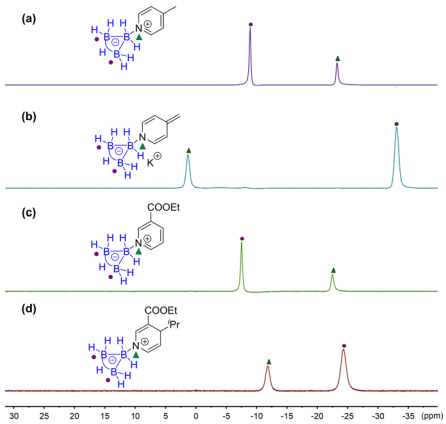
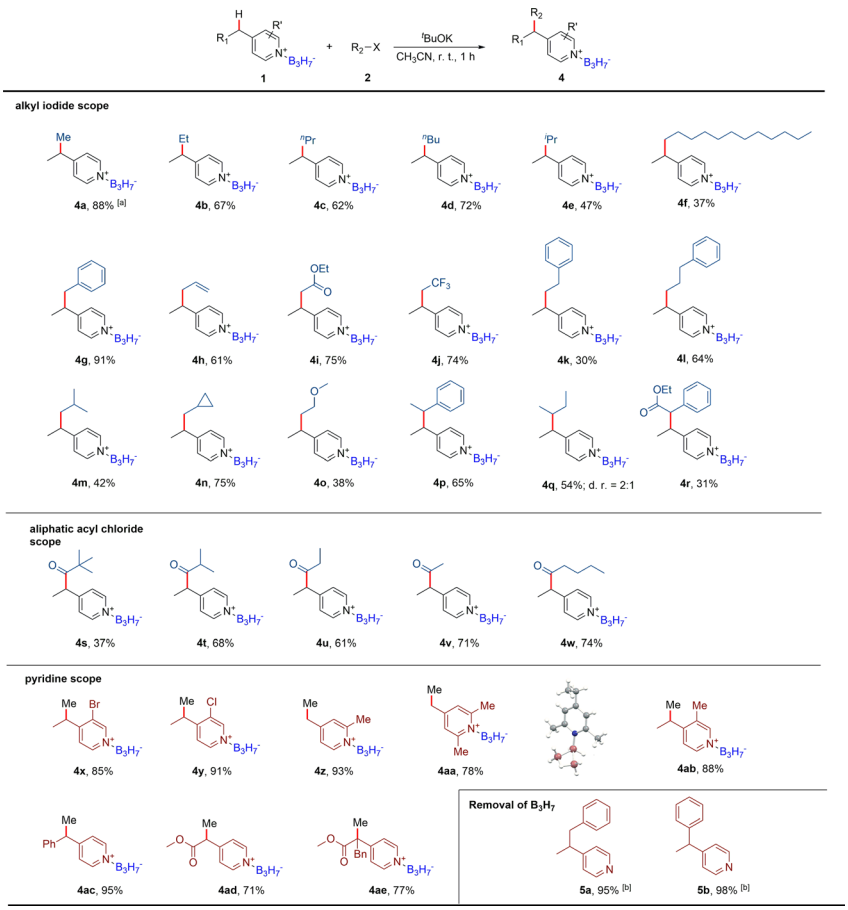


Fig. 2 (a) $^{11}B\{^1H\}$ NMR of **1b** in $CDCl_3$. (b) $^{11}B\{^1H\}$ NMR of 4-methylene dihydropyridine **3a** in THF-d_8 at −78 °C. (c) $^{11}B\{^1H\}$ NMR of ethyl nicotinate·B_3H_7 **6a** in $CDCl_3$. (d) $^{11}B\{^1H\}$ NMR of ethyl 4-isopropyl 3-carboxylate dihydropyridine complex **3b** in THF-d_8 at room temperature.

no reaction occurred when the BH_3 adduct **1f** was used (entry 18 in Table S4†) and the product decomposed when the BF_3 adduct **1g** was used (entry 19 in Table S4†). Only a trace amount of the product was detected. The reaction with 4-ethyl pyridine, without B_3H_7 coordinated, was also conducted at similar conditions and no reaction occurred (entry 20 in Table S4†). As expected, the starting material 4-ethyl pyridine was collected. These results suggested that the Py·B_3H_7 adducts have a unique stability and reactivity.

