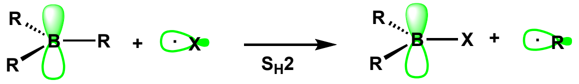
Hu GM

Lewis Base Boryl Radicals

Zhu rongjin

Radical Reactivity of Organoboranes: Homolytic Substitution at the Boron Atom

- Boryl radical was directly detected by Mass Spectrometry in 1964



X: ${}^tBuO$, R_2N, RS, $PhSO_2$, Ketone Triplets

entry	BDE(Kcal/mol)
Et_2B-Et	344
$(EtS)_2B-SEt$	377
$[(CH_3)_2N]_2B-N(CH_3)_2$	422
$(EtO)_2B-OEt$	519

- The Autoxidation of Organoboranes was widely used in organic synthesis

Mechanism of Autoxidation of Organoboranes

Initiation

$$R_3B + O_2 \xrightarrow[S_H2]{} R_2BOO\cdot + R\cdot$$

Propagation

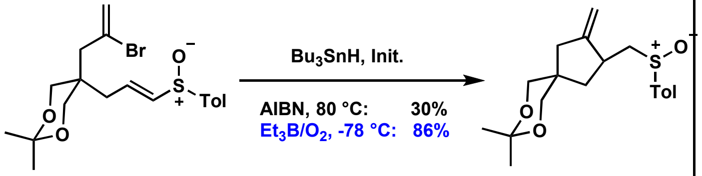
$$R\cdot + O_2 \longrightarrow R_2OO\cdot$$

$$R_2OO\cdot + R_3B \xrightarrow[S_H2]{} (ROO)BR_2 + R\cdot$$

- synthetic appliction

1) Triethylborane as a Radical Initiator

1.1 XAT



Bu_3SnH, Init.

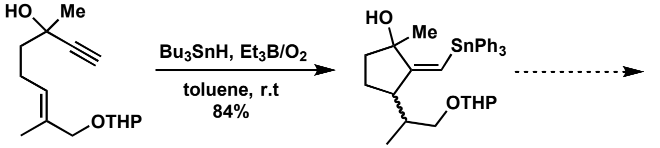
AIBN, 80 °C: 30%

Et_3B/O_2, -78 °C: 86%

Lower temperatures inhibit ß-elimination

Laco Ăte, E.; Malacria, M. C. R. Acad. Sci. Paris, Ser. IIc 1998,191.

1.2 Addition to Alkynes and Alkenes



Bu_3SnH, Et_3B/O_2

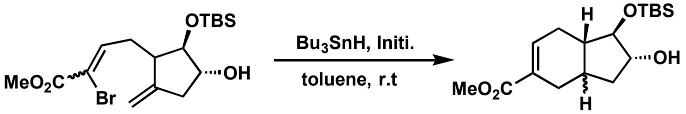
toluene, r.t

84%

dehydroiridodiol and isodehydroiridodiol

Koichiro Oshima JACS 1987,109, 2547

1.3 Control of Diastereoselectivity



Bu_3SnH, Initi.

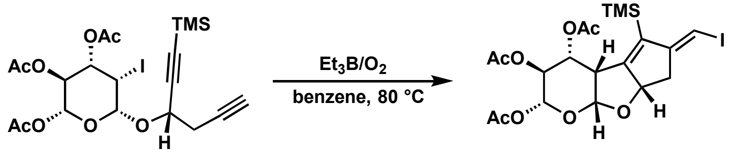
toluene, r.t

AIBN, 110 °C 72% trans/cis 63:37

Et_3B/O_2, -78 °C 97% trans/cis 100:0

Shibasaki, M. JOC 1991, 56, 2278.

2) Atom (Br or I) Transfer Reactions

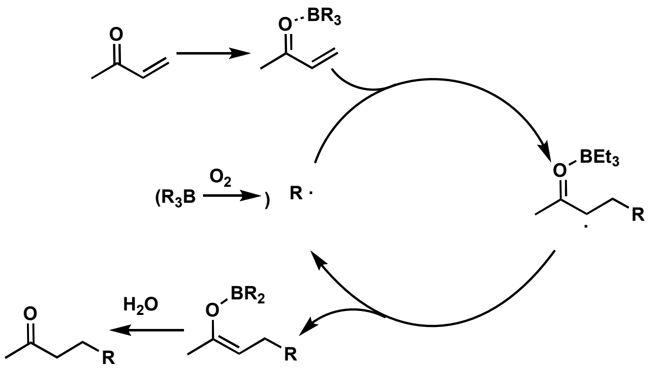


Et_3B/O_2

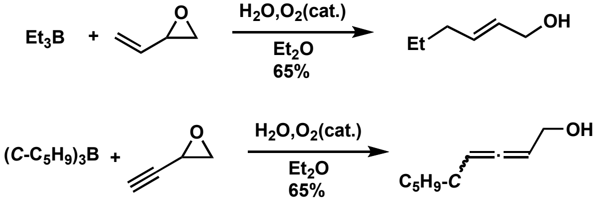
benzene, 80 °C

Hoffmann, H. M. R. Tetrahedron 1995, 51, 7389

3) 1,2 or 1,4 addition invovled boryl radical



4) Addition to Ethenyl - and Ethynyloxiranes



H_2O,O_2(cat.)

Et_2O

65%

H_2O,O_2(cat.)

Et_2O

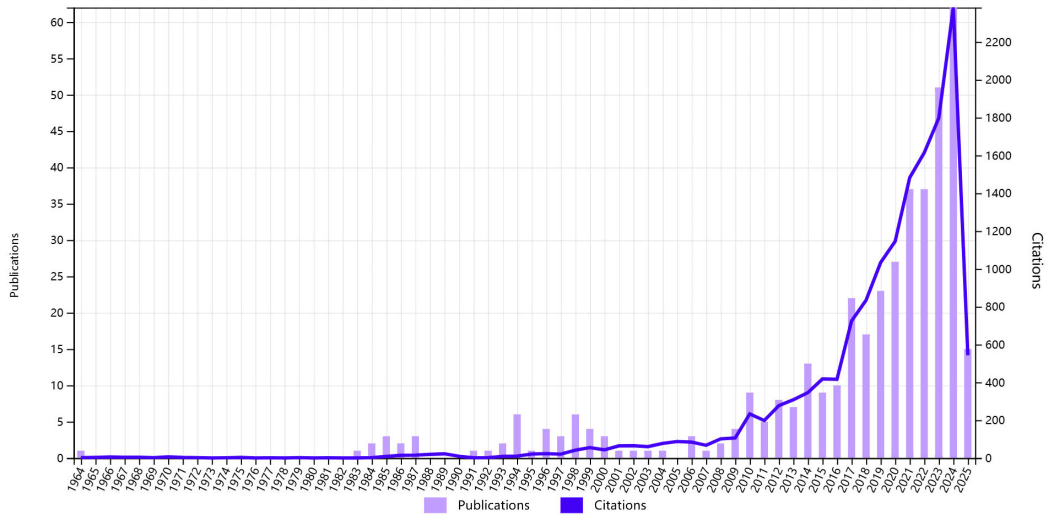
65%

Herbert C. BrownJACS. 1971, 93, 2792

5) addition/eliminations to alkenes & arenes;
Azidation; Sulfurization; Halogenation

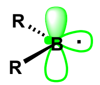
The synthetic applications of boryl radicals have been limited to serving as radical initiators and generating alkyl radicals, with the preparation of alkyl radical precursors remaining challenging.

Lewis Base Boryl Radicals



Data compiled from Web of Science topic search accessed on 10 March 2025.

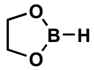
What factors contributed to the limited exploration of boryl radical chemistry prior to 2008



extremly instability of 3-center- 5-electron

highelectron-deficiency (Electrophilicity)

hard to detect

Entry	Bond	BDE 298 K (Kcal/mol) G -2	CBS -4
1	$MeCH_2$-H	102.5	101.7
2	H_2B-H	106.6	105.5
3	F_2B-H	110.3	108.6
4		-	110.8
5	PhMeB-H	-	105.4
6	NH_3BH_2-H	103.6	102.6

1 BDE's of the B-H bonds remarkably insensitive to structural variation (108 ± 4 kcal/mol.)

2) The first BDE(B-H) of borane larger than C-H

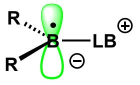
3) lone electron is in an approximately SP_2-orbital rather than a P orbital.

⇩

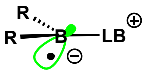
explain the dearth of two-coordinate borane radical chemistry.

Paul R. Rablen JACS.. 1996, 118, 4648 -4653

Solution - Lewis Base Boryl Radicals



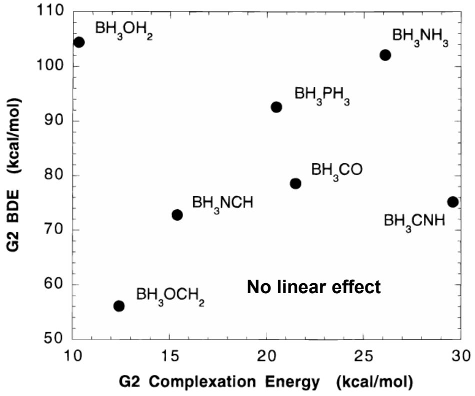
π -type



σ -type

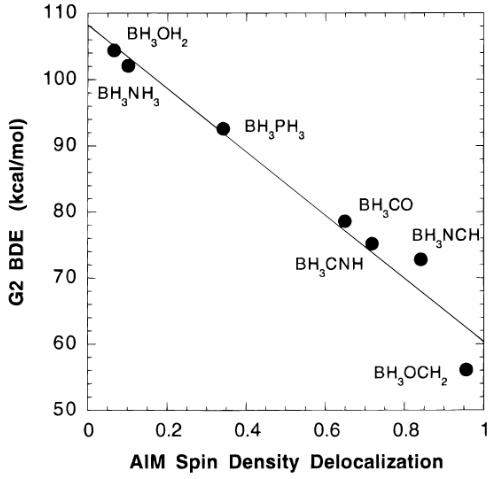
- 4-center- 7-electronboryl radicals
- relatively more stable
- BDE's of the B-H bonds remarkably sensitive to complex variation (3-50 kcal/mol.)
- easily undergo HAT provide boryl radical

Entry	Bond	BDE 298 K (Kcal/mol) G -2	CBS -4
1	H_2B-H	106.6	105.5
2	NH_3BH_2-H	103.6	102.6
3	THF• BH_2-H	-	103.5
4	Me_3P• BH_2-H	-	95.5
5	Me_2S• BH_2-H	-	95.5
6	O≡C• BH_2-H	79.9	76.8
7	CH_2O• BH_2-H	57.3	55.4
8	Pyr• BH_2-H		68.8



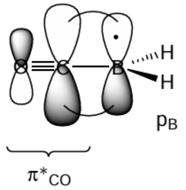
The magnitude of the decrease in the BDE is not correlated with the strength of coordination.

