



The Yang Research Group  
Precise Synthesis Lab at Tongji University



同濟大學  
TONGJI UNIVERSITY

# Topic

## 硼自由基催化的新反应——汪义丰

---

汇报人：李连杰

时间：2026.05.29

## Professional experience



2015年8月-至今, 中国科学技术大学, 教授;

2011年3月-2015年8月, 新加坡南洋理工大学, 博士后, 导师: Shunsuke Chiba;

2006年8月-2011年3月, 新加坡南洋理工大学, 博士, 导师: Shunsuke Chiba;

2003年9月-2006年6月, 南开大学, 硕士;

1999年9月-2003年6月, 华中师范大学, 学士;

**汪义丰**

**国家杰青**

## Research

有机合成化学; 自由基化学; 硼化学; 光化学合成; 药物化学

01

研究背景

02

C-B 键构建

03

C-X键活化

04

不对称催化

## 自由基反应研究的主要元素

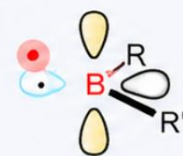
<b>C</b> carbon	<b>N</b> nitrogen	<b>O</b> oxygen
<b>Si</b> silicon	<b>P</b> phosphorous	<b>S</b> sulphur
<b>Sn</b> tin	<b>Br</b> bromine	<b>I</b> iodine

- 反应活性和机制与元素性质密切相关
- p轨道饱和

自由基中心  
元素的拓展

## 有机硼自由基

**B**  
boron



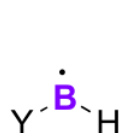
机遇：新反应和新策略

- 准金属元素性质 **(新反应)**
- 空p轨道可填充 **(新策略)**

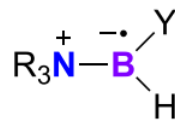
普通硼自由基缺电子、稳定性较差；通过路易斯碱配位，可稳定硼中心自由基，使其成为更易利用的合成中间体。

### (a) Boron-centered radicals

#### Neutral Boryl Radicals

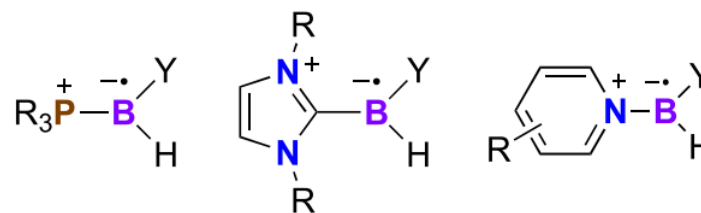


Lewis base  
coordination



3-center-5-electron  
highly electron-deficient, unstable

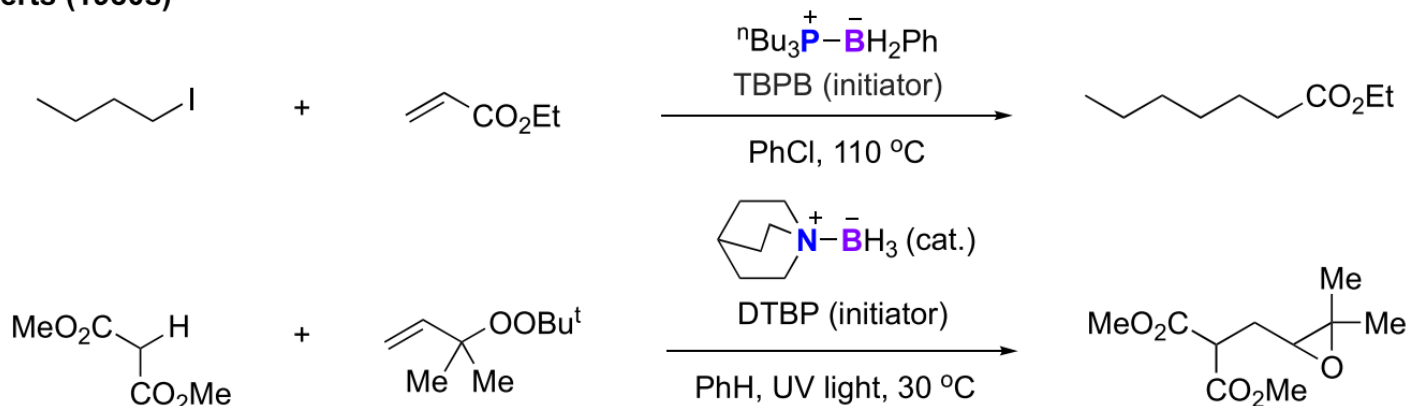
#### Lewis Base-Boryl Radicals (LBRs)



4-center-7-electron  
relatively more stable

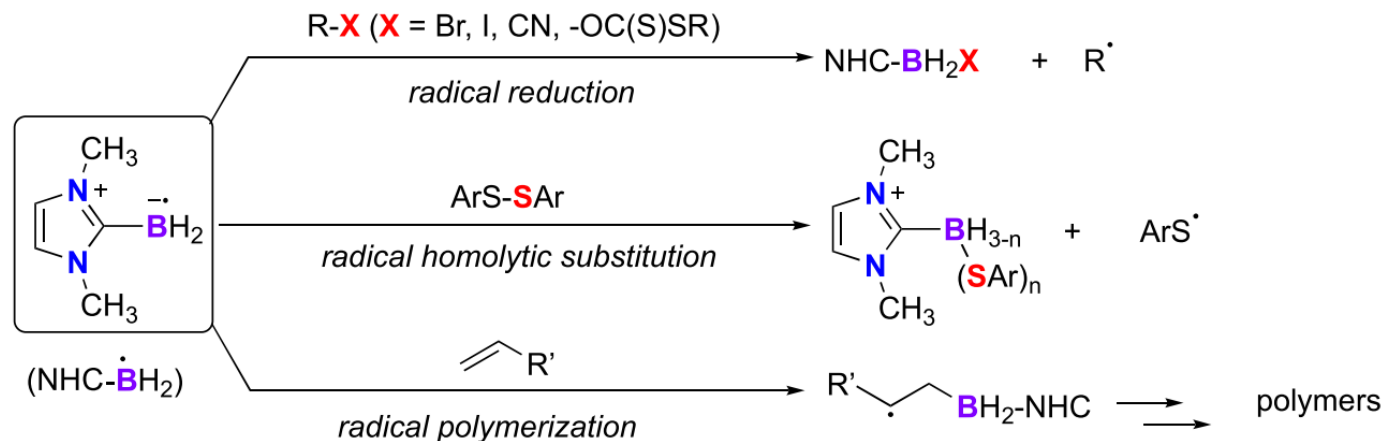
## 路易斯碱-硼自由基的早期发展与代表性应用

Roberts (1980s)

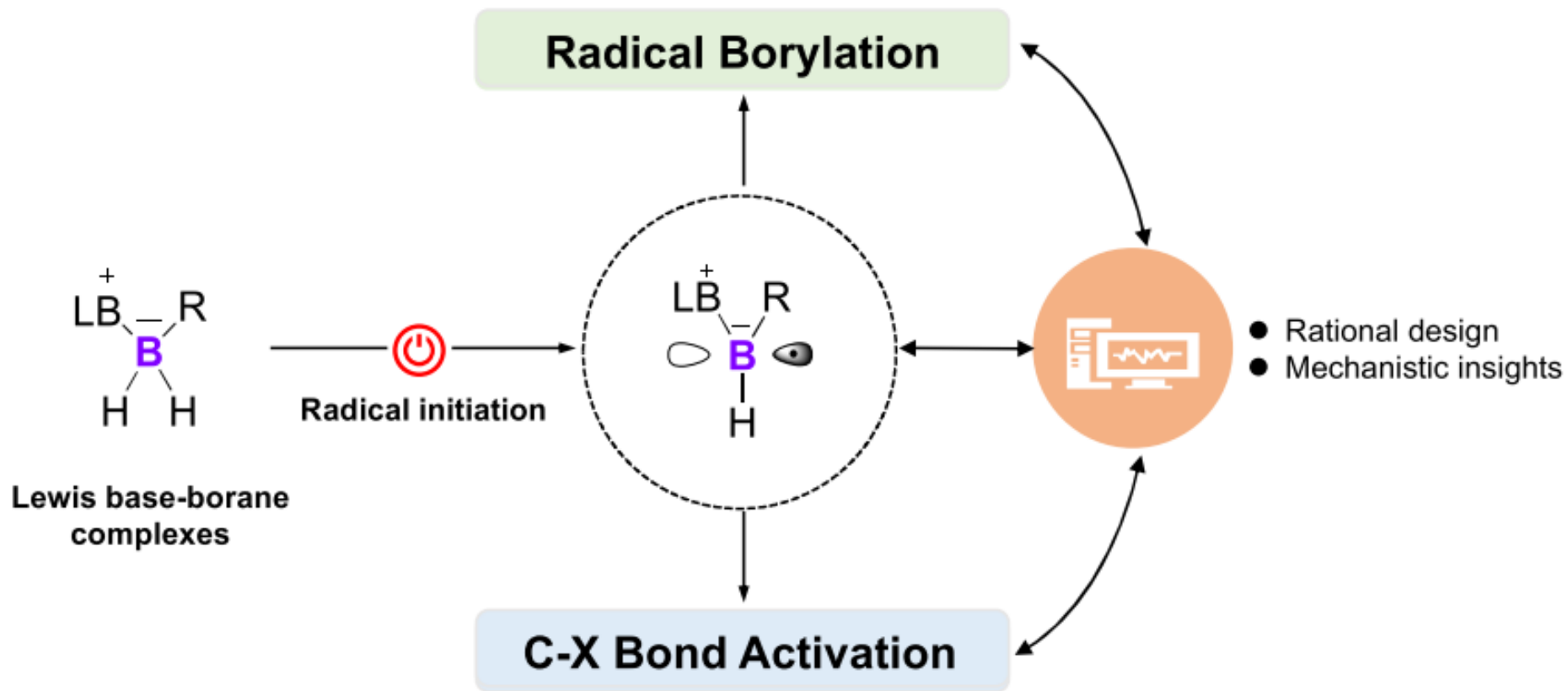


TBPB = *tert*-Butyl perbenzoate, DTBP = Di-*tert*-butyl peroxide

Curran and coworkers (2008-2015)