Considering the excellent stability of the Py·B_3H_7 adducts and the importance of boron-containing compounds in BNCT, we further examined the scope of the electrophiles (Table 1). Firstly, different alkyl iodides were detected. As shown in Table 1, regardless of whether the alkyl iodides were primary or secondary, products (**4b–4r**) were obtained in moderate to good yields. Additionally, this transformation shows a high functional group tolerance, such as allyl, ester, trifluoromethyl, cyclopropyl, and alkoxy were all compatible. We also found that the yields of the reactions using the alkyl bromides were significantly low compared to the alkyl iodines. Encouraged by these results, we further screened other electrophilic reagents and found that acyl chlorides could also be used in this reaction to produce stable Py·B_3H_7 derivatives (**4s–4w**). The scope for the pyridine core was assessed next (**4x–4ae**). Gratifyingly, our method showed a good C4 regioselectivity for the pyridines that

Table 1 Reaction scope[a]



[a] Conditions: **1** (0.5 mmol, 1.0 eq.), **2** (1.25 mmol, 2.5 eq.), and base (1.25 mmol, 2.5 eq.) in CH_3CN (15 mL) at room temperature for 1 hour. Isolated yield. The d.r. value was determined by ^1H NMR analysis of the crude reaction mixture. [b] Conditions: **4** (0.5 mmol, 1.0 eq.), MeOH : H_2O (5 : 0.5 mL), 60 °C, 12 h.

contained multiple methyl groups at C2, C3, or C6 (**4z–4ab**). We thought this was because the high steric hindrance of B_3H_7 decreased the reactivity of the C2 and C6 positions, and the acidity of the methyl group at the C3 position is relatively weak. It was worth noting that the reaction of 4-methyl Py·B_3H_7 with methyl iodide gave a mixture of 4-ethyl Py·B_3H_7, 4-isopropyl Py·B_3H_7, and 4-*tert*-butyl Py·B_3H_7. Introducing methyl groups to the C2 and C6 positions could weaken the acidity of the C4 methyl to give the mono-methylation products (**4z**, **4aa**) in high yields. The structure of **4aa** was determined by single-crystal X-ray diffraction. Regardless of whether the substituent group at the C4 position was the primary, secondary, or tertiary alkyl group, the reactions transpired smoothly in high yields. In addition, the halogen atom (**4x**, **4y**) and ester group (**4ad**, **4ae**) were compatible in this transformation.

To remove B_3H_7 from pyridine derivatives has also been explored to expand the application of this protocol. After a series of explorations for the reaction conditions, the B_3H_7 unit was successfully removed with MeOH and H_2O at 60 °C, and the corresponding pyridine compounds were obtained in almost quantitative yields (**5a**, **5b**).[20]

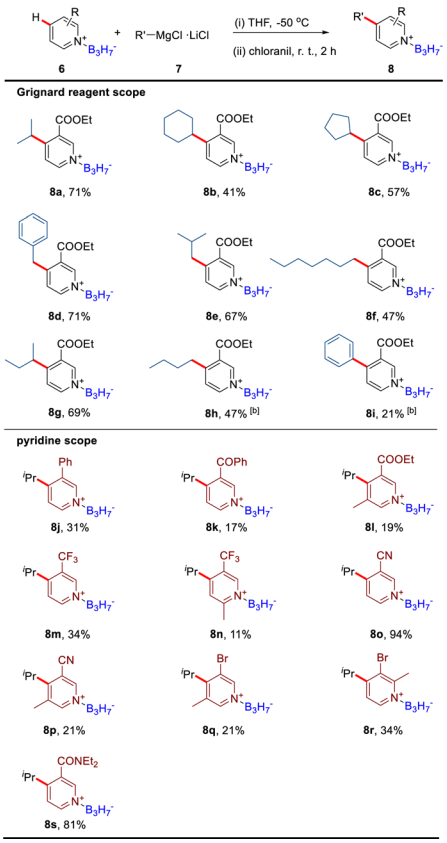
The B_3H_7 mediated nucleophilic addition of Grignard reagents to electron deficient pyridines and their subsequent oxidation