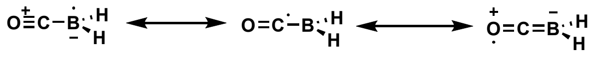
Lewis Base Boryl Radicals



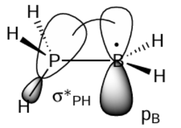
* The spin density thus describes the" location" of the unpaired electron in a radical

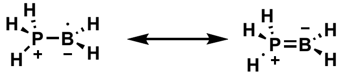
delocalization of the unpaired electronon boron and the corresponding stabilization of the radical is the primary cause of the reduced B-H BDE's





43% a-spin on B
37% a-spin on C
20% a-spin on O





66% a-spin on B

34% a-spin on P

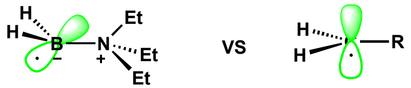
Rablen, P. R. JACS 1997, 119, 8350 -8360

Pioneering work on LBRS

Brian Peter Roberts

Study of Trialkylamine-Boryl radical

The amine-boranes $R_3\overset{+}{N}\text{-}\overset{-}{B}H_3$ are isoelectronic with the alkanes $R_3C\text{-}CH_3$ and amine-boryl radicals $R_3\overset{+}{N}\text{-}\overset{-}{\dot{B}}H_2$ are similarly related to the alkyl radicals $R_3C\text{-}\dot{C}H_2$. amine-boryl radicals are nucleophilic and metalloid-like in their reactivity patterns.



pyramidal
σ-type radical

Planer

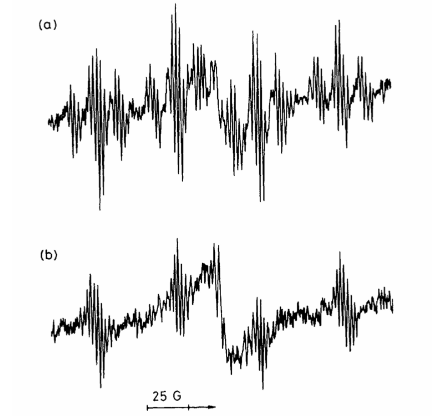
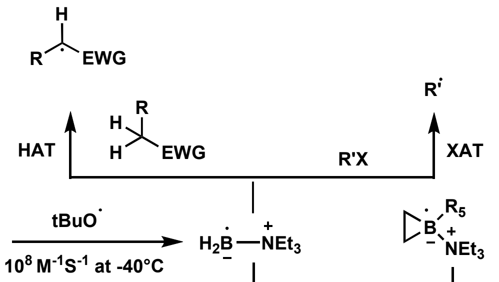
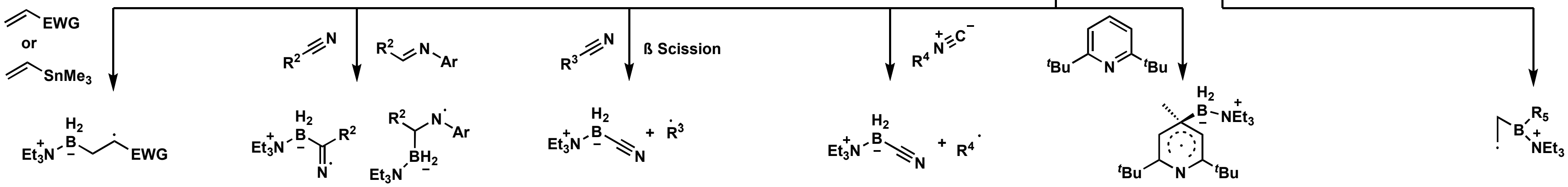


Figure 1. E.s.r. spectra at 193 K of (a) $Et_3\overset{+}{N}\text{-}\overset{-}{B}H_2^{\cdot}$ generated from $Et_3\overset{+}{N}\text{-}\overset{-}{B}H_3$ (97.5 atom% ^{11}B) in cyclopropane–THF (3 : 1 v/v) and (b) $Et_3\overset{+}{N}\text{-}\overset{-}{B}D_2^{\cdot}$ generated from $Et_3\overset{+}{N}\text{-}\overset{-}{B}D_3$ (81.2 atom% ^{11}B) in cyclopropane–[$^2H_8$]THF (3 : 1 v/v). Some unidentified lines are present in both spectra. No e.s.r. signals were observed during photolysis of $Et_3\overset{+}{N}\text{-}\overset{-}{B}H_3$ alone in cyclopropane–THF.

Reactivity of Trialkylamine-Boryl radical



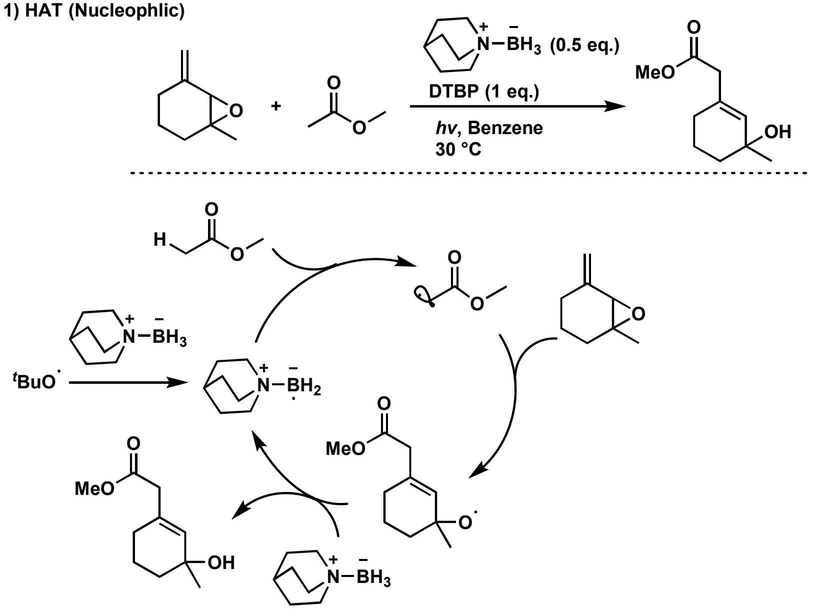


Roberts, B. P J. Chem. Soc., Chem. Commun. 1983, 1224- 1226.
Roberts, B. P. J. Chem. Soc., Perkin Trans. 2 1985, 1723 –1733.

Lewis Base Boryl Radicals

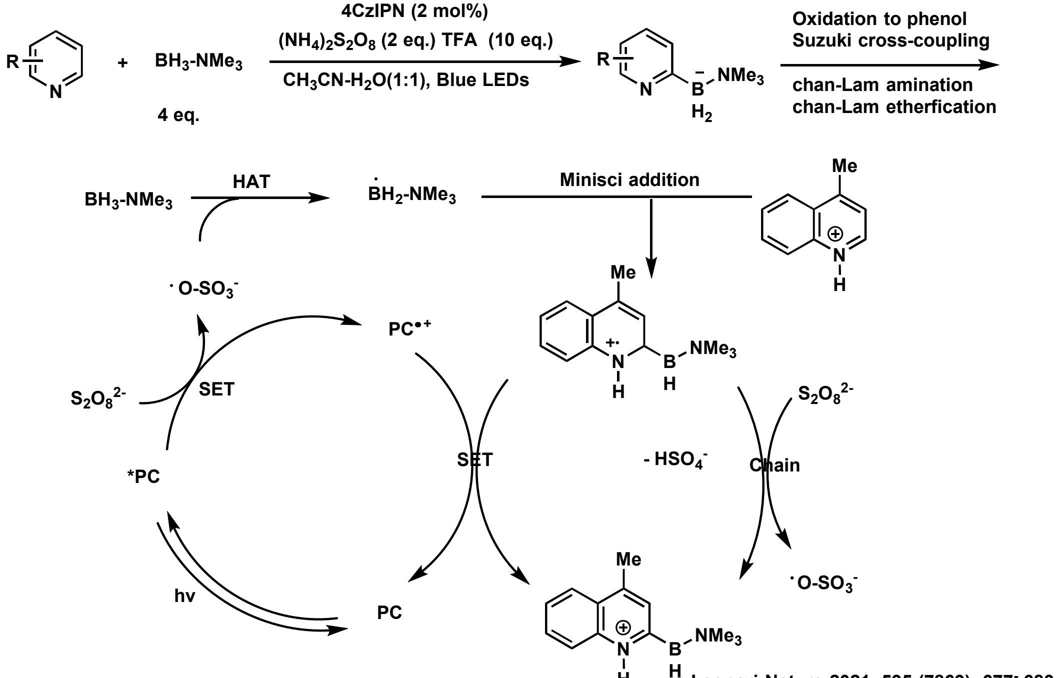
synthetic application

1) HAT (Nucleophlic)

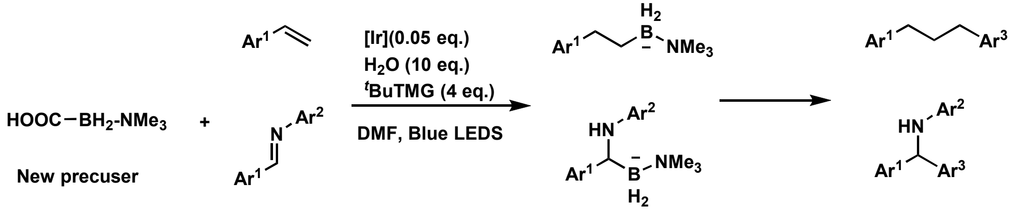


Roberts, B. P. J. Chem. Soc., Perkin Trans. 1 1993, 891 –898.