- 多作为自由基媒介或还原剂使用直接用于 C-B 键构建较少。
- 生成方式不够温和常依赖引发剂、高温或紫外光。
- 惰性键活化仍有限如 C-F、C-Cl键活化较少

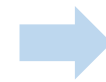


- New reaction development
- Synthetic applications
- Mechanistic investigation

调控结构改变  
Lewis base 和硼取代基



调控反应性实现温和  
生成与选择性控制



拓展应用自由基硼化：构  
建 C-B 键和C-X 键活化

01

研究背景

02

C-B 键构建

03

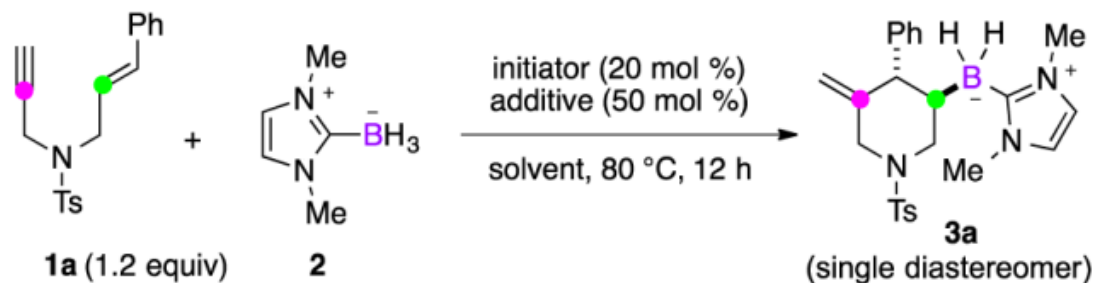
C-X键活化

04

不对称催化

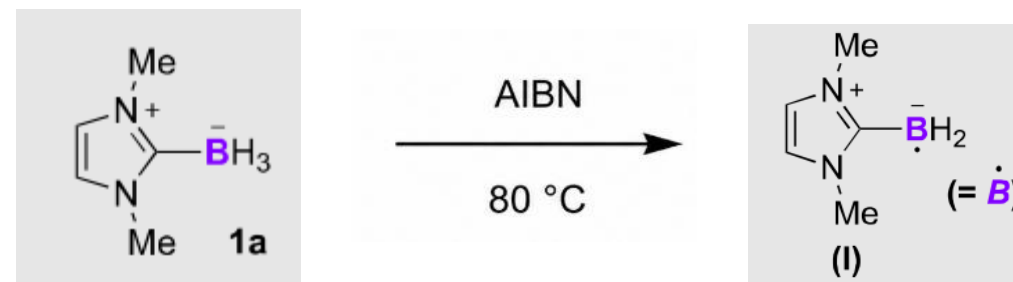
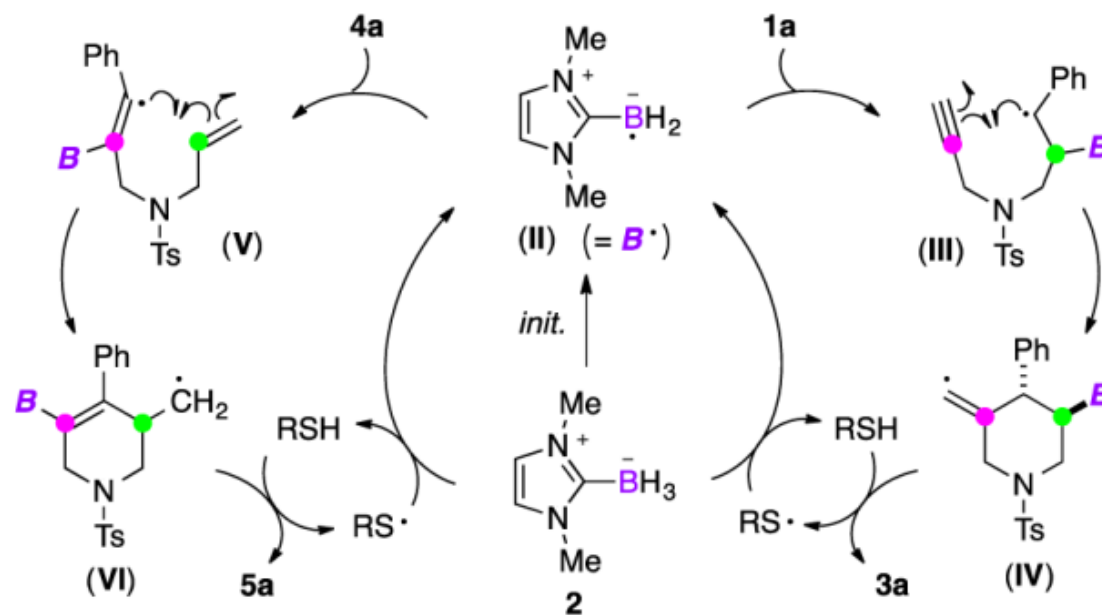
# Radical Borylation/Cyclization Cascade of 1,6-Enynes for the Synthesis of Boron-Handled Hetero- and Carbocycles

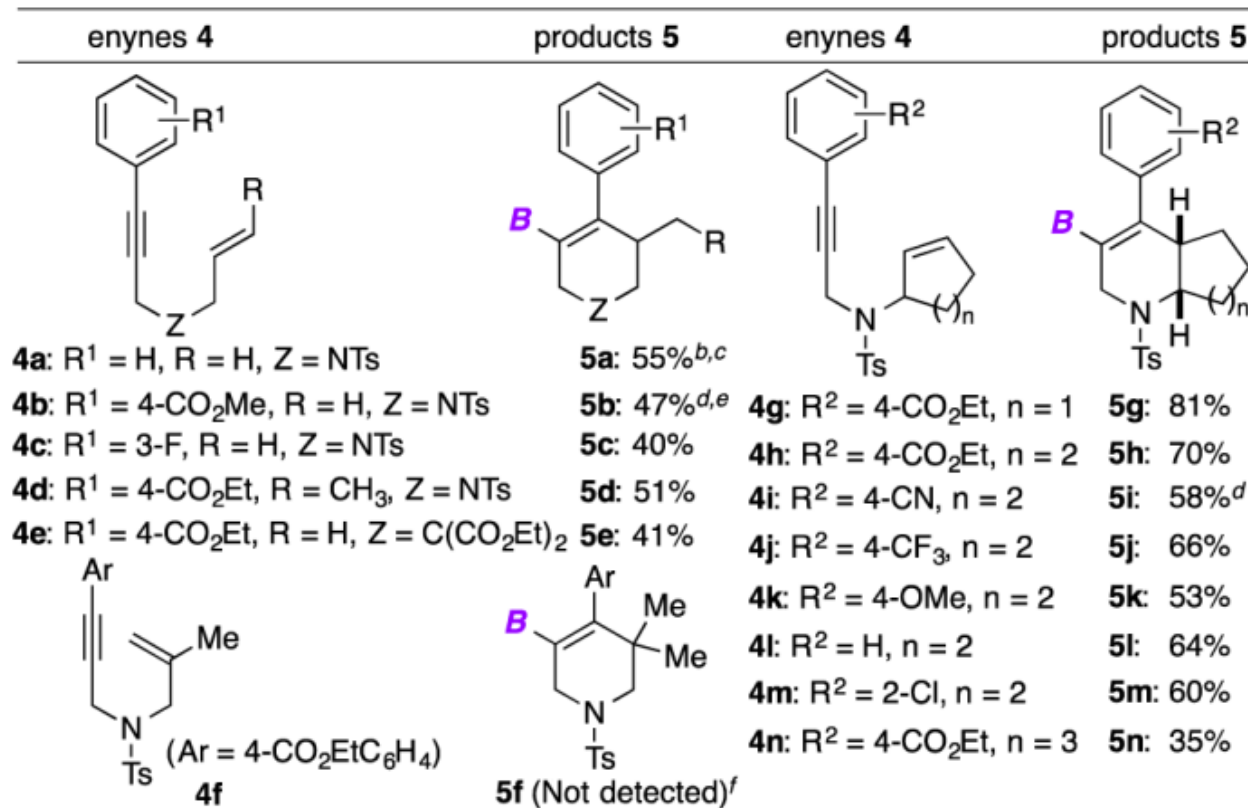
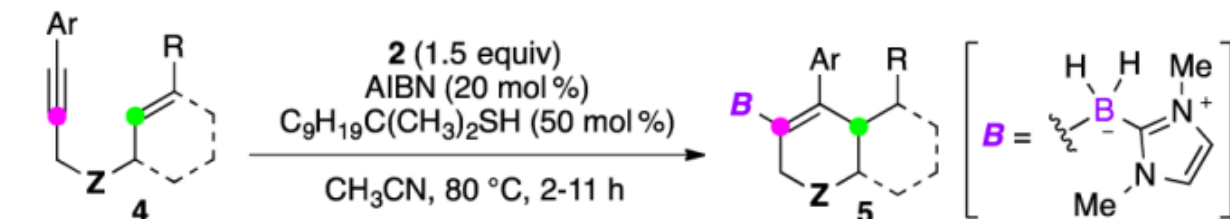
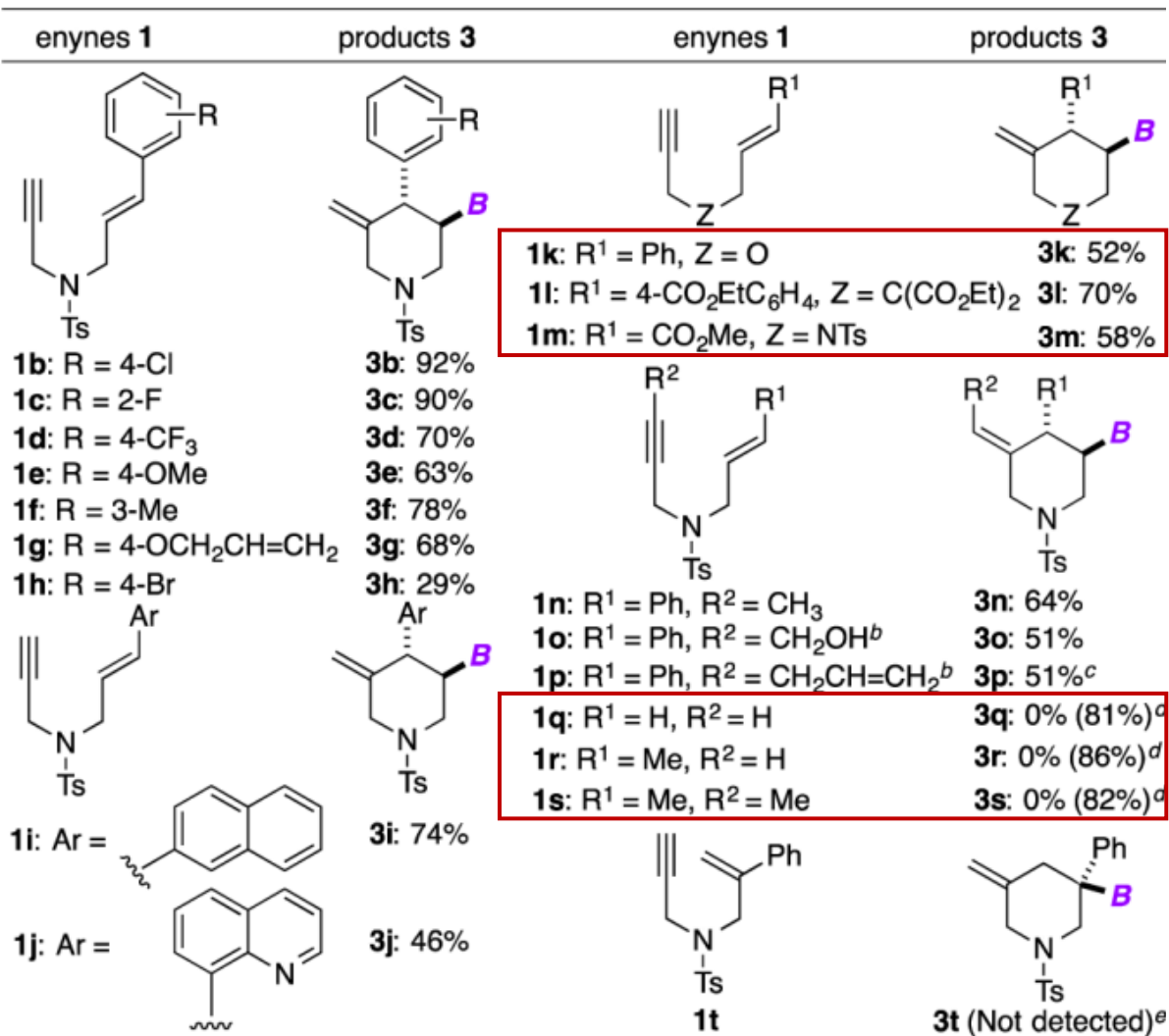
Shi-Chao Ren,<sup>‡</sup> Feng-Lian Zhang,<sup>‡</sup> Jing Qi, Yun-Shuai Huang, Ai-Qing Xu, Hong-Yi Yan, and Yi-Feng Wang\*<sup>ID</sup>