The BF_3 promoted C4 direct alkylation of functionalized pyridines has been reported, in which BF_3-mediated 4-isopropyl-dihydropyridine was considered a potential intermediate.[4a] We have obtained the dearomatic dihydropyridine intermediate by the nucleophilic addition of ^{i}PrMgCl·LiCl to ethyl nicotinate B_3H_7 adduct (Fig. 2d), further oxidation aromatization mediated by chloranil provided the 4-alkylated product **8a** in 71% yield (Table 2). Based on this, we examined the scope of Grignard reagents and pyridine derivatives and successfully introduced different alkyl and aryl groups into the C4 position of electron-deficient pyridines (Table 2). In these reactions, moderate yields of products could be obtained (**8b–8g**). The low yields of **8h** and **8i** are probably due to using strong bases such as organic lithium reagents. The ethyl nicotinate B_3H_7 adduct would be destroyed by strong bases to produce the pyridine BH_3 adduct, decreasing the yield. In addition, the electronic effects also played an important role in this reaction. The strength and stability of the electron-withdrawing group at the C3 position would affect the yields of products (**8j**, **8k**, **8m**, **8o**, and **8s**). When the pyridine had electron-donating groups, the yield would decrease due to the increase of the electron density at the C4 position (**8l**, **8n**, **8p–8r**). For all the low-yield reactions, the starting materials could be detected and recovered, such as the starting material for **8l** could be recovered in 72%.

Mechanistic studies

To gain insight into the reaction mechanism, quantum chemical studies using density functional theory (DFT) have been performed. From the theoretical data, the reaction mechanism is proposed, as shown in Fig. 3.

Table 2 The C-4 substitution reaction scope[a]



[a] Conditions: **6** (0.5 mmol, 1.0 eq.), **7** (0.5 mmol, 1 eq.), and chloranil (1 mmol, 2 eq.). Isolated yield. [b] R–Li (0.5 mmol, 1 eq.).

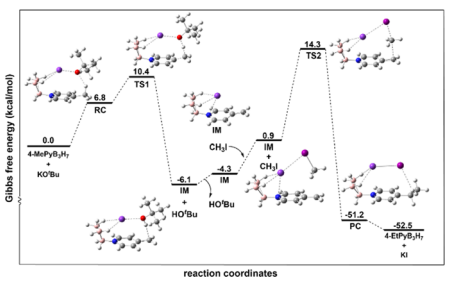


Fig. 3 The energy profile of the reaction calculated at M06-2X-D3-SMD/def2-QZVP//B3LYP-D3(BJ)/6-311G(d,p)/SDD level of theory.

First, the reactants 4-methyl Py·B_3H_7 and potassium *tert*-butoxide form the reaction complex RC. The relative free energy of RC is 6.8 kcal mol^{-1}. In RC, the K^+ cation interacted with the H of the B_3H_7 fragment, the K–H bond is 2.80 and 2.84 Å, and a hydrogen bond exists between the O of *tert*-butoxy and the H of the methyl group with a bond length of 2.10 Å. Subsequently, RC traverses transition state TS1 to yield a complex of intermediate (IM) and a *tert*-butanol with a relative free energy of −6.1 kcal mol^{-1}. From RC to TS1, the K–H bond shortened to 2.77 Å and the O–H bond shortened from 2.10 Å to 1.37 Å. At the same time, the C–H bond enlarged from 1.11 Å to 1.29 Å. The relative free energy of TS1 is 10.4 kcal mol^{-1}, indicating a modest energy