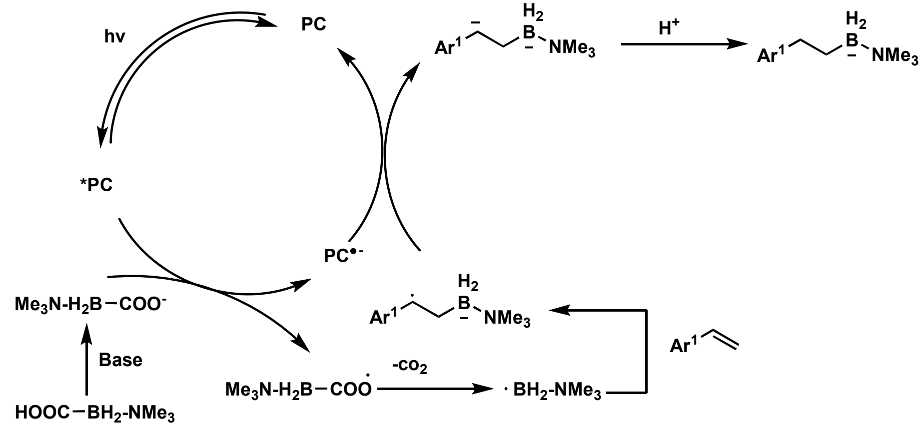
2) addition (Nuclephilic radical)



Leonori Nature 2021, 595 (7869), 677- 683.



stable alkyl amine borane
directly use for Suzuki coupling
slowly release of boronic acids

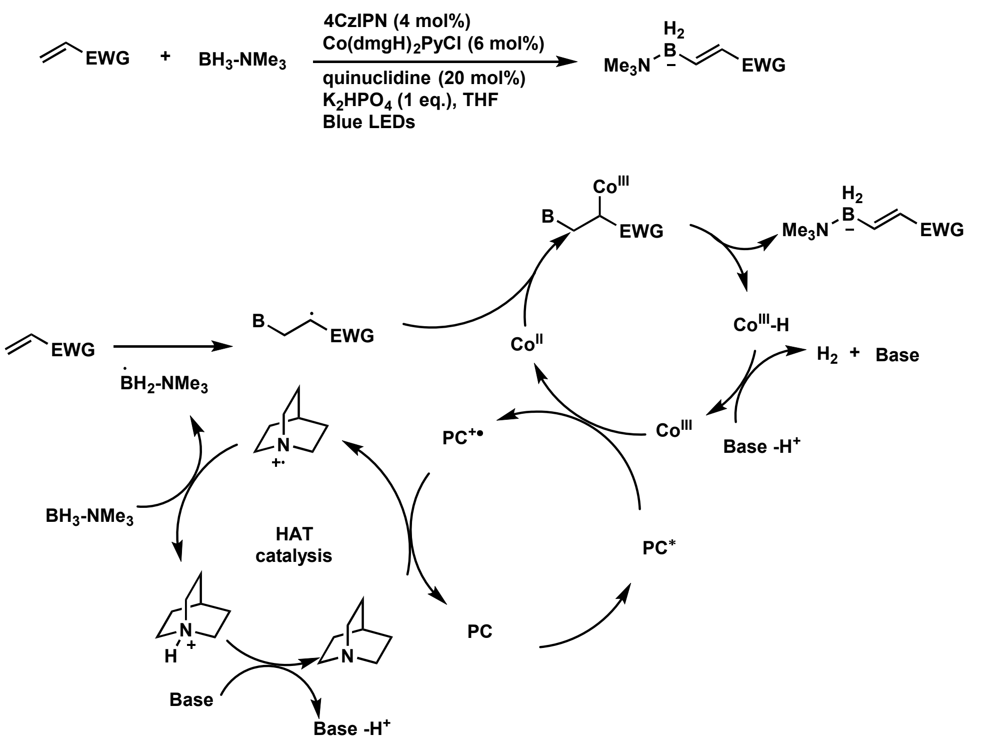


Leonori JACS. 2024, 146, 24042 -24052

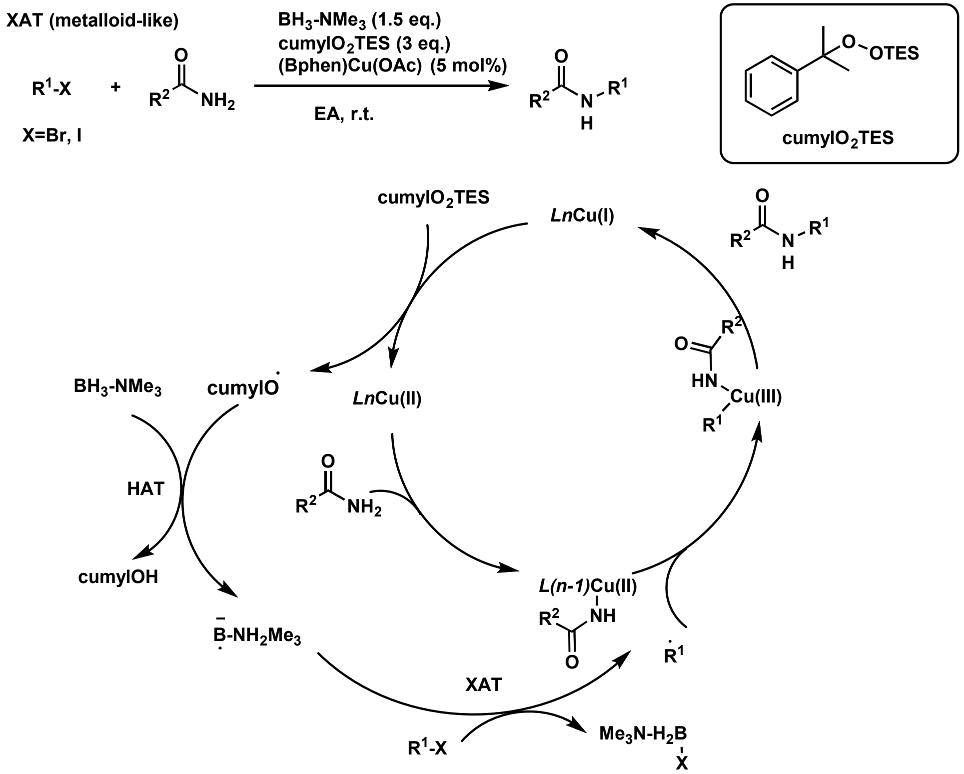
Hu GM

Lewis Base Boryl Radicals

Zhu rongjin



Xu ACS Catal. 2024, 14, 8666- 8675

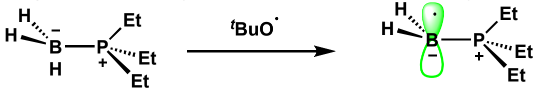


Leonori JACS 2024, 15, 19113 –19118

LeonoriChem. Sci.,2024, 15, 19113 –19118

Study of Phosphine-Boryl radical

The phosphine-boryl radicals are less reactive than borane radical anion,
and fail to add
to benzene, ethylene, or vinyltrimethylsilane. They do abstract halogen atoms from alkyl bromides but
not, in general, from alkyl chlorides, ß-scission has not yet observed.



Planer
σ-type radical

Roberts, B. P. J. Chem. Soc., Perkin Trans. 2 1984, 1717 –1722.

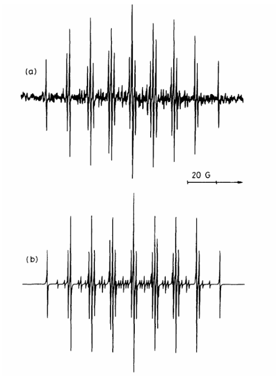
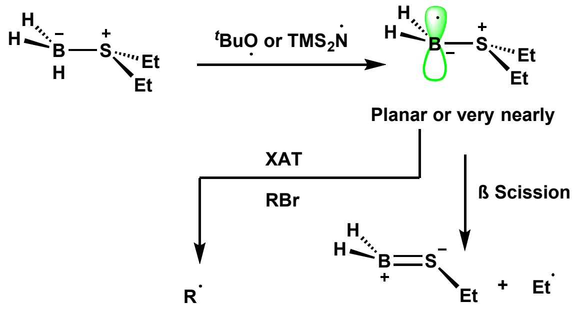


Figure 1. (a) E.s.r. spectrum of the trimethyl phosphite-boryl radical in cyclopropane at 198 K. The more intense lines are from $(MeO)_3\overset{+}{P}—{}^{11}\overset{-}{B}H_2^{\cdot}$, the weaker lines are from $(MeO)_3\overset{+}{P}—{}^{10}\overset{-}{B}H_2^{\cdot}$. (b) Computer simulation of (a) as a superposition of spectra from the ^{11}B- and ^{10}B-containing radicals present in natural abundance

Study of Dialkyl Sulphide–Boryl radical



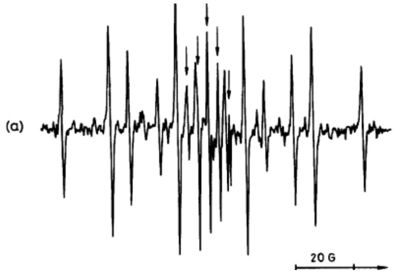
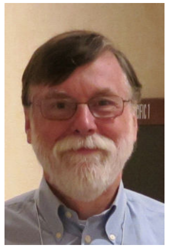


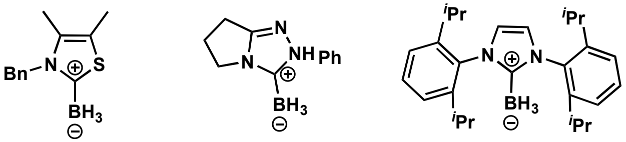
Figure 1. (a) E.s.r. spectrum at 154 K obtained during u.v. irradiation of DTBP and $(CD_3)_2S{\rightarrow}BH_3$ in oxirane–cyclopropane (1:1 v/v). The arrows mark positions of the five most intense lines from $D_3C^{\cdot}$. (b)

Roberts, B. P. J. Chem. Soc., Perkin Trans. 2 1987, 497 –505

Curran's Pioneer work: N-Heterocyclic Carbenes-boryl radical



Dennis P. Curran

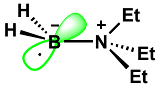


74 Kcal/mol 79 Kcal/mol 80 Kcal/mol BDE (B-H)

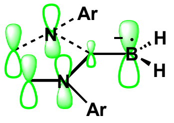
1) Bonds of borane complexes of amines and phosphines (BDEs, 94 -104kcal/mol) are too stronger to ultilize radical hydrogen donors (Bu_3Sn-H (74 kcal/mol), $(Me_3Si)_3Si$-H (79 kcal/mol)

2) Many complexes with computationally determined low BDE (HCN or formaldehyde) are transitory in solution.Further, such ligands are reduced by BH_3.

3) Complexes of Borane and N-Heterocyclic Carbenes largely lowered BDEs (σ–donor/ π-acceptor, sterically shielded) ; air-stable, white crystalline solids.



pyramidal
σ-type radical



π-type radical

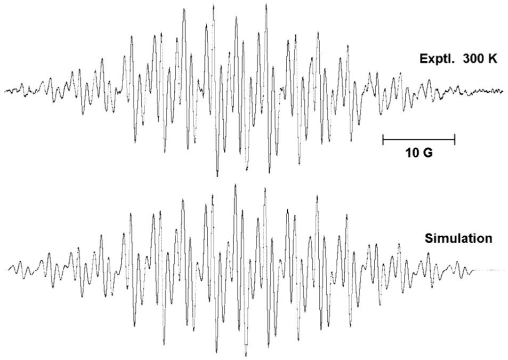
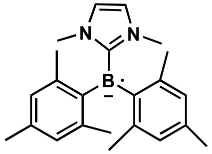


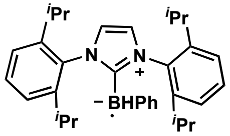
Figure 7. Solution EPR spectrum of NHC-BH₂• radical **3a**. Top: First derivative experimental spectrum at 300 K in *t*-BuPh. Bottom: Computer simulation with parameters noted in Table 1.