**Table 1. Optimization of the Radical Borylation/Cyclization Reaction of 1,6-Enyne<sup>a</sup>**


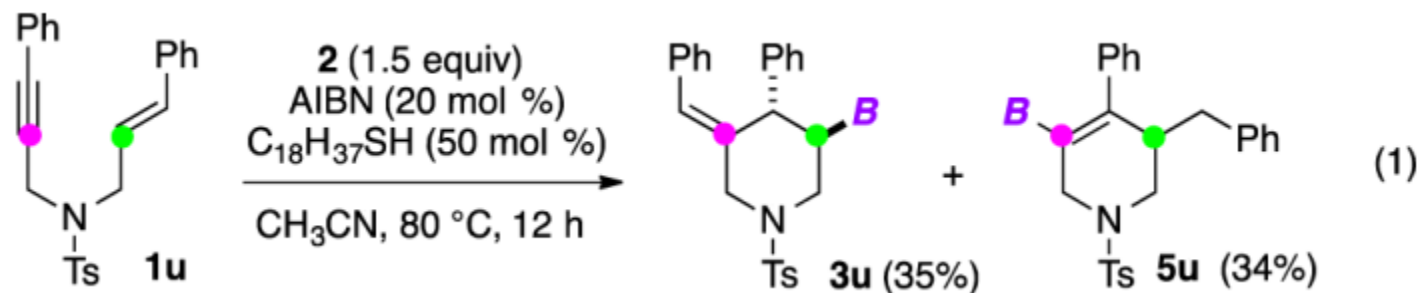
entry	initiator	additive	solvent	3a yield (%) <sup>b</sup>
1	AIBN	—	PhCH <sub>3</sub>	21 (61) <sup>c</sup>
2	AIBN	PhSH	PhCH <sub>3</sub>	33 (20) <sup>c</sup>
3	AIBN	C <sub>9</sub> H <sub>19</sub> C(CH <sub>3</sub> ) <sub>2</sub> SH	PhCH <sub>3</sub>	58 (13) <sup>c</sup>
4	AIBN	C <sub>9</sub> H <sub>19</sub> C(CH <sub>3</sub> ) <sub>2</sub> SH	CH <sub>3</sub> CN	84 <sup>d</sup>
5	TBHN	C <sub>9</sub> H <sub>19</sub> C(CH <sub>3</sub> ) <sub>2</sub> SH	CH <sub>3</sub> CN	80
6 <sup>e</sup>	Et <sub>3</sub> B/O <sub>2</sub>	C <sub>9</sub> H <sub>19</sub> C(CH <sub>3</sub> ) <sub>2</sub> SH	CH <sub>3</sub> CN	0 (90) <sup>c</sup>
7	—	C <sub>9</sub> H <sub>19</sub> C(CH <sub>3</sub> ) <sub>2</sub> SH	CH <sub>3</sub> CN	0 (98) <sup>c</sup>

<sup>a</sup>Reaction conditions: 2 (0.2–0.3 mmol), 1a (1.2 equiv), initiator (20 mol %), additive (50 mol %), solvent (2 mL), 80 °C for 12 h. <sup>b</sup>NMR yield using tetrachloroethane as an internal standard. <sup>c</sup>Recovery yield of 2 is shown in parentheses. <sup>d</sup>Isolated yield. <sup>e</sup>The reaction was run at room temperature under an air atmosphere.