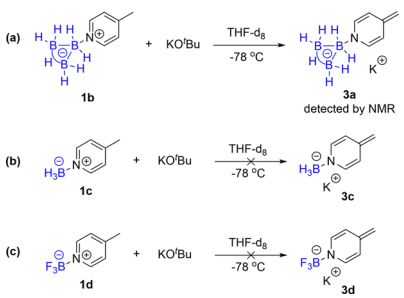
barrier of 3.6 kcal mol^{-1} for this step. Then *tert*-butanol dissociates, leaving behind IM. Following this, a new complex, IM with CH_3I, formed with a relative energy of 0.9 kcal mol^{-1} with the I–C bond of 2.23 Å. The subsequent reaction of IM and CH_3I *via* transition state TS2 results in the final product. During this step, the I–C bond enlarged to 2.53 Å, and the C–C bond formed with a bond length of 2.47 Å. The relative energy of TS2 is 14.3 kcal mol^{-1}, implying a barrier of 13.4 kcal mol^{-1} for the second step. With the Walden inversion of CH_3, the final product formed and exhibits a relative free energy of −52.5 kcal mol^{-1}. The negative ΔG of the whole reaction and the low energy barrier indicate that this reaction will easily proceed spontaneously. The charge distribution of CH_3Py, $CH_3PyB_3H_7$, $KCH_3PyB_3H_7^+$, and $CH_2PyB_3H_7^-$ was further analysed by using Natural Population Analysis (NPA). As delineated in Table S5,† the formation of the N–B dative bond and the preferential association of the K ions near the B_3H_7 fragment caused the electron concentration to be towards the B_3H_7 fragment. Such intramolecular charge transfer facilitates the deprotonation.

The proposed mechanism is supported by the experimental results of the capture of the reaction intermediate (Scheme 3a–c). The ^{1}H NMR spectroscopy showed that the B_3H_7 coordinated 4-methylene dihydropyridine anion intermediate **3a** (IM) was formed in an almost quantitative yield by the deprotonation of 4-methyl Py·B_3H_7 **1b** with KO^{t}Bu in THF-d_8 at −78 °C (Fig. 1e).[21] The intermediate of 4-alkalene dihydropyridine was frequently discussed in the literature.[22] However, the BH_3 and BF_3 coordinated 4-methylene dihydropyridine anion intermediates **3c** and **3d** could not be formed in similar reactions (Scheme 3b and c).

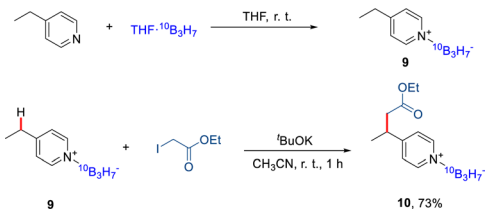
These results were consistent with the theoretical prediction that the interaction between the alkali metal cation and the NB_3H_7 moiety induced the additional intramolecular charge transfer from CH_3/CH_2 to the B_3H_7 end to facilitate the reaction and also stabilized the formed 4-methylene dihydropyridine intermediate (Table S5†). This result was further confirmed by the fact that the addition of 18–C-6 to the reaction mixture would decrease the yields from 88% to 54% (Fig. S2†) because the formation of the K-18–C-6 complex weakened the interaction between the K cation and the B_3H_7 moiety.

^{10}B-labeled $^{10}B_3H_7$ reactions

To evaluate the potential of this protocol in BNCT,[23] a ^{10}B-labeled $^{10}B_3H_7$ was introduced to the pyridine core (Scheme 4). Firstly,



Scheme 3 A mechanism study.



Scheme 4 ^{10}B-labeled experiments.

the ^{10}B-labeled $Na^{10}B_3H_8$ was synthesized by the reaction of $Na^{10}BH_4$ with I_2. The reaction of 4-ethyl pyridine with the THF·$^{10}B_3H_7$ formed the *in situ* produced 4-ethyl Py·$^{10}B_3H_7$ **9** in 60% yield.[24] The ^{10}B-labeled 4-ethyl Py·$^{10}B_3H_7$ could also react with alkyl iodide under KO^{t}Bu to afford the alkylated product **10** in a good yield.