Curran JACS 2010, 132 (7), 2350- 2358

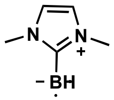
NHC-boryl radicals are species that have very different structures and solution lifetime



High persistant



somewhat persistent
$2K_t = 5 \times 10^4\ M^{-1}S^{-1}$

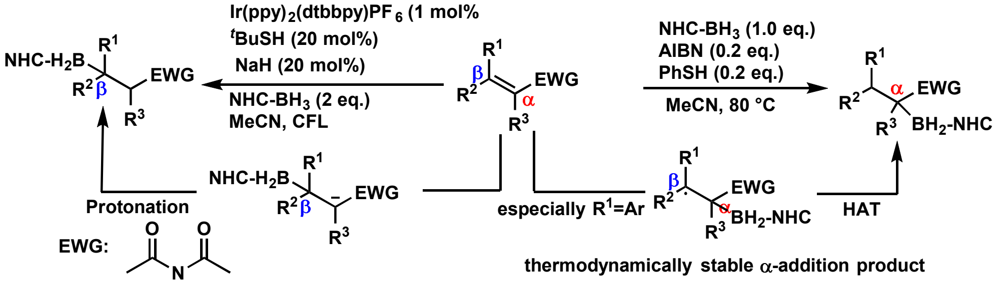


transient
$2K_t > 10^9\ M^{-1}S^{-1}$

Reactivity patterns of NHC-Boryl radical are similar to all lewis base Boryl Radicals

synthetic application

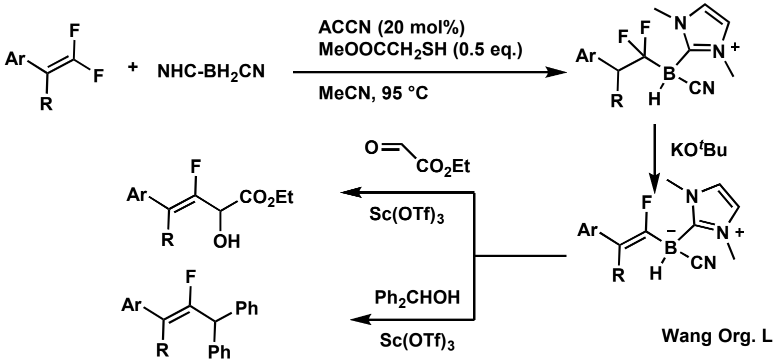
1) Regioselective Radical addition of alkene

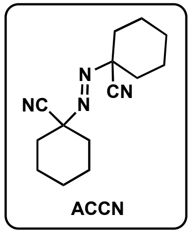


thermodynamically stable α-addition product

Xie ACIE. 2020, 59, 12817 –12821

Wang Nat. Commun. 2019, 10, 1934.



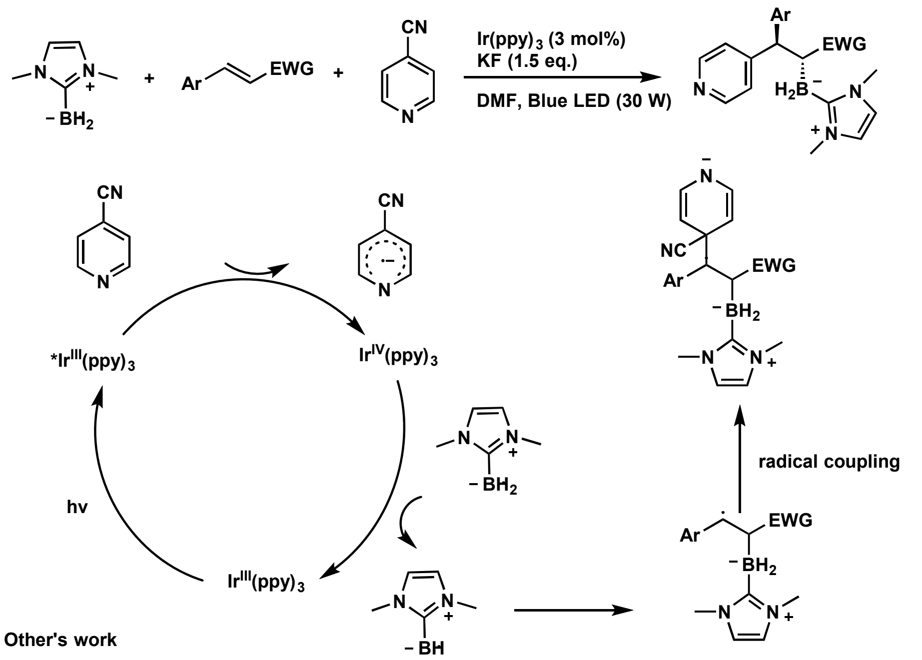


Wang Org. Lett. 2019, 21, 8414- 8418

Hu GM

Lewis Base Boryl Radicals

Zhu rongjin

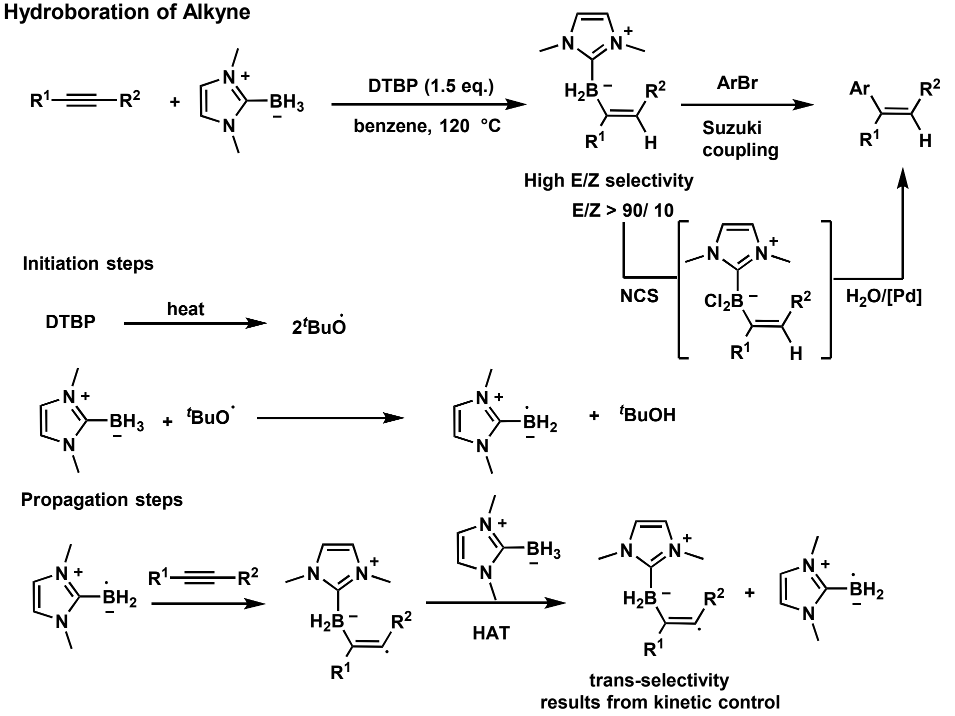


Other's work

Curran JACS, 2019, 141, 12355 –12361.
Yang ACIE. 2020, 59, 6706 –6710
Zhu CC 2020,56, 15647--15650

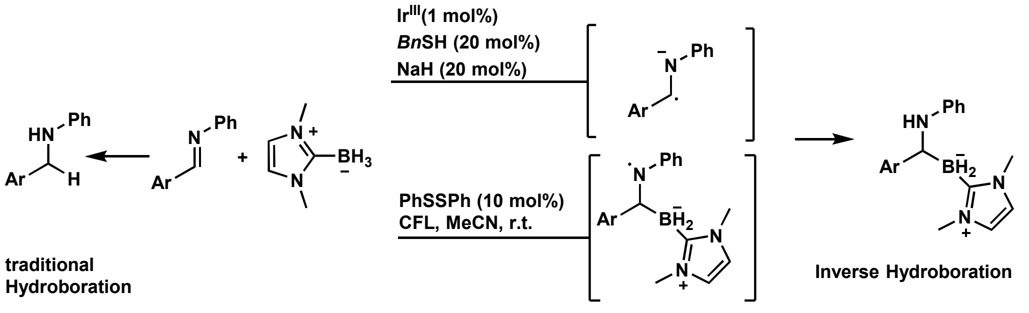
Wang ACIE. 2020, 59, 12876 – 12884

Hydroboration of Alkyne



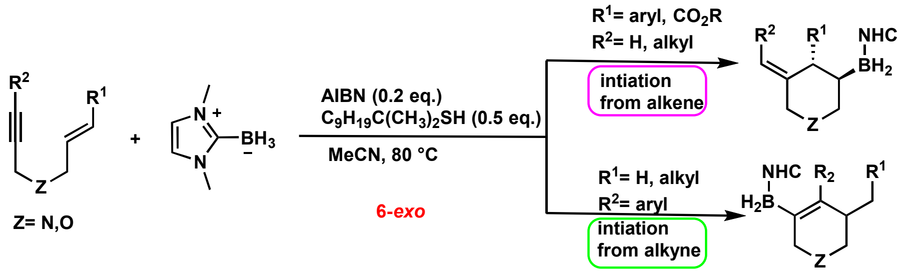
Taniguchi ACIE. 2018, 57, 9485 –9490

Inverse Hydroboration of Imines

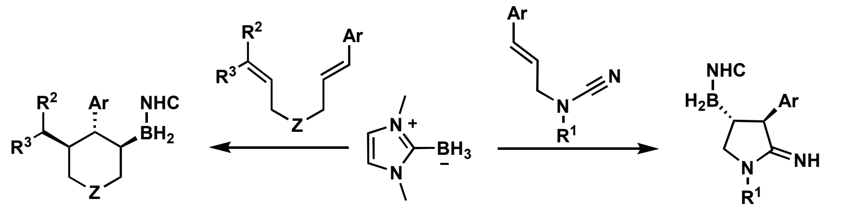


Xie ACIE. 2018, 57, 3990- 3994.
Kawamoto OL 2021,23, 1825- 1828.

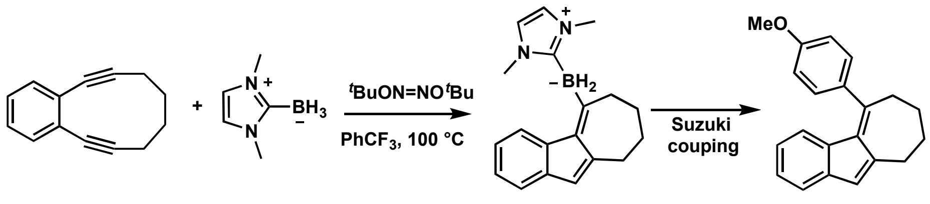
NHC-boryl radical addition/cyclization cascade.