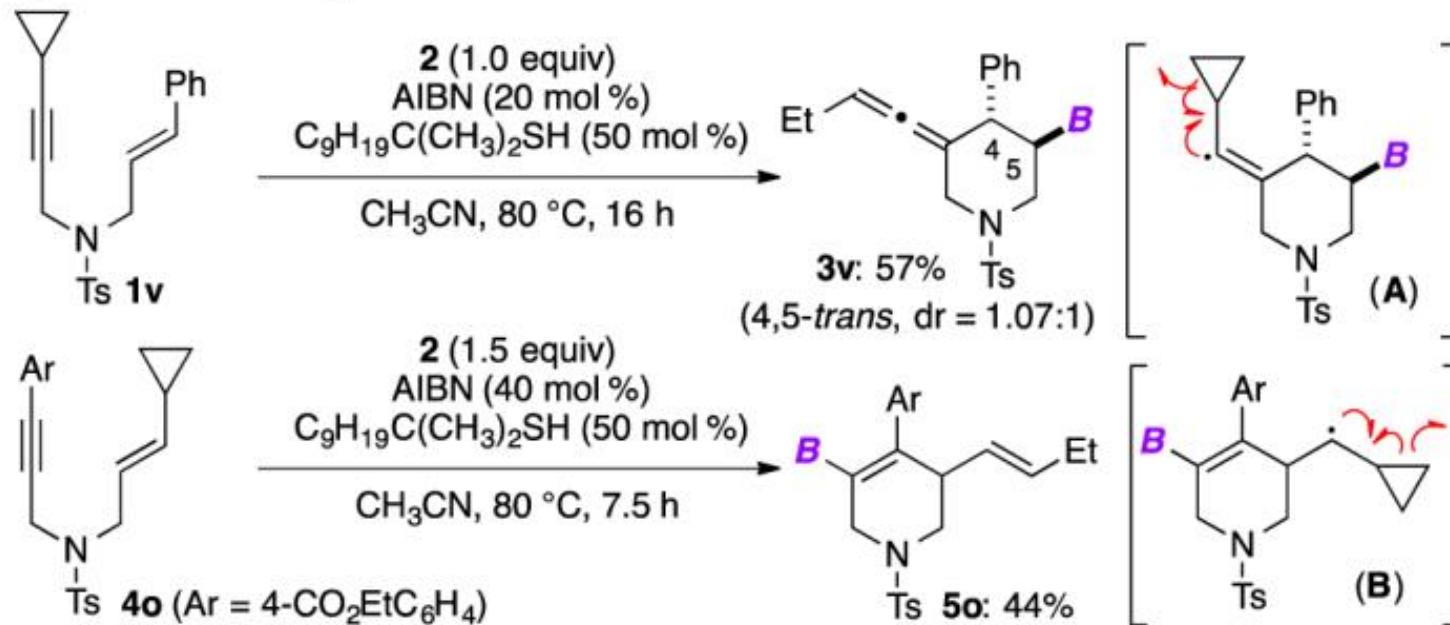

**Plausible mechanisms of the formation of 3a and 5a**


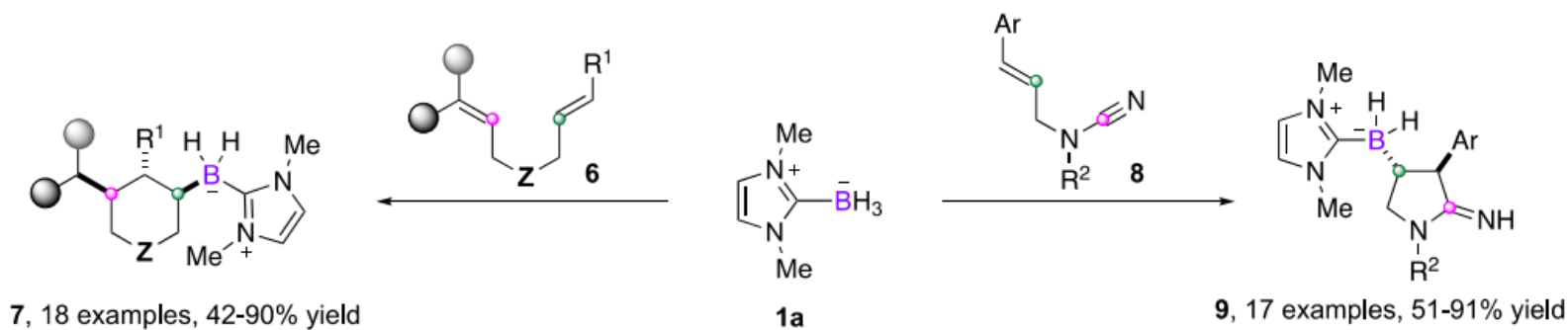


硼自由基既可以从烯烃端启动，也可以从炔烃端启动；加到哪里，取决于哪一侧能形成更稳定的自由基中间体



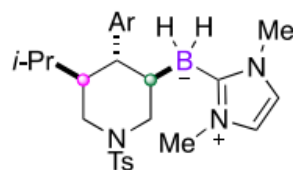
## a) Radical clock experiments



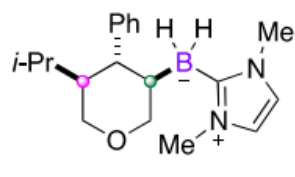


condition: AIBN (20 mol%), C<sub>9</sub>H<sub>19</sub>C(CH<sub>3</sub>)<sub>2</sub>SH (20 mol%), CH<sub>3</sub>CN, 80 °C, 12 h  
 R<sup>1</sup> = Ar, CO<sub>2</sub>Et, CONET<sub>2</sub>, R<sup>2</sup> = Ts, Ar, Bn, Boc, Z = NTs, O, C(CO<sub>2</sub>Et)<sub>2</sub>

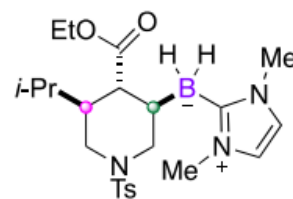
## representative products from 1,6-dienes



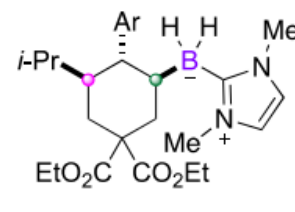
7a, 80%  
(Ar = 2-ClC<sub>6</sub>H<sub>4</sub>)



7b, 72%

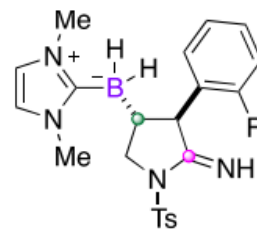


7c, 61%

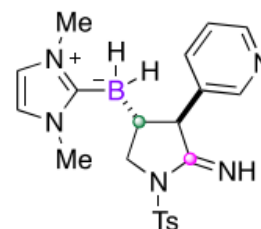


7d, 63%  
(Ar = 4-CO<sub>2</sub>EtC<sub>6</sub>H<sub>4</sub>)

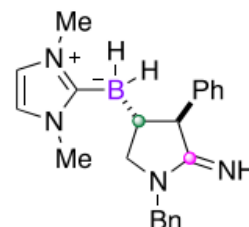
## representative products from N-allylcyanamides



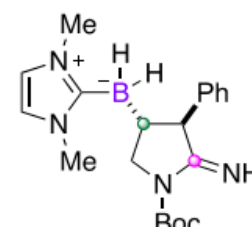
9a, 83%



9b, 66%



9c, 71%





9d, 66%

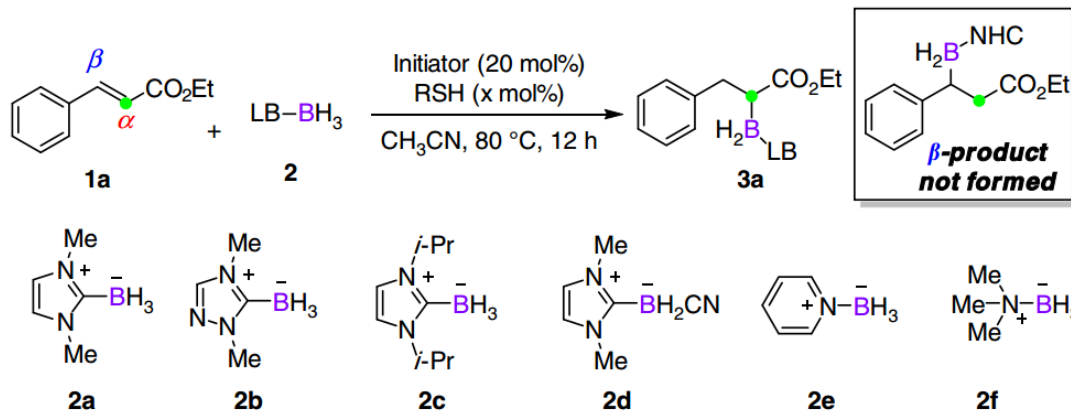
ARTICLE

<https://doi.org/10.1038/s41467-019-09825-3>

OPEN

# Regioselective radical $\alpha$ -borylation of $\alpha,\beta$ -unsaturated carbonyl compounds for direct synthesis of $\alpha$ -borylcarbonyl molecules

Shi-Chao Ren<sup>1,4</sup>, Feng-Lian Zhang<sup>1,4</sup>, Ai-Qing Xu<sup>1</sup>, Yinuo Yang<sup>1</sup>, Min Zheng<sup>2</sup>, Xiaoguo Zhou <sup>2</sup>, Yao Fu<sup>1</sup> & Yi-Feng Wang <sup>1,3</sup>



Entry	LB-BH <sub>3</sub>	Initiator	RSH (x mol%)	3a Yield (%) <sup>b</sup>
1	<b>2a</b>	AIBN	<i>tert</i> -dodecanethiol (20)	49 (39) <sup>d</sup>
2	<b>2a</b>	AIBN	<i>tert</i> -dodecanethiol (50)	81 <sup>c</sup>
3	<b>2a</b>	AIBN	PhSH (20)	77
4	<b>2a</b>	AIBN	4-MeOC <sub>6</sub> H <sub>4</sub> SH (20)	75
5	<b>2a</b>	AIBN	4-CO <sub>2</sub> MeC <sub>6</sub> H <sub>4</sub> SH (20)	73
6	<b>2a</b>	AIBN	MeO <sub>2</sub> CCH <sub>2</sub> SH (20)	80
7	<b>2b</b>	AIBN	PhSH (20)	89
8	<b>2c</b>	AIBN	PhSH (20)	70
9	<b>2d</b>	AIBN	PhSH (20)	67
10	<b>2e</b>	AIBN	PhSH (20)	0 (95) <sup>e</sup>
11	<b>2f</b>	AIBN	PhSH (20)	0 (98) <sup>e</sup>
12	<b>2a</b>	AIBN	--	0 (83) <sup>d</sup>
13 <sup>f</sup>	<b>2a</b>	TBHN	<i>tert</i> -dodecanethiol (50)	67 (17) <sup>d</sup>
14 <sup>f</sup>	<b>2a</b>	TBHN	PhSH (20)	60
15	<b>2a</b>	--	<i>tert</i> -dodecanethiol (50)	0 (98) <sup>d</sup>
16	<b>2a</b>	--	PhSH (20)	0 (88) <sup>d</sup>

<sup>a</sup>Reaction conditions: **2** (0.2-0.3 mmol), **1a** (1.2 equiv), initiator (20 mol%), RSH (x mol%), CH<sub>3</sub>CN (2 ml), 80 °C for 12 h

<sup>b</sup>NMR yield using tetrachloroethane as an internal standard

<sup>c</sup>Isolated yield

<sup>d</sup>Recovery yield of **2a** is shown in parentheses

<sup>e</sup>Recovery yield of **1a** is shown in parentheses

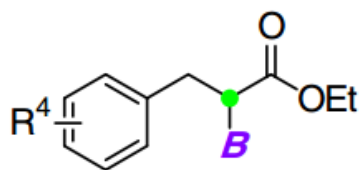
<sup>f</sup>The reaction was conducted at 50 °C

**2b 为有效硼自由基前体**

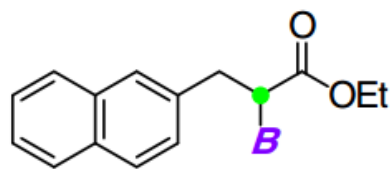
**吡啶-BH<sub>3</sub> / Me<sub>3</sub>N-BH<sub>3</sub> 不反应**

**硫醇对反应至关重要**

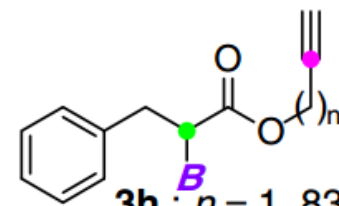
**引发剂不反应，支持自由基机理**

**$\alpha$ -boryl- $\beta$ -aryl esters**

- 3b** :  $R^4 = 2\text{-Me}$ , 78%  
**3c** :  $R^4 = 2\text{-NH}_2$ , 77%  
**3d** :  $R^4 = 3\text{-OH}$ , 74%  
**3e** :  $R^4 = 4\text{-F}$ , 85%  
**3f** :  $R^4 = 4\text{-CN}$ , 52%<sup>b,c</sup>