Conclusions

In summary, we have synthesized a novel class of Py·B_3H_7 compounds and studied the reactions of 4-alkyl Py·B_3H_7 with different electrophiles and pyridine bearing an electron-withdrawing group with nucleophiles. The relatively high stability of the Py·B_3H_7 adducts results in the formation of stable dearomatic intermediates, dihydropyridine, under mild conditions, from which the rearomatization has further transpired to form different alkylation and acylation products. The mechanistic study reveals that the coordination of the B_3H_7 unit led to the intra-molecular charge transfer from the pyridine ring to borane, realizing the alkylation and acylation reactions of the C(sp^3)–H bond of the C-4 position with excellent regioselectivity and high yields under mild reaction conditions. The B_3H_7 coordinated dihydropyridine intermediate was obtained in solution and characterized by ^{1}H and ^{11}B NMR. Such an intramolecular charge transfer also promoted C-4 direct alkylation of the pyridines bearing an electron-withdrawing group to provide the 4-alkylated products. Compared with BH_3 and BF_3, B_3H_7 possesses remarkable features, such as relatively higher stability, a weaker reducing ability, and a higher ability to coordinate with metals, as well as steric effects and σ aromaticity. All these properties will enable the B_3H_7 group to mediate different organic reactions. In addition, stable Py·B_3H_7 will play a significant role in boron-containing drugs and organic synthesis. Further research into the effect of B_3H_7 on other series of Lewis bases and the reaction mechanisms is underway in our laboratory.

Data availability

Data for all compounds in this manuscript are available in the ESI,† which includes experimental details, characterisation data, computational data and copies of ^{1}H, ^{13}C, ^{19}F, and ^{11}B NMR spectra. The data supporting this article have been included as part of the ESI.† Crystallographic data have been deposited with the Cambridge Crystallographic Data Center as supplementary publication no. CCDC-2308054 (**1a**) and CCDC-2308050 (**4aa**).

Author contributions

Y.-N. M. and X. C. conceived and designed the study; Z.-H. F., Q.-J. P., L. C., S. J., and X.-M. C. performed the experiments. J.-X. K. and C.-Q. X. performed the mechanistic and DFT studies. Y.-N. M. and X. C. prepared the manuscript.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (No. 22171246 and 22271256).

Notes and references

1 (*a*) B. T. Cho, *Chem. Soc. Rev.*, 2009, **38**, 443–452; (*b*) J. Yang, Z. Li and S. Zhu, *Chin. J. Org. Chem.*, 2017, **37**, 2481–2497; (*c*) Y.-J. Yu, F.-L. Zhang, T.-Y. Peng, C.-L. Wang, J. Cheng, C. Chen, K. N. Houk and Y.-F. Wang, *Science*, 2021, **371**, 1232–1240; (*d*) J. H. Kim, T. Constantin, M. Simonetti, J. Llaveria, N. S. Sheikh and D. Leonori, *Nature*, 2021, **595**, 677–684; (*e*) Z. Chen, Q. Fan, B. Yin, Q. Li and H. Wang, *Chin. J. Org. Chem.*, 2023, **43**, 1706–1712; (*f*) T.-Y. Peng, F.-L. Zhang and Y.-F. Wang, *Acc. Chem. Res.*, 2023, **56**, 169–186; (*g*) Y.-Q. Miao, X.-Y. Li, Q.-J. Pan, Y. Ma, J.-X. Kang, Y.-N. Ma, Z. Liu and X. Chen, *Green Chem.*, 2022, **24**, 7113–7121; (*h*) M. Yamashita and K. Nozaki, *Bull. Chem. Soc. Jpn.*, 2008, **81**, 1377–1392; (*i*) R. Kinjo, B. Donnadieu, M. A. Celik, G. Frenking and G. Bertrand, *Science*, 2011, **333**, 610–613.

2 (*a*) G. C. Welch, R. R. S. Juan, J. D. Masuda and D. W. Stephan, *Science*, 2006, **314**, 1124–1126; (*b*) H. C. Brown, H. I. Schlesinger and S. Z. Cardon, *J. Am. Chem. Soc.*, 1942, **64**, 325–329; (*c*) G. Erős, H. Mehdi, I. Pápai, T. A. Rokob, P. Király, G. Tárkányi and T. Soós, *Angew. Chem., Int. Ed.*, 2010, **49**, 6559–6563; (*d*) T. Wang, G. Kehr, L. Liu, S. Grimme, C. G. Daniliuc and G. Erker, *J. Am. Chem. Soc.*, 2016, **138**, 4302–4305.