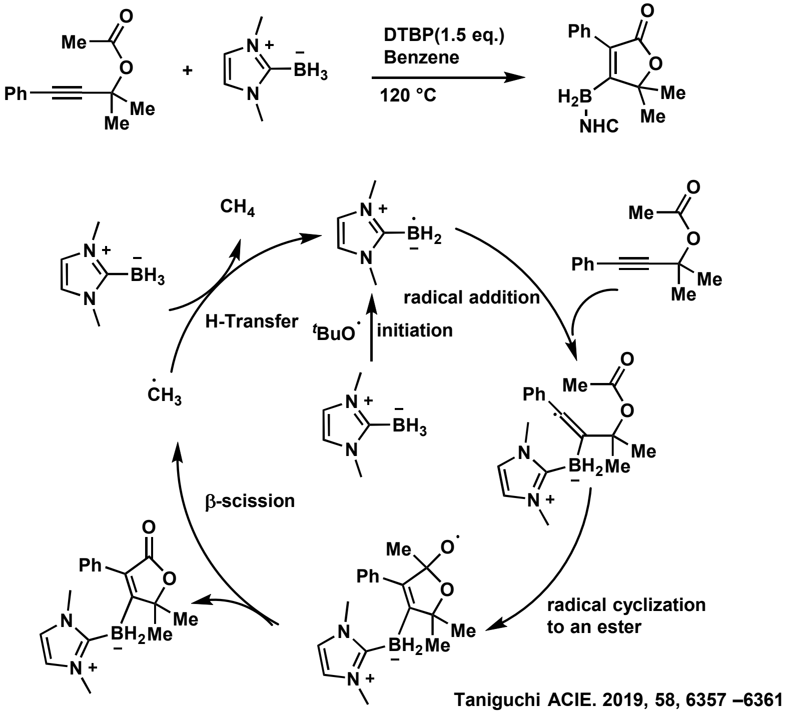
Wang J. Am. Chem. Soc. 2017, 139, 6050 -6053.



Wang OL 2018,20,7558 -7562
Wang OL 2018,20,2360-2364

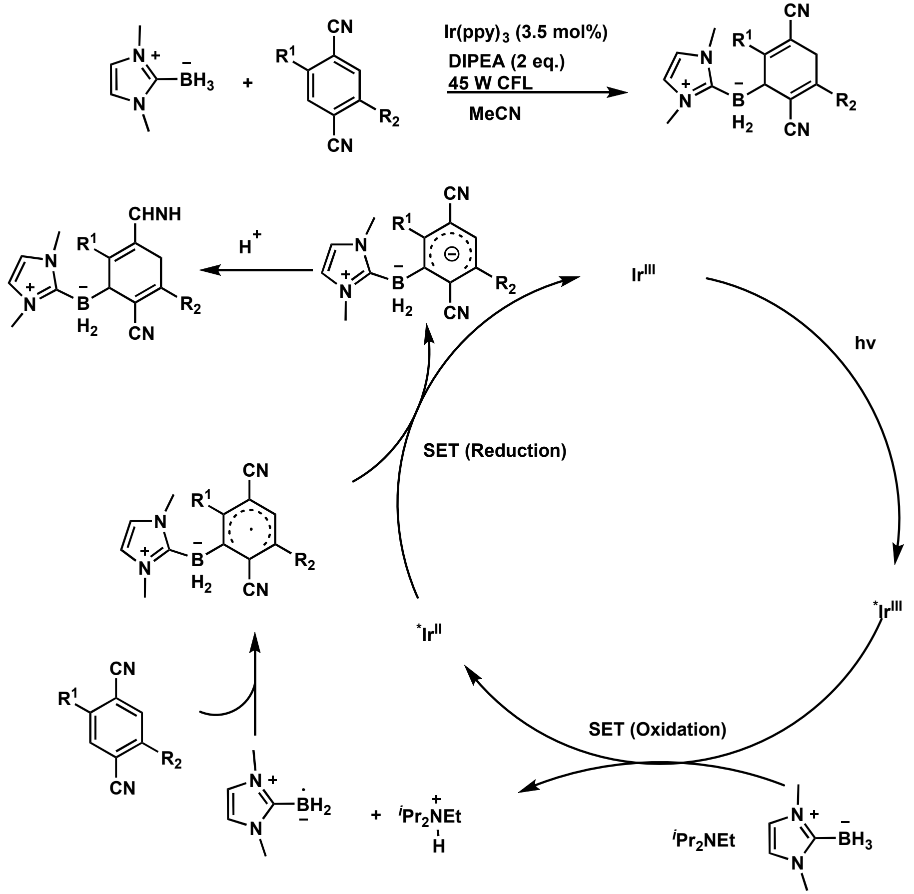


Chem. Eur. J. 2017, 23, 5404 – 5409
other's work
OL 2021, 23, 1891- 1897.
OL. 2022, 24, 668- 674.



Taniguchi ACIE. 2019, 58, 6357 –6361

Reactions of Electron-Poor Aromatic Rings



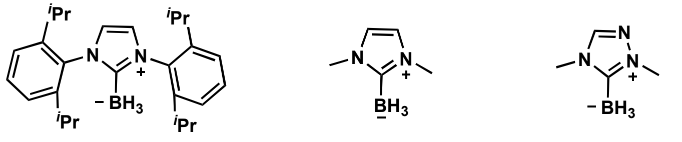
CUrran JACS 2020, 142, 6261- 6267

Taniguchi OL, 2020, 22, 2054 –2059.
Yang OL, 2020, 22, 1742 –1747.
Wu ACIE 2020, 59, 4009 –4016.

Lewis Base Boryl Radicals

NHC–boryl radicals as radical mediators (β-scission, HAT, XAT)

$$\dot{C}_9H_{19} + H_3\bar{B}-NHC \xrightarrow{k} C_9H_{20} + H_2\dot{\bar{B}}-NHC$$

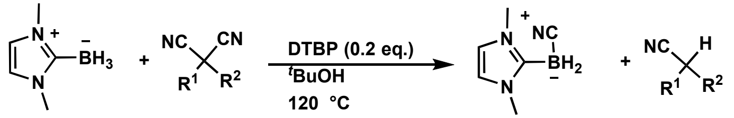


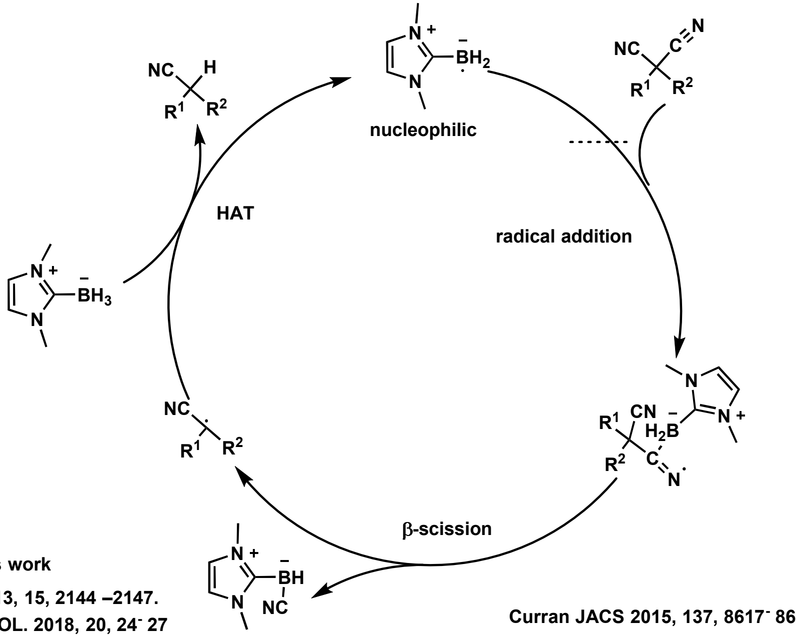
k= 2x 10⁴ $M^{-1}S^{-1}$ *k*= 8x 10⁴ $M^{-1}S^{-1}$ *k*= 8x 10⁴ $M^{-1}S^{-1}$

^{n}BuSnH TMSSiH Et_3SiH

k= 2x 10⁶ $M^{-1}S^{-1}$ *k*= 3.9x 10⁵ $M^{-1}S^{-1}$ *k*= 3.2x 10² $M^{-1}S^{-1}$

Curran OL, 2010, 12, 2998 –3001.





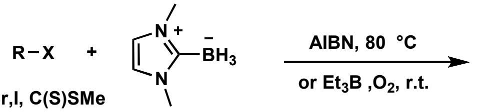
other's work

OL 2013, 15, 2144 –2147.

Wang OL. 2018, 20, 24- 27

Wang CCS Chem., 2019, 1, 504 –512.