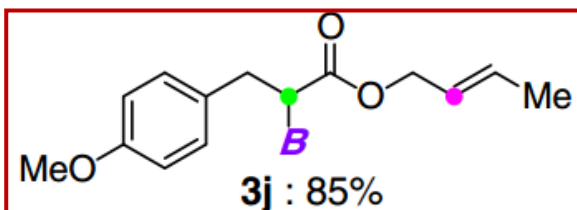


**3g** : 72%<sup>b</sup>

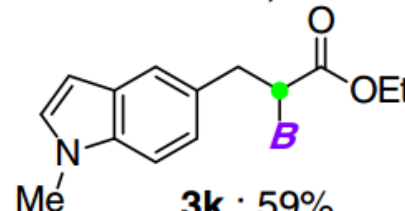


**3h** :  $n = 1$ , 83%

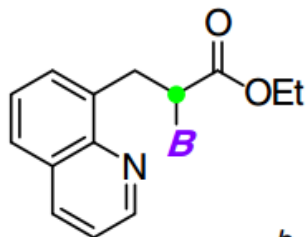
**3i** :  $n = 2$ , 89%



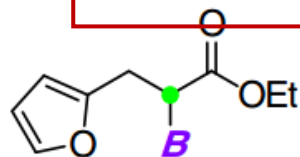
**3j** : 85%



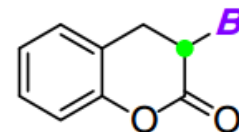
**3k** : 59%



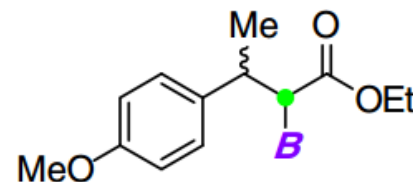
**3l** : 82%<sup>b</sup>



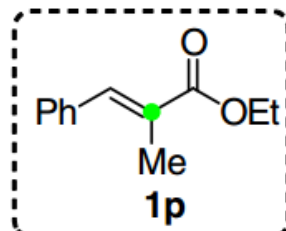
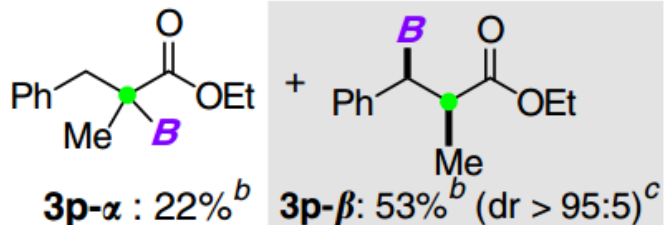
**3m** : 95%<sup>b</sup>



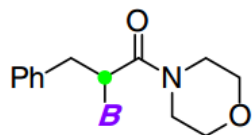
**3n** : 72%<sup>b</sup>



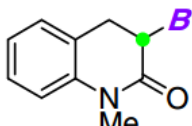
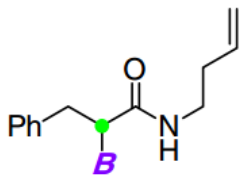
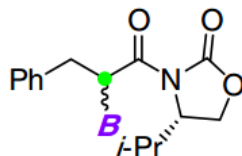
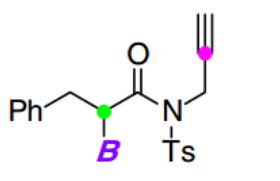
**3o** : 95%<sup>b</sup> (dr = 4:1)

 **$\alpha$ -vs.  $\beta$ - borylation**

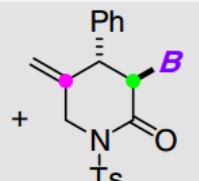
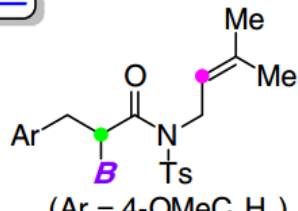
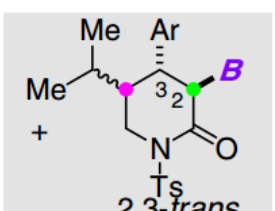
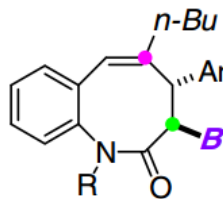
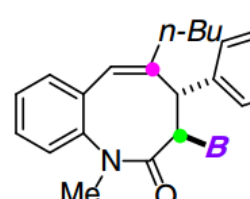
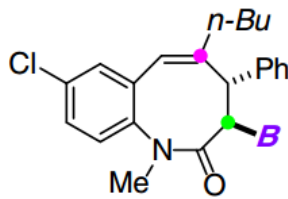
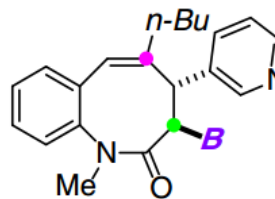
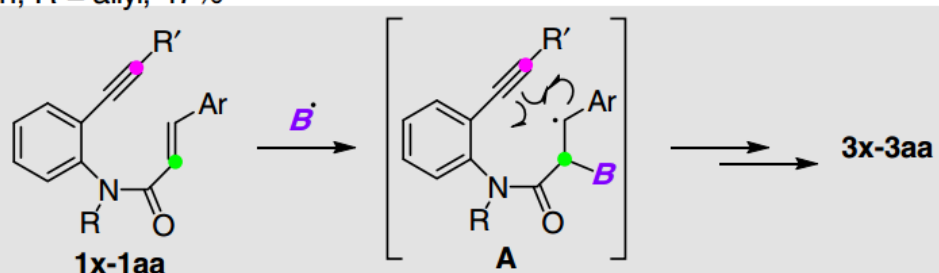
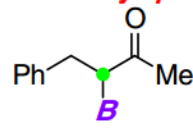
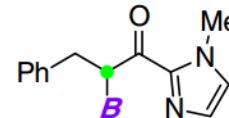
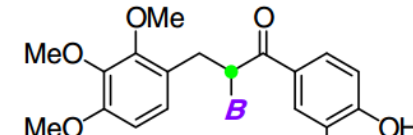
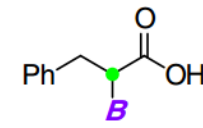
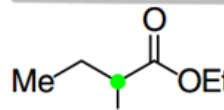
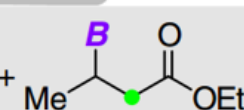
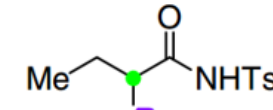
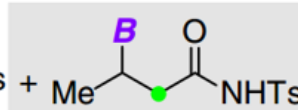
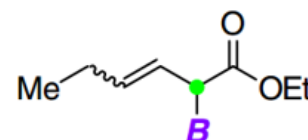
**$\alpha$  位位阻变大, B 自由基加到  $\alpha$  位变困难**

**$\alpha$ -boryl- $\beta$ -arylamides**

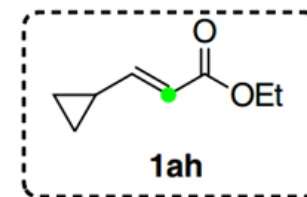
3q : 86%

3r : 79%<sup>b,d</sup>3s : 88%<sup>b</sup>3t : 96% (dr = 1.7:1)<sup>t</sup>**— hydroboration vs. borylation/cyclization —**

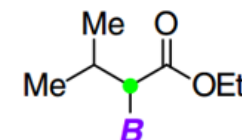
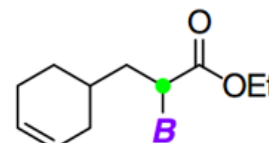
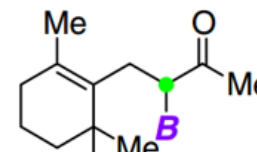
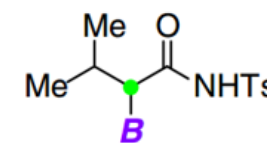
3u : 29%

3u' : 42%<sup>c</sup>3v : 15%  
(Ar = 4-OMeC<sub>6</sub>H<sub>4</sub>)3v' : 34% (dr = 2.8:1)  
2,3-trans**— borylation/cyclization —**3w : Ar = Ph, R = Me, 70%<sup>e</sup>3x : Ar = Ph, R = allyl, 47%<sup>e</sup>3y : 55%<sup>e</sup>3z : 62%<sup>e</sup>3aa : 58%<sup>c,e</sup> **$\alpha$ -boryl- $\beta$ -aryl ketones and acids**3ab : 94%<sup>b</sup>3ac : 86%<sup>b</sup>3ad : 91%<sup>b</sup>3ae : 70%<sup>b</sup>**—  $\alpha$ -vs.  $\beta$ -borylation —**3af- $\alpha$  : 41%3af- $\alpha$  : 22%<sup>b</sup>3af- $\beta$  : 26%3af- $\beta$  : 45%<sup>b</sup>3ag- $\alpha$  : 49%3ag- $\beta$  : < 5%**—  $\alpha$ -borylation only —**