3 (*a*) S. V. Kessar, P. Singh, K. N. Singh and M. Dutt, *J. Chem. Soc. Chem. Commun.*, 1991, 570–571; (*b*) S. V. Kessar, P. Singh, R. Vohra, N. Kaur and K. Singh, *J. Chem. Soc. Chem. Commun.*, 1991, 568–570; (*c*) M. Jaric, B. A. Haag, A. Unsinn, K. Karaghiosoff and P. Knochel, *Angew. Chem., Int. Ed.*, 2010, **49**, 5451–5455.

4 (*a*) Q. Chen, X. M. du Jourdin and P. Knochel, *J. Am. Chem. Soc.*, 2013, **135**, 4958–4961; (*b*) M. Jaric, B. A. Haag, S. M. Manolikakes and P. Knochel, *Org. Lett.*, 2011, **13**, 2306–2309; (*c*) S. M. Manolikakes, M. Jaric, K. Karaghiosoff and P. Knochel, *Chem. Commun.*, 2013, **49**, 2124–2126.

5 (*a*) B. M. Trost and D. A. Thaisrivongs, *J. Am. Chem. Soc.*, 2008, **130**, 14092–14093; (*b*) B. M. Trost and D. A. Thaisrivongs, *J. Am. Chem. Soc.*, 2009, **131**, 12056–12057; (*c*) Z.-J. Cai, S.-Y. Wang and S.-J. Ji, *Adv. Synth. Catal.*, 2013, **355**, 2686–2692; (*d*) S. Dutta, J. H. Kim, K. Bhatt, D. R. L. Rickertsen, K. A. Abboud, I. Ghiviriga and D. Seidel, *Angew. Chem., Int. Ed.*, 2023, e202313247.

6 (*a*) Z. Liu, J.-H. He, M. Zhang, Z.-J. Shi, H. Tang, X.-Y. Zhou, J.-J. Tian and X.-C. Wang, *J. Am. Chem. Soc.*, 2022, **144**, 4810–4818; (*b*) M. Xu, Z. Wang, Z. Sun, Y. Ouyang, Z. Ding, T. Yu, L. Xu and P. Li, *Angew. Chem., Int. Ed.*, 2022, e202214507; (*c*) S. Chakraborty and A. T. Biju, *Angew. Chem., Int. Ed.*, 2022, **135**, e202300049.

7 (*a*) X.-Y. Zhou, M. Zhang, Z. Liu, J.-H. He and X.-C. Wang, *J. Am. Chem. Soc.*, 2023, **144**, 14463–14470; (*b*) R. Muta, T. Torigoe and Y. Kuninobu, *Org. Lett.*, 2022, **24**, 8218–8222; (*c*) C. M. Josephitis, H. M. H. Nguyen and A. McNally, *Chem. Rev.*, 2023, **123**, 7655–7691; (*d*) J. Wang, X.-X. Lu, R.-P. Yang, B.-B. Zhang, Z.-H. Xiang, J.-C. Li, L. Liu, S. Chao and X. Shang, *Org. Lett.*, 2023, **25**, 8489–8494.

8 (*a*) J.-J. Tian, R.-R. Li, G.-X. Tian and X.-C. Wang, *Angew. Chem., Int. Ed.*, 2023, **62**, e202307697; (*b*) Z. Liu, Z.-J. Shi, L. Liu, M. Zhang, M.-C. Zhang, H.-Y. Guo and X.-C. Wang, *J. Am. Chem. Soc.*, 2023, **145**, 11789–11797; (*c*) F.-Y. Zhou and L. Jiao, *Angew. Chem., Int. Ed.*, 2022, **61**, e202201102Z.

9 (*a*) M. Zhang, Q. Zhou, H. Luo, Z.-L. Tang, X. Xu and X.-C. Wang, *Angew. Chem., Int. Ed.*, 2023, **62**, e202216894; (*b*) H. Cao, Q. Cheng and A. Studer, *Angew. Chem., Int. Ed.*, 2023, **62**, e202302941.