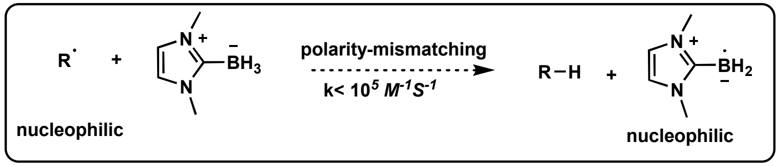
Curran JACS 2015, 137, 8617- 8622

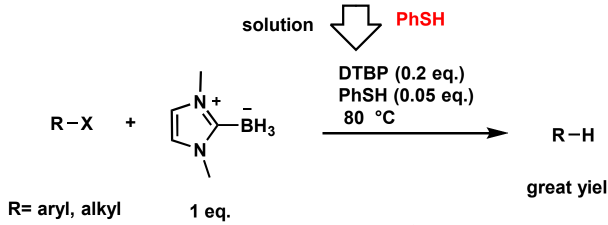


stoichiometric amounts of initiators

moderate yield

inefficient HAT

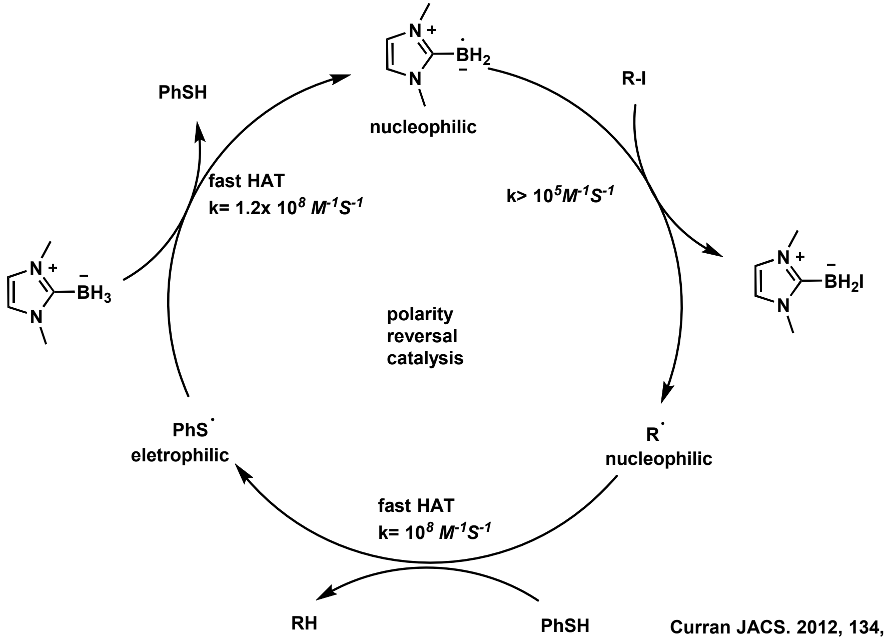




Curran JACS. 2008, 130, 10082 –10083

Curran Org. Lett., 2010, 12, 3002 –3005

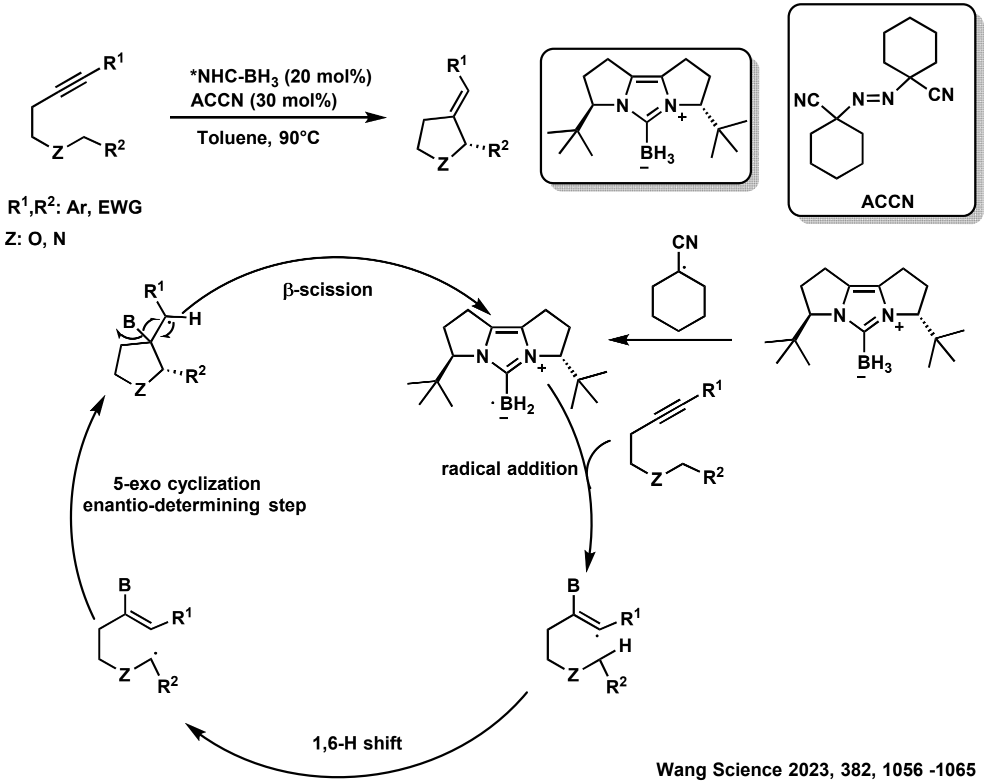
Curran OBC., 2011, 9, 3415 –3420



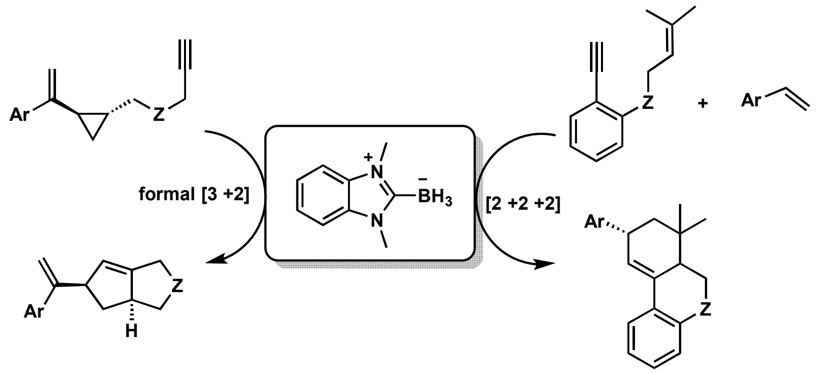
Curran JACS. 2012, 134, 5669- 5674

Giese reaction of RBr with NHC-BH₃ was reported by Timothy Noël JACS 2023, 145, 991- 999

Lewis Base Boryl Radicals

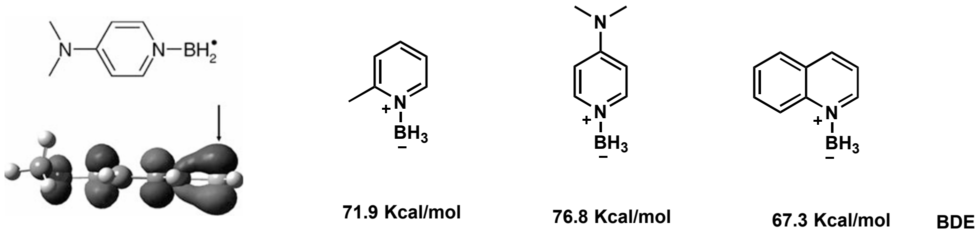


Wang Science 2023, 382, 1056 -1065



Wang ACIE 2024, 63, e 202405863.

heterocycle ligated Boryl radical



π type boryl radical

71.9 Kcal/mol

76.8 Kcal/mol

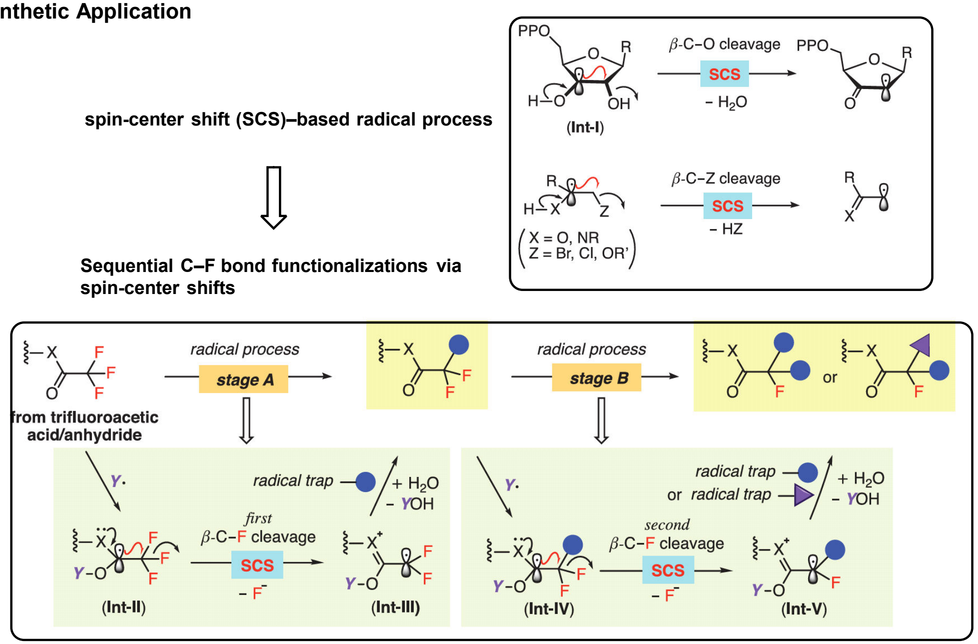
67.3 Kcal/mol

Lalevée, J. J. Phys. Org. Chem. 2009, 22, 986–993.
Lalevée, J. Chem. Eur. J. 2010, 16, 12920–12927

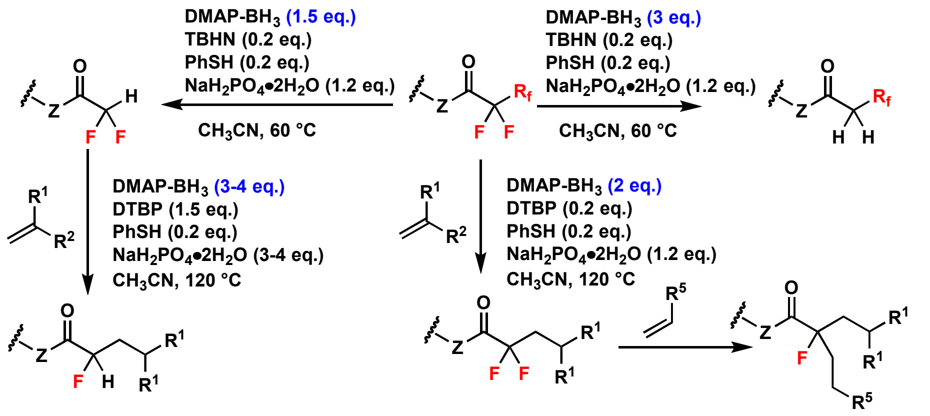
Synthetic Application

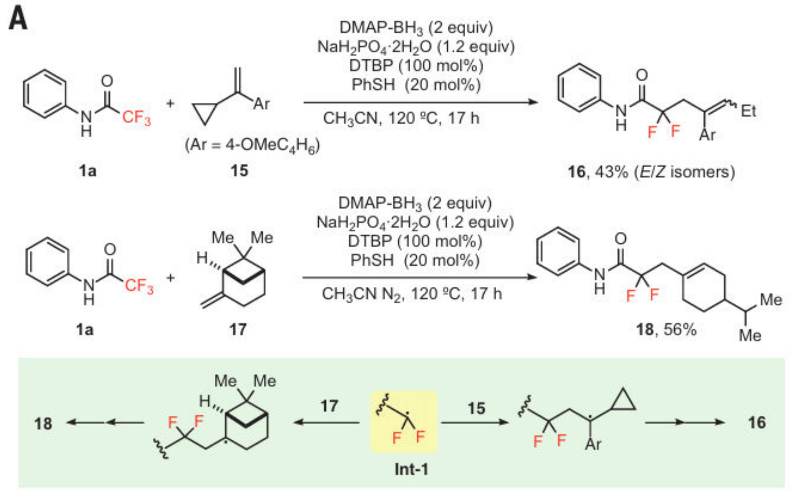
spin-center shift (SCS)–based radical process

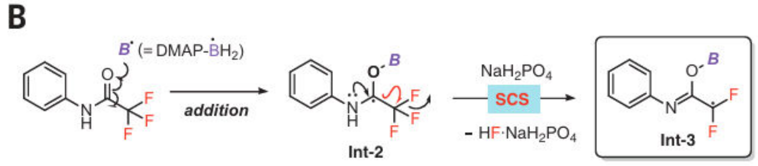
Sequential C–F bond functionalizations via spin-center shifts