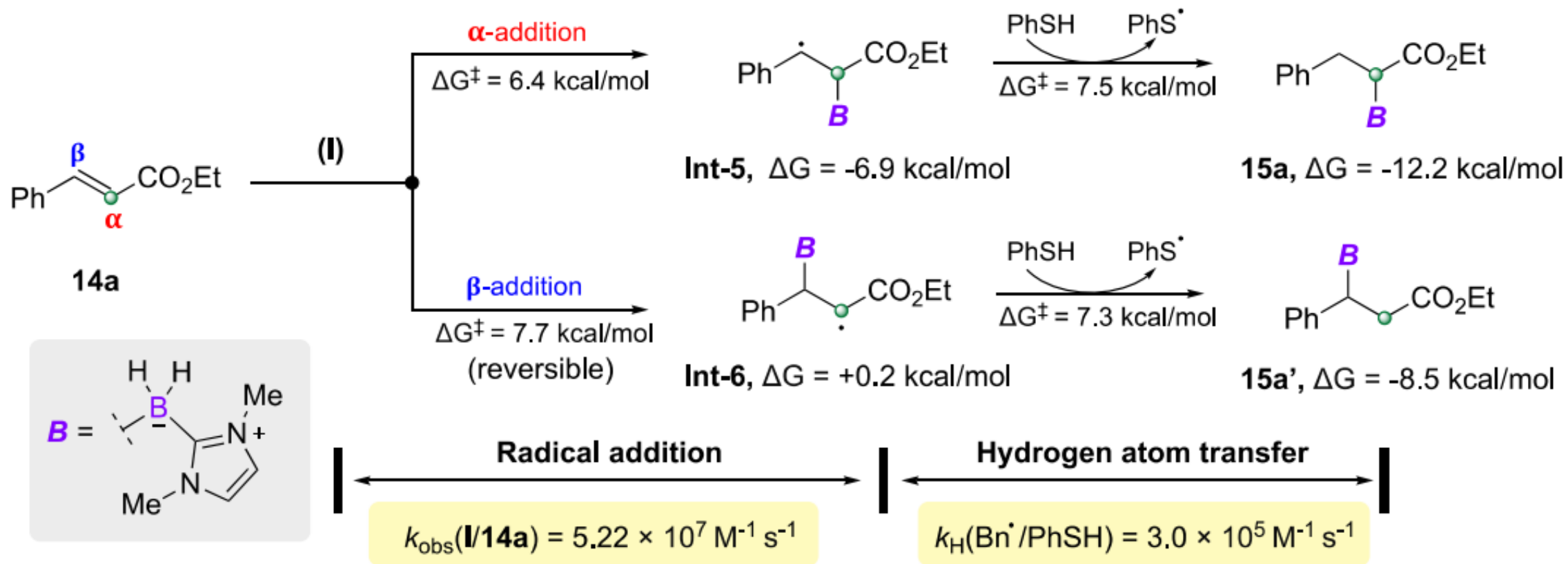
3ah : 64% (E:Z = 2:1)



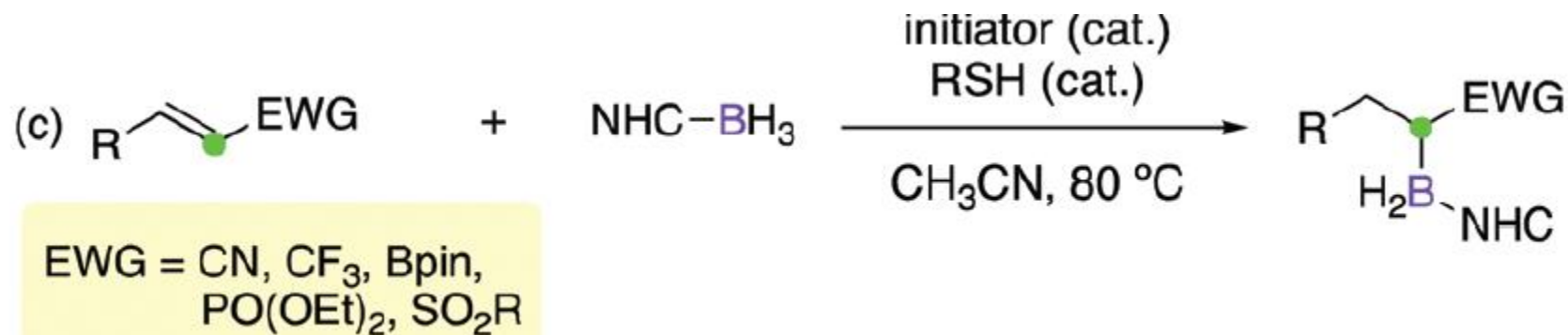
1ah

3ai : 56% (43%<sup>b</sup>)3aj : 39% (dr = 1:1)<sup>b</sup>3ak : 70%<sup>b</sup>

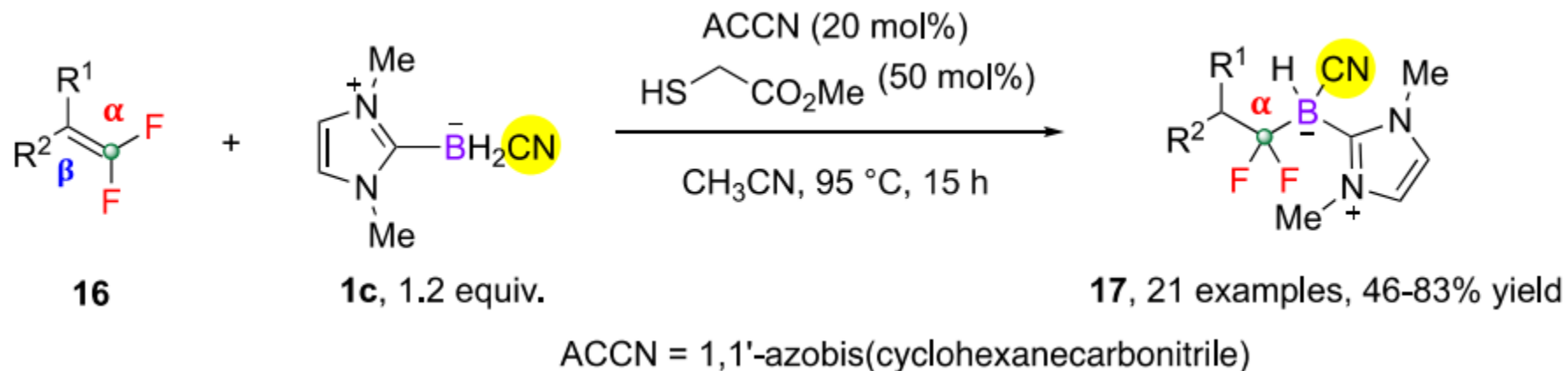
3al : 47%



$\alpha$  加成和  $\beta$  加成的能垒差别不大，但  $\alpha$  加成后形成的自由基中间体更稳定；  
同时加成步骤快于 HAT，使  $\beta$  加成可以可逆返回，最终积累热力学更稳定的  $\alpha$ -硼化产物。



*Chem. Commun.* **2019**, *55*, 11904.



*Org. Lett.* **2019**, *21*, 8414.

**Radical Borylation Reactions****New Radical Borylation Pathways for Organoboron Synthesis Enabled by Photoredox Catalysis**

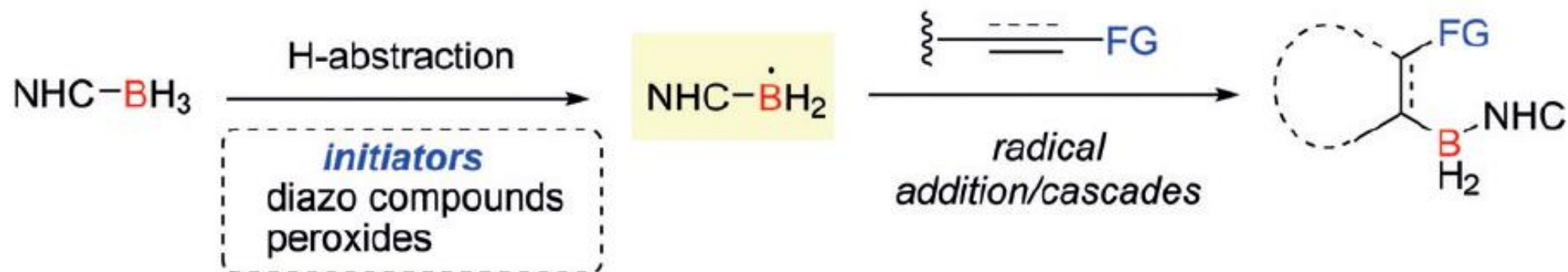
*Jing Qi, Feng-Lian Zhang, Ji-Kang Jin, Qiang Zhao, Bin Li, Lin-Xuan Liu, and Yi-Feng Wang\**

How to cite: *Angew. Chem. Int. Ed.* **2020**, 59, 12876–12884

International Edition: [doi.org/10.1002/anie.201915619](https://doi.org/10.1002/anie.201915619)

German Edition: [doi.org/10.1002/ange.201915619](https://doi.org/10.1002/ange.201915619)