10 (*a*) E. Marcantoni, S. Alessandrini, M. Malavolta, G. Bartoli, M. C. Bellucci, L. Sambri and R. Dalpozzo, *J. Org. Chem.*, 1999, **64**, 1986–1992; (*b*) M. Morimoto, W. Cao, R. G. Bergman, K. N. Raymond and F. D. Toste, *J. Am. Chem. Soc.*, 2021, **143**, 2108–2114; (*c*) M. Ding, J. Chang, J.-X. Mao, J. Zhang and X. Chen, *J. Org. Chem.*, 2022, **87**, 16230–16235; (*d*) J. Wang, M.-Y. Ju, X. Wang, Y.-N. Ma, D. Wei and X. Chen, *J. Org. Chem.*, 2021, **86**, 5305–5316.

11 (*a*) Y. Guo, R.-Y. Wang, J.-X. Kang, Y.-N. Ma, C.-Q. Xu, J. Li and X. Chen, *Nat. Commun.*, 2021, **12**, 5964; (*b*) Y.-Q. Miao, J.-X. Kang, Y.-N. Ma and X. Chen, *Green Chem.*, 2021, **23**, 3595–3599.

12 A. Theppawong, P. Ploypradith, P. Chuawong, S. Ruchirawat and C. Montakarn, *Chem.–Asian J.*, 2015, **10**, 2631–2650.

13 (*a*) J. W. Bae, S. H. Lee, Y. J. Jung, C. O. M. Yoon and C. M. Yoon, *Tetrahedron Lett.*, 2001, **42**, 2137–2139; (*b*) Y. J. Jung, Y. M. Chang, J. H. Lee and C. M. Yoon, *Tetrahedron Lett.*, 2002, **43**, 8735–8739; (*c*) X. Li, T. Mi, W. Guo, Z. Ruan, Y. Guo, Y.-N. Ma and X. Chen, *Chem. Commun.*, 2021, **57**, 12776–12779.

14 (*a*) S. Kim, J. W. Treacy, Y. A. Nelson, J. A. M. Gonzalez, M. Gembicky, K. N. Houk and A. M. Spokoyny, *Nat. Commun.*, 2023, **14**, 1671; (*b*) X. Mu, J. C. Axtell, N. A. Bernier, K. O. Kirlikovali, D. Jung, A. Umanzor, K. Qian, X. Chen, K. L. Bay, M. Kirollos, A. L. Rheingold, K. N. Houk and A. M. Spokoyny, *Chem*, 2019, **5**, 2461–2469.

15 (*a*) B. Shao, A. L. Bagdasarian, S. Popov and H. M. Nelson, *Science*, 2017, **355**, 1403–1407; (*b*) C. N. Kona, R. Oku, S. Nakamura, M. Miura, K. Hirano and Y. Nishii, *Chem*, 2024, **10**, 402–413; (*c*) M. Scholz and E. Hey-Hawkins, *Chem. Rev.*, 2011, **111**, 7035–7062.

16 (*a*) X. Chen, Y. Jing, J.-X. Kang, Y. Wang, Y. Guo and X. Chen, *Inorg. Chem.*, 2021, **60**, 18466–18472; (*b*) M.-Y. Ju, Z.-H. Fan,

Y. Ma, Y. Jing, X.-M. Chen and X. Chen, *Inorg. Chem.*, 2023, **62**, 8700–8709.

17 (*a*) C. W. Yoon, P. J. Carroll and L. G. Sneddon, *J. Am. Chem. Soc.*, 2009, **131**, 855–864; (*b*) C. W. Yoon and L. G. Sneddon, *J. Am. Chem. Soc.*, 2006, **128**, 13992–13993; (*c*) A. B. Baylis, G. A. Pressley, E. J. Sinke and F. E. Stafford, *J. Am. Chem. Soc.*, 1964, **86**, 5358–5359; (*d*) B. J. Duke, J. W. Gauld and H. F. Schaefer III, *J. Am. Chem. Soc.*, 1995, **117**, 7753–7755.