Lewis Base Boryl Radicals

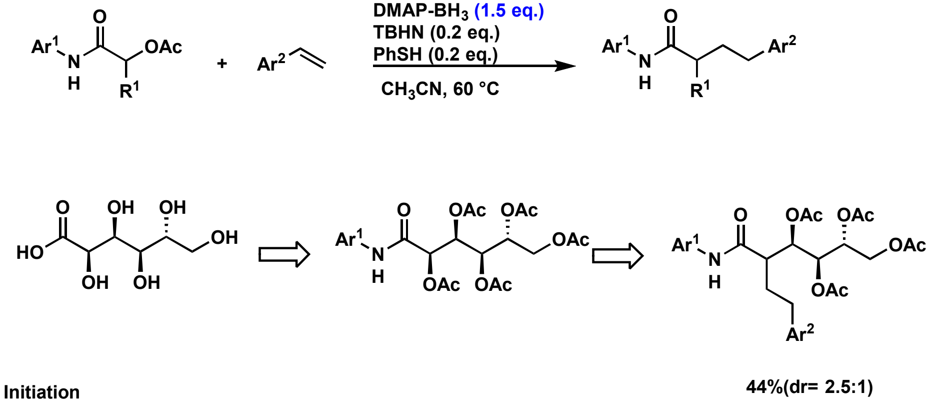




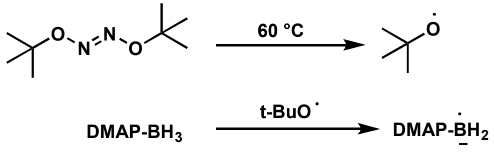


the presence of alkali metal salts is indispensable to promote the defluorination, and NaH$_2$PO$_4$ was found to be optimal

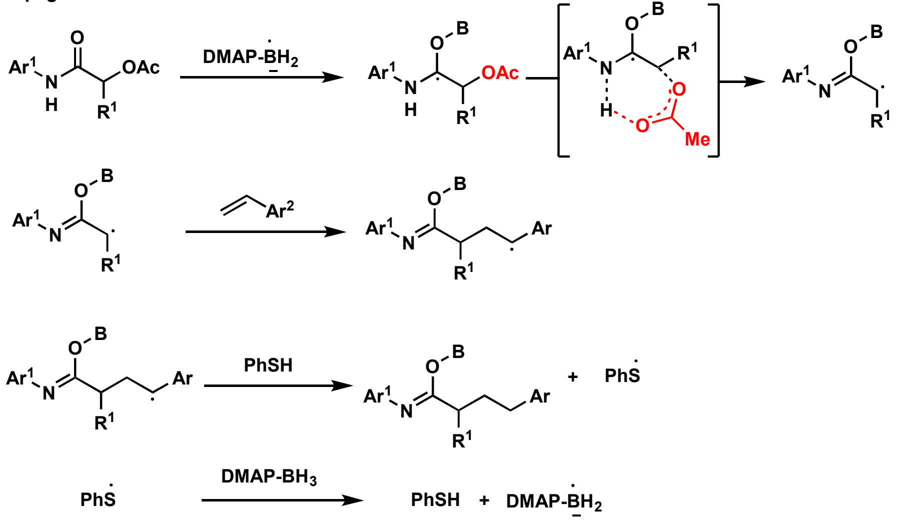
Wang Science 2021, 371, 1232 -1240



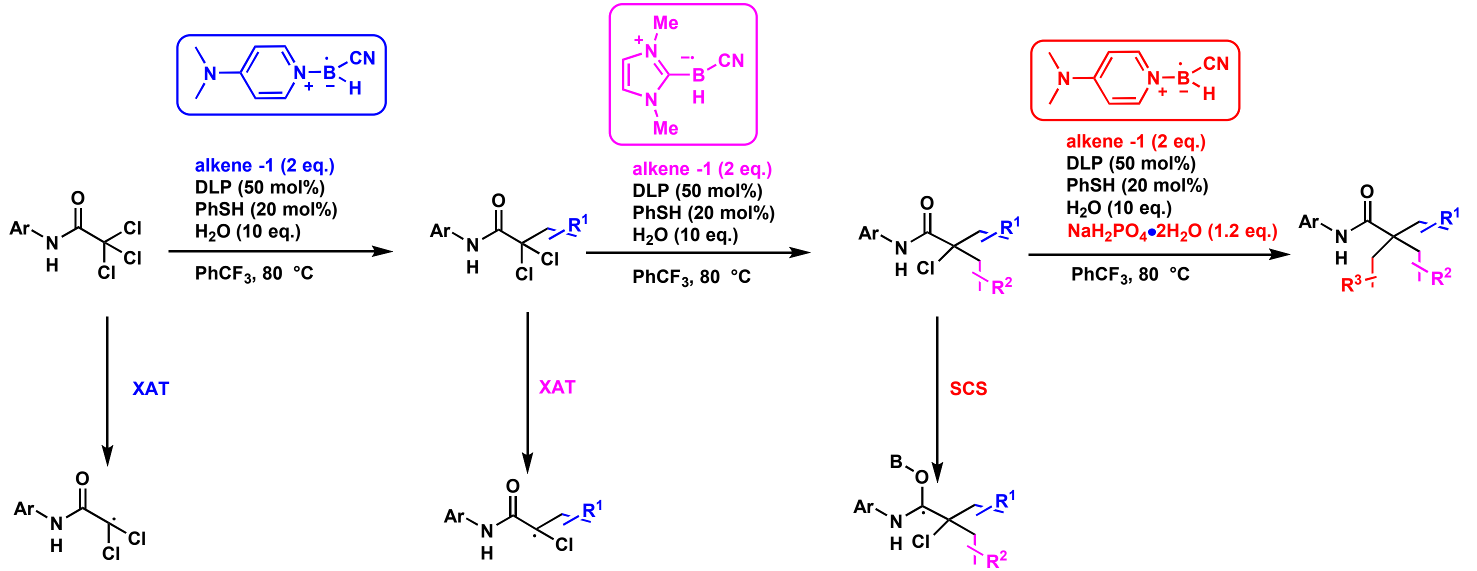
Initiation

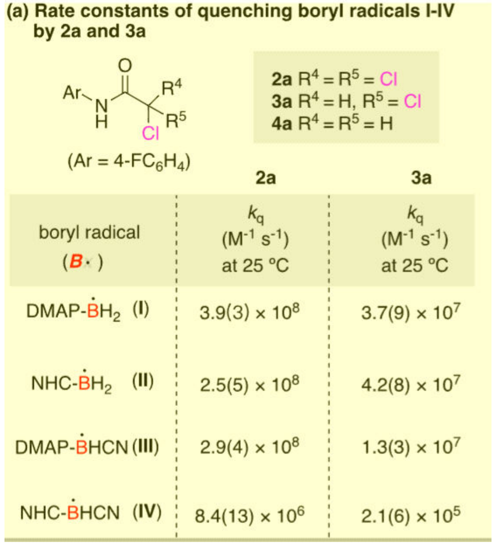


Propagation



Wang ACIE. 2022, e 202201329





(a) Rate constants of quenching boryl radicals I-IV by 2a and 3a

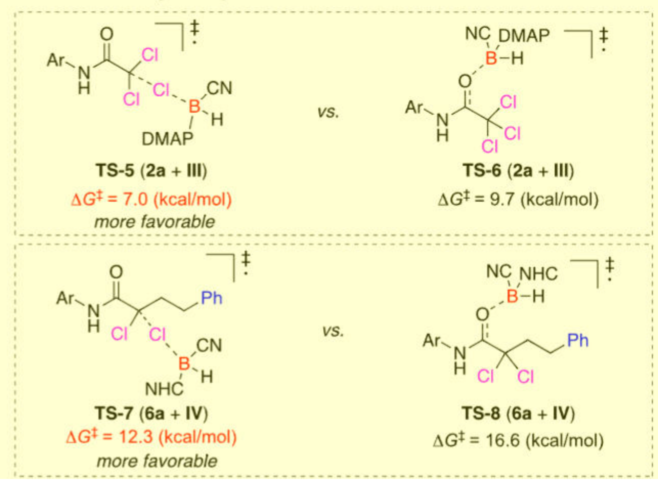
2a $R^4 = R^5 = Cl$
3a $R^4 = H$, $R^5 = Cl$
4a $R^4 = R^5 = H$

(Ar = 4-FC_6H_4)

boryl radical ($B\cdot$)	**2a** k_q (M^{-1} s^{-1}) at 25 °C	**3a** k_q (M^{-1} s^{-1}) at 25 °C
DMAP-$\dot{B}H_2$ (I)	$3.9(3) \times 10^8$	$3.7(9) \times 10^7$
NHC-$\dot{B}H_2$ (II)	$2.5(5) \times 10^8$	$4.2(8) \times 10^7$
DMAP-$\dot{B}$HCN (III)	$2.9(4) \times 10^8$	$1.3(3) \times 10^7$
NHC-$\dot{B}$HCN (IV)	$8.4(13) \times 10^6$	$2.1(6) \times 10^5$

unable to see quenching of radical for monochlorine

Possible reaction pathways of 2a with III and 6a with IV

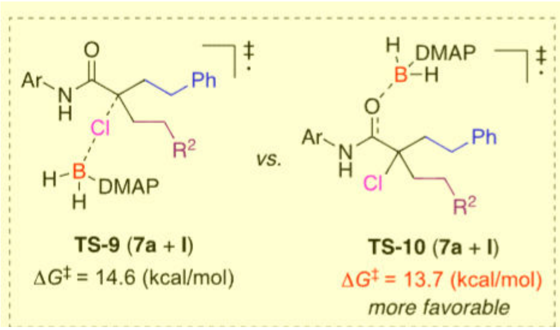


TS-5 (2a + III)
$\Delta G^{\ddagger}$ = 7.0 (kcal/mol)
more favorable

TS-6 (2a + III)
$\Delta G^{\ddagger}$ = 9.7 (kcal/mol)

TS-7 (6a + IV)
$\Delta G^{\ddagger}$ = 12.3 (kcal/mol)
more favorable

TS-8 (6a + IV)
$\Delta G^{\ddagger}$ = 16.6 (kcal/mol)

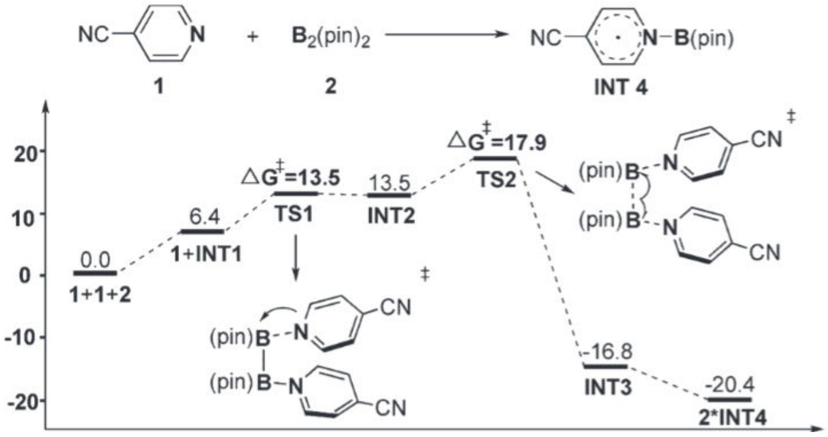


TS-9 (7a + I)
$\Delta G^{\ddagger}$ = 14.6 (kcal/mol)

TS-10 (7a + I)
$\Delta G^{\ddagger}$ = 13.7 (kcal/mol)
more favorable

Wang JACS. 2022, 144, 15275- 15285.