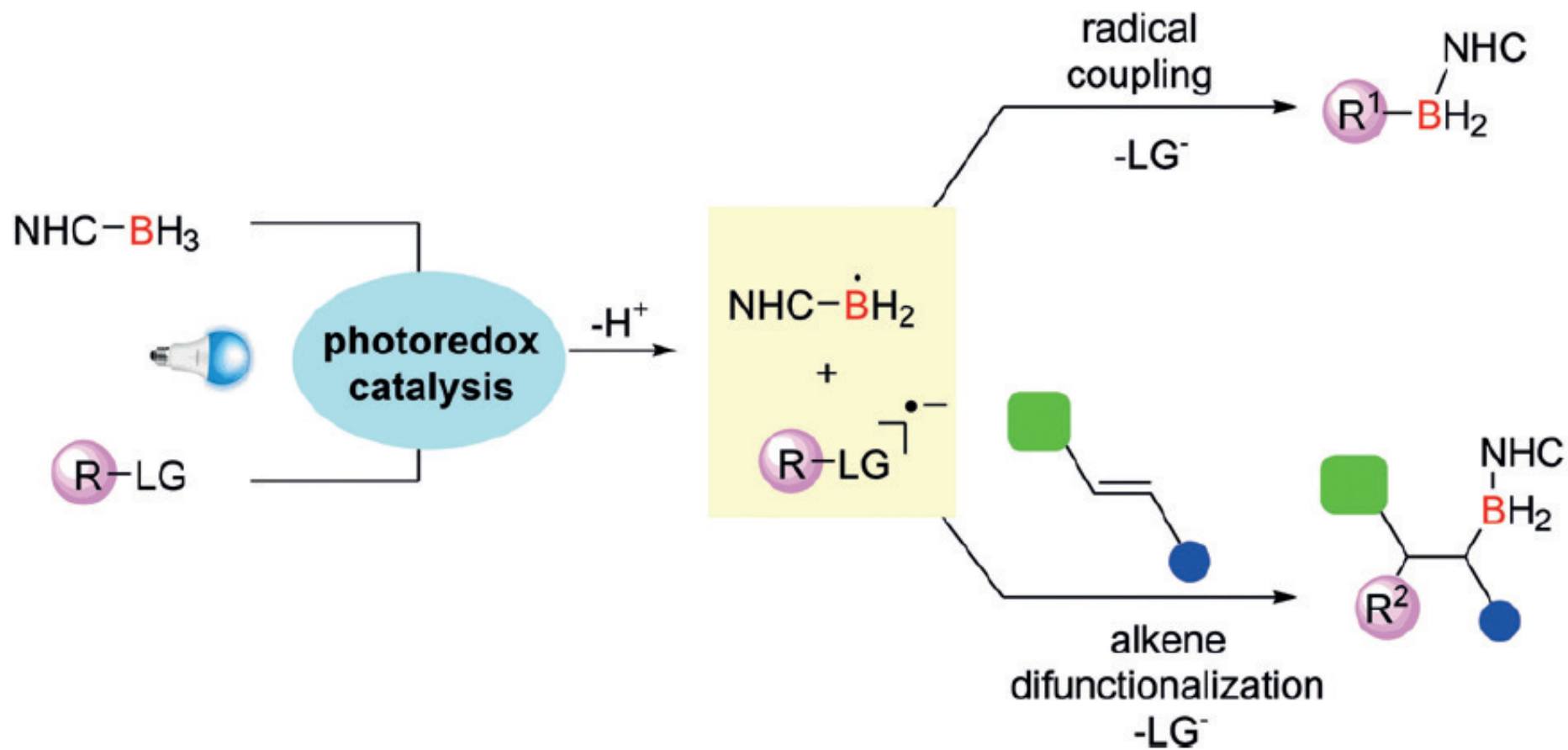
a. Reported initiation methods and reactions of NHC-boryl radicals for the construction of organoboron molecules



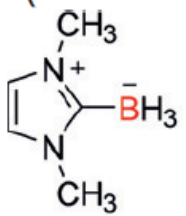
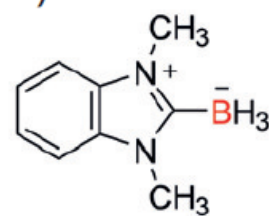

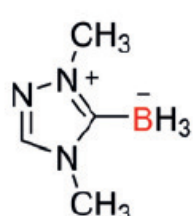

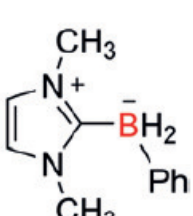
**Limitations:**

- 1) specific alkenes/alkynes for radical borylation
- 2) high temperature (50-120 °C) for initiation
- 3) limited numbers of initiation methods and reaction modes

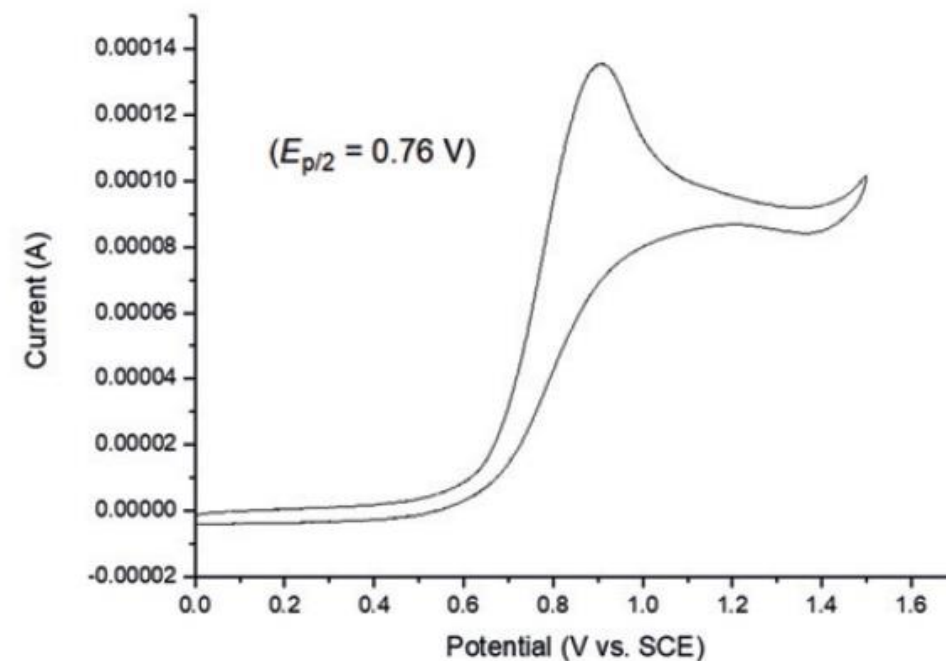
b. New reaction modes of NHC-boryl radicals to synthesize organoborons based on photoredox catalysis (This work)



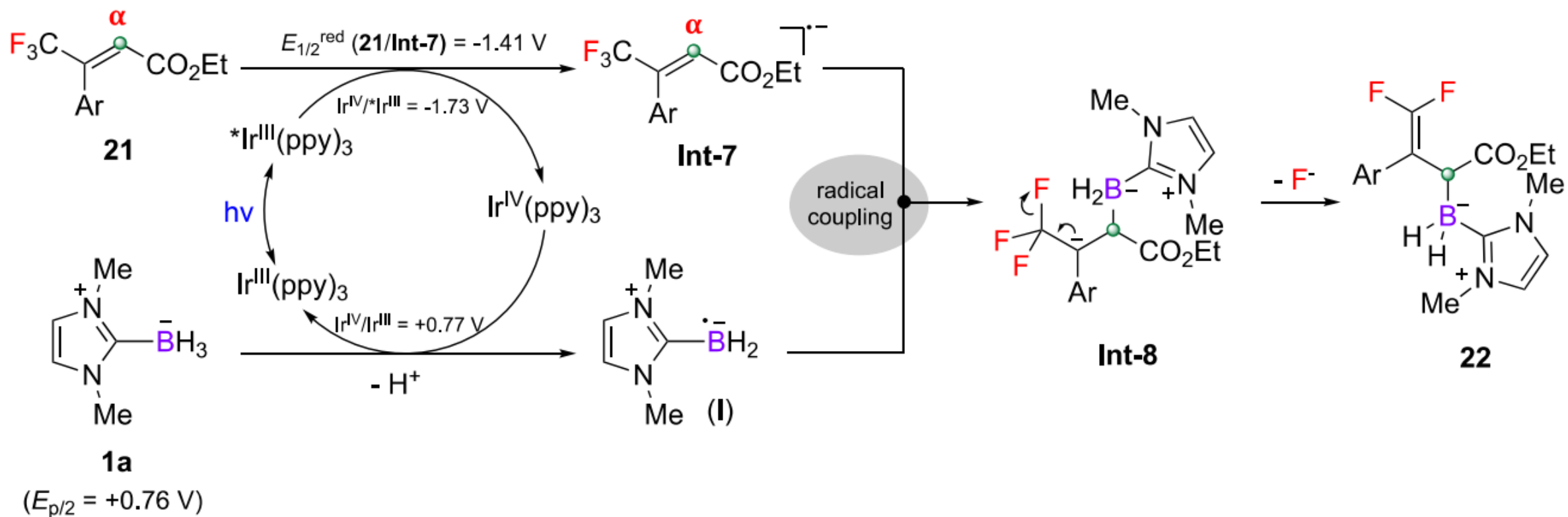
**Table 1:** Oxidation potentials of NHC-BH<sub>3</sub> **1**.

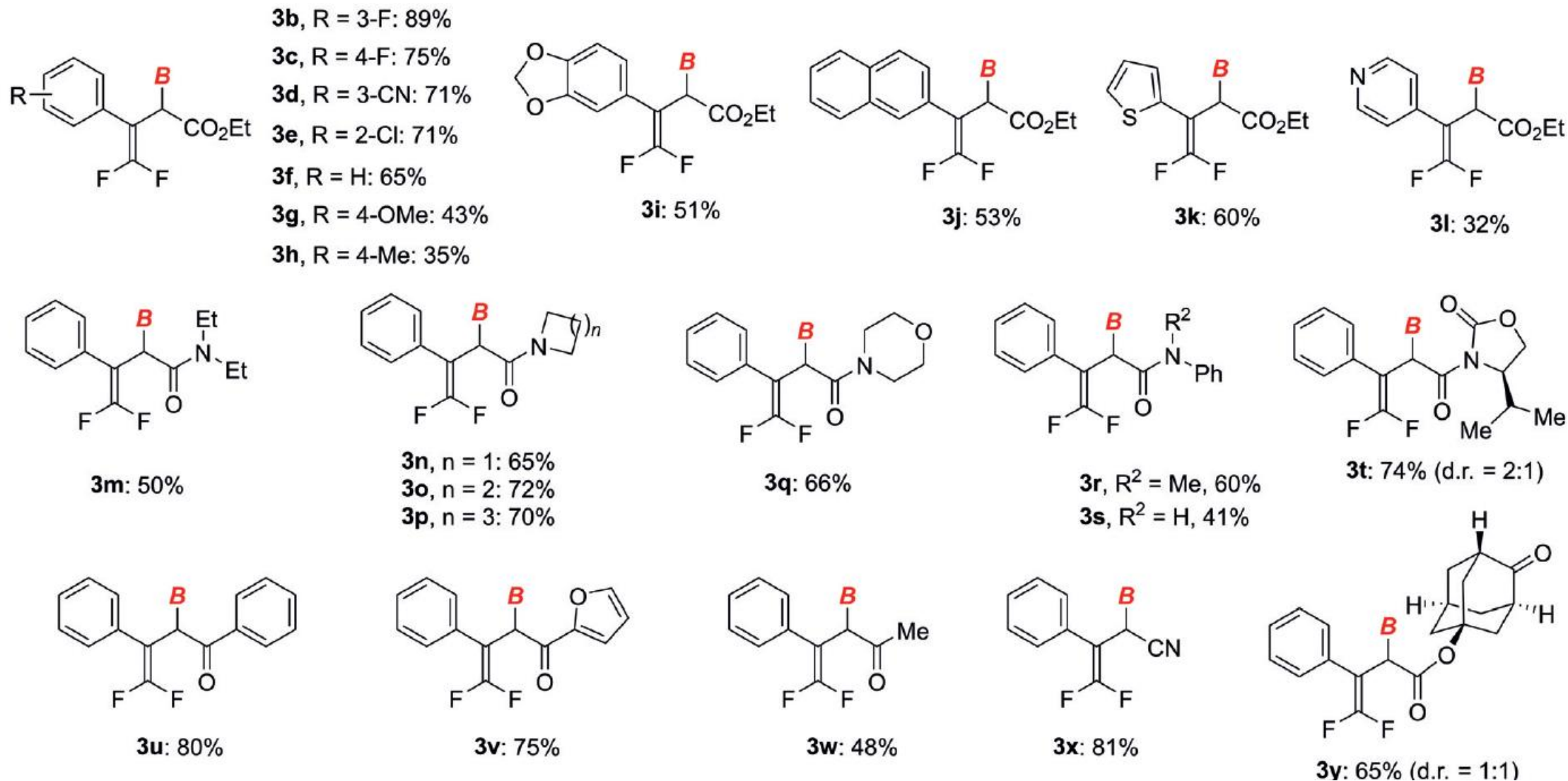
NHC-BH <sub>3</sub> ( <b>1</b> )	<b>1a</b>	<b>1b</b>	<b>1c</b>	<b>1d</b>	<b>1e</b>	<b>1f</b>
$E_{p/2}$ (V vs. SCE)	0.76	0.77	0.78	0.85	0.82	0.78
 <b>1a</b>	 <b>1b</b>	 <b>1c</b>	 <b>1d</b>	 <b>1e</b>	 <b>1f</b>	