18 (*a*) Y. Ling, Z. Y. Hao, D. Liang, C. L. Zhang, Y. F. Liu and Y. Wang, *Drug Des., Dev. Ther.*, 2021, **15**, 4289–4338; (*b*) E. Vitaku, D. T. Smith and J. T. Njardarson, *J. Med. Chem.*, 2014, **57**, 10257–10274; (*c*) C. Campagnuolo, C. Fattorusso, E. Fattorusso, A. Ianaro and B. Pisano, *Org. Lett.*, 2003, **5**, 673–676; (*d*) K. Murakami, S. Yamada, T. Kaneda and K. Itami, *Chem. Rev.*, 2017, **117**, 9302–9332.

19 (*a*) Q. Chen, T. León and P. Knochel, *Angew. Chem., Int. Ed.*, 2014, **53**, 8746–8750; (*b*) Y. Cai, Y. Li, M. Zhang, J. Fu and Z. Miao, *RSC Adv.*, 2016, **6**, 69352–69356; (*c*) M. Balkenhohl, B. Salgues, T. Hirai, K. Karaghiosoff and P. Knochel, *Org. Lett.*, 2018, **20**, 3114–3118; (*d*) Q. Zhong, S. Qin, Y. Yin, J. Hu and H. Zhang, *Angew. Chem., Int. Ed.*, 2018, **57**, 14891–14895.

20 (*a*) H. Dong and H. Berke, *J. Organomet. Chem.*, 2011, **696**, 1803; (*b*) S. Lau, D. Gasperini and R. L. Webster, *Angew. Chem., Int. Ed.*, 2021, **60**, 14272–14294.

21 (*a*) K. Konishi, H. Matsumoto, K. Saito and K. Takahashi, *Bull. Chem. Soc. Jpn.*, 1985, **58**, 2294–2297; (*b*) M. Meanwell, M. B. Nodwell, R. E. Martin and R. Britton, *Angew. Chem., Int. Ed.*, 2016, **55**, 1–6; (*c*) A. I. Lansakara, S. V. S. Mariappan and F. C. Pigge, *J. Org. Chem.*, 2016, **81**, 10266–10278; (*d*) N. Wasfy, F. Rasheed, R. Robidas, I. Hunter, J. Shi, B. Doan, C. Y. Legault, D. Fishlock and A. Orellana, *Chem. Sci.*, 2021, **12**, 1503–1512.

22 (*a*) B. Qian, S. Guo, J. Shao, Q. Zhu, L. Yang, C. Xia and H. Huang, *J. Am. Chem. Soc.*, 2010, **132**, 3650–3651; (*b*) B. M. Trost and D. A. Thaisrivongs, *J. Am. Chem. Soc.*, 2008, **130**, 14092–14093; (*c*) S. C. Sha, J. D. Zhang, P. J. Carroll and P. J. Walsh, *J. Am. Chem. Soc.*, 2013, **135**, 17602–17609; (*d*) F. Rasheed, J. Q. Shi, T. Zeng, Y. K. Krishna, D. Fishlock and A. Orellana, *Org. Lett.*, 2023, **25**, 8628–8633; (*e*) M. Meanwell, M. B. Nodwell, R. E. Martin and R. A Britton, *Angew. Chem., Int. Ed.*, 2016, **55**, 13244–13248.

23 (*a*) D. Chen, L. Xu, Z. Wang and C. Liu, *Chem*, 2023, **9**, 3212–3223; (*b*) J. Li, Q. Sun, C. Lu, H. Xiao, Z. Guo, D. Duan, Z. Zhang, T. Liu and Z. Liu, *Nat. Commun.*, 2022, **13**, 2143.

24 (*a*) L. Adams, S. N. Hosmane, J. E. Eklund, J. Wang and N. S. Hosmane, *J. Am. Chem. Soc.*, 2002, **124**, 7292–7293; (*b*) X.-M. Chen, N. Ma, Q.-F. Zhang, J. Wang, X. Feng, C. Wei, L.-S. Wang, J. Zhang and X. Chen, *J. Am. Chem. Soc.*, 2018, **140**, 6178–6726; (*c*) S. Liang, Y. Ma and X. Chen, *Chin. J. Org. Chem.*, 2023, **43**, 1772–1776.