Lewis Base Boryl Radicals



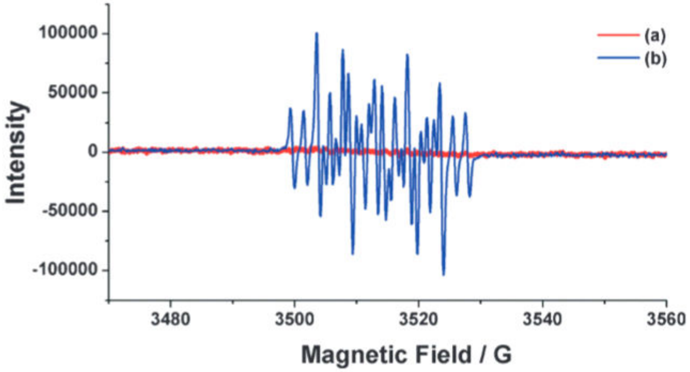
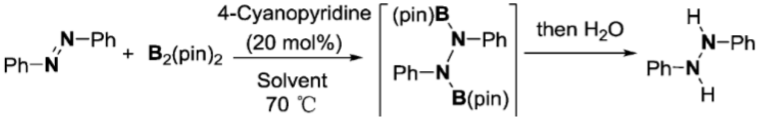
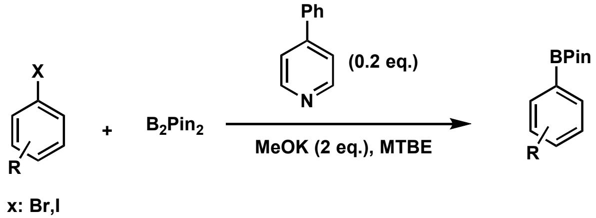


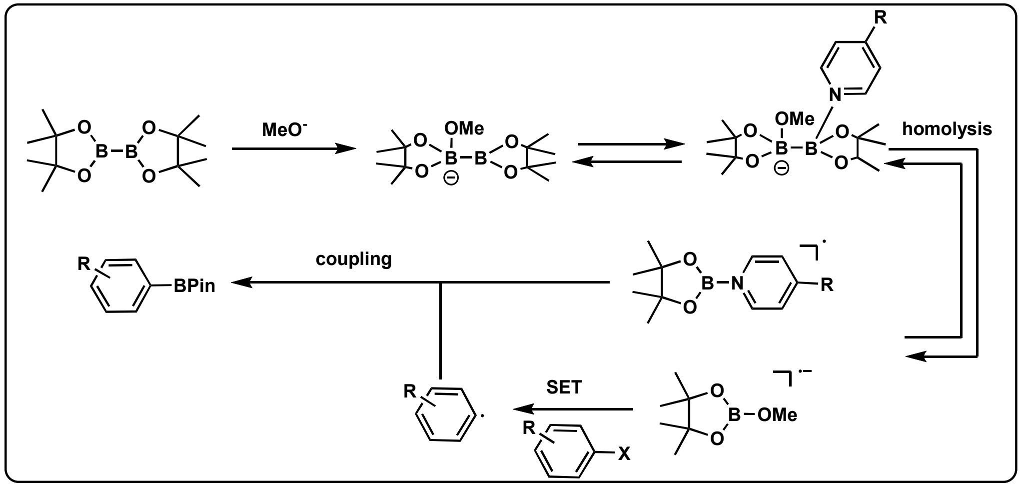
Figure 2. X Band EPR spectrum obtained in THF at 298 K. a) Spectrum of 0.1 M solutions of 4-cyanopyridine. b) Spectrum of a 1:1 mixture of 4-cyanopyridine and $B_2(pin)_2$.



Zhu ACIE. 2016, 55, 5985 –5989

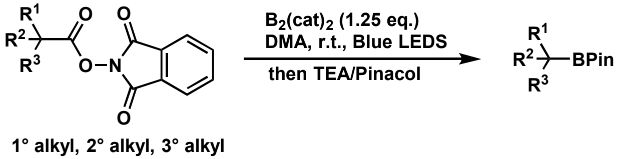
Radical Borylation of Aryl Halide

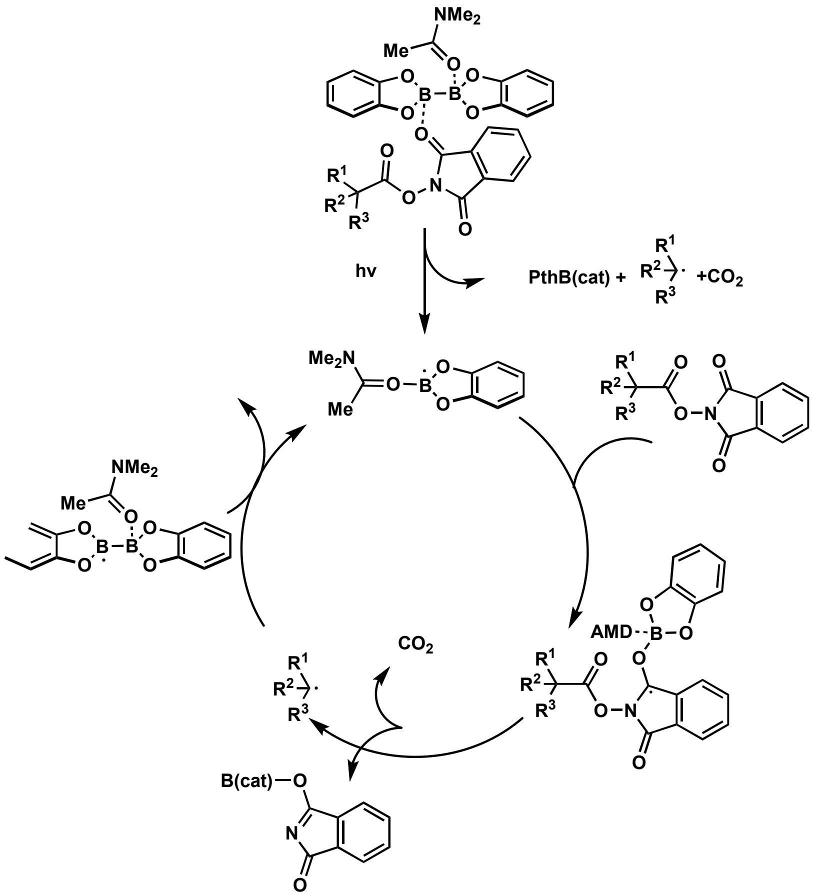




Jiao JACS. 2017, 139, 607- 610

Decarboxylation Borylation of NHPI ester

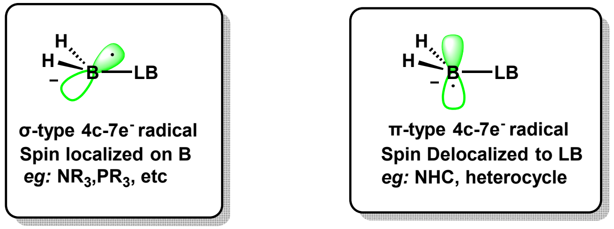




Aggarwal,V. K. Science, 2017, 357, 283 –286

Summary

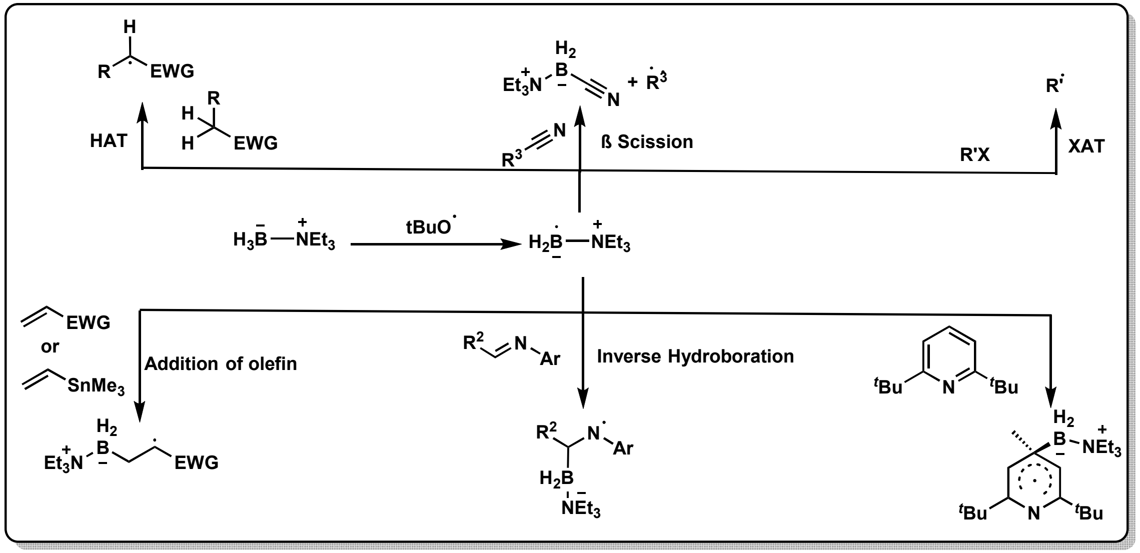
structure



σ-type 4c-7e⁻ radical
Spin localized on B
eg: NR_3,PR_3, etc

π-type 4c-7e⁻ radical
Spin Delocalized to LB
eg: NHC, heterocycle

reactivity



synthetic appilcation

1) Hydroalkylation of Olefins and alkyne
2) Xanthate Reduction/Deoxygenation
3) PRC Chain Reactions
4) Reduction of Alkyl & Aryl Halides
5) Enediyne & Enyne Cyclizations
6) Decarboxylative Borylation
7) Dehalogenative Borylation
8)Photoredox Inverse Hydroboration
9) 1,4-hydroborylation of Electron-Poor Aromatic Ring
10) Sequential C–x bond functionalizations
11) Directly borylation of azine via Minisci type reaction
12) XAT for $C(sp_3)$–$C(sp_3)$ Bond Formation
13) XAT for Giese reaction
14) Enable asymmetric radical cycloisomerization reactions