(a) Redox potential studies of **1a**<sup>[a]</sup>

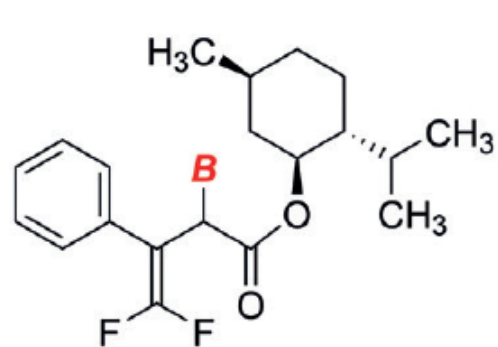


单电子氧化 → 脱质子 → 硼自由基生成

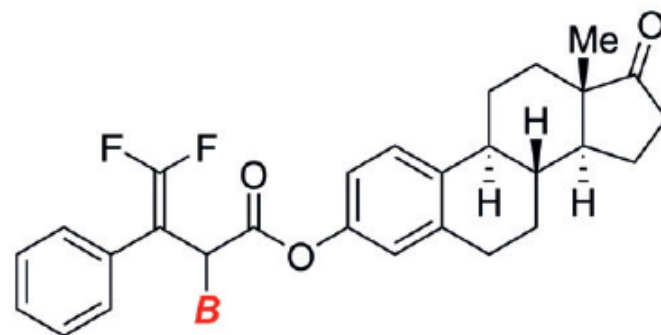




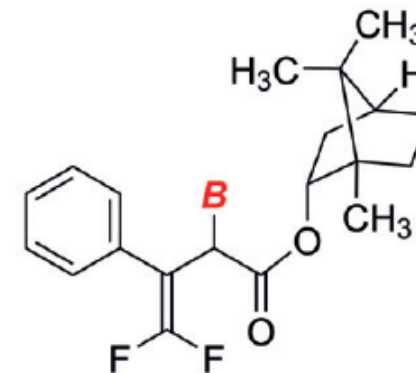
# 02 C-B 键构建



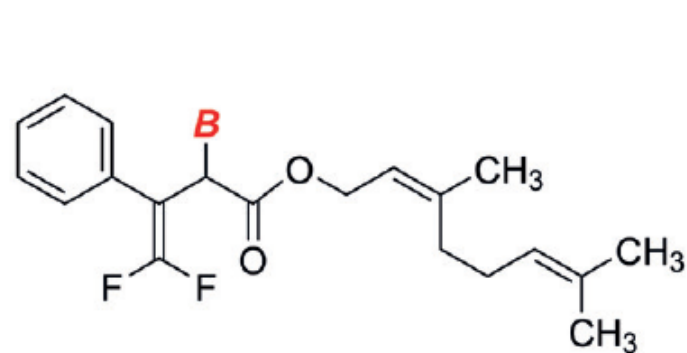
**3z**: 87% (d.r. = 1.3:1)



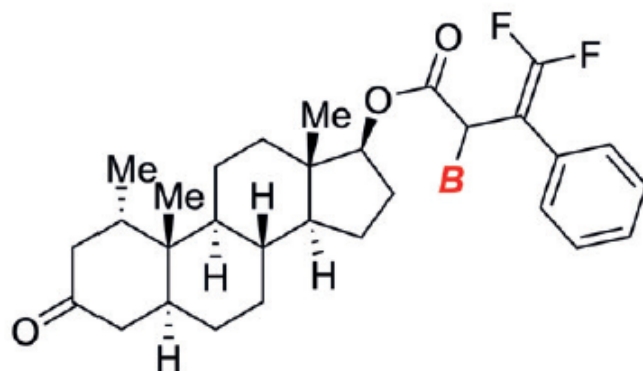
**3aa**: 64% (d.r. = 1:1)



**3ab**: 84% (d.r. = 1.2:1)

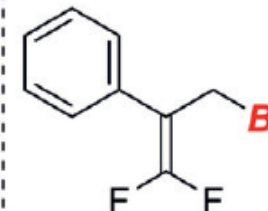


**3ac**: 74%

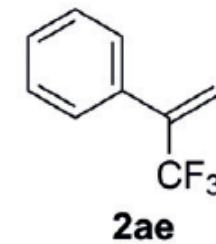


**3ad**: 70% (d.r. = 1.2:1)

An unsuccessful result

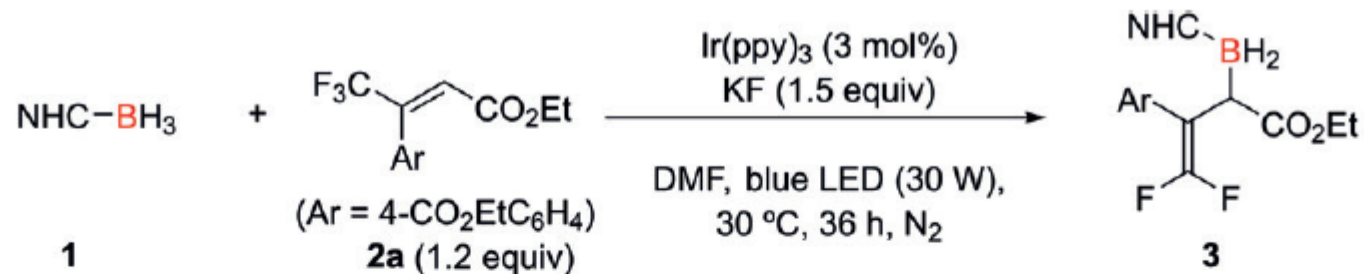


**3ae**: ND



**2ae**

( $E_{p/2}^{red} = -2.2$  V vs. SCE)

NHC-BH<sub>3</sub> 1

1b

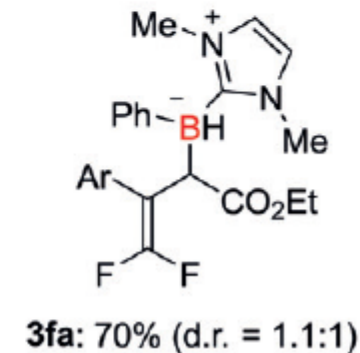
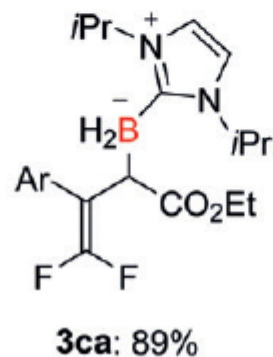
1c

1d

1e

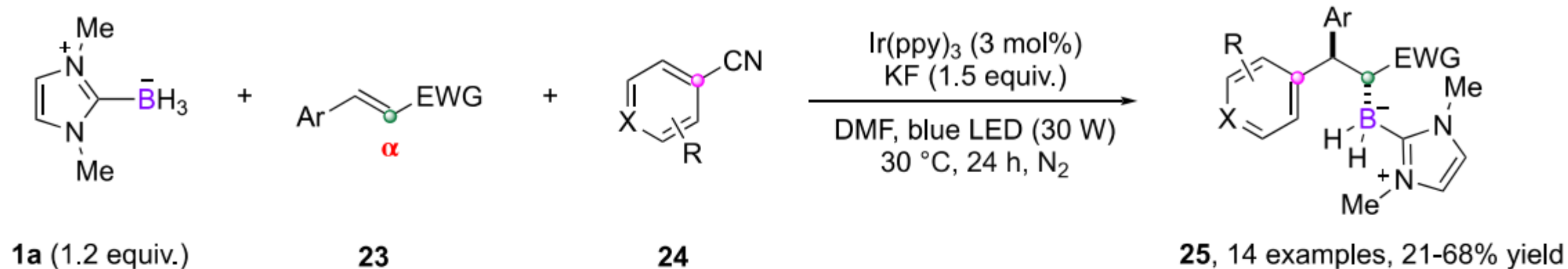
1f

products 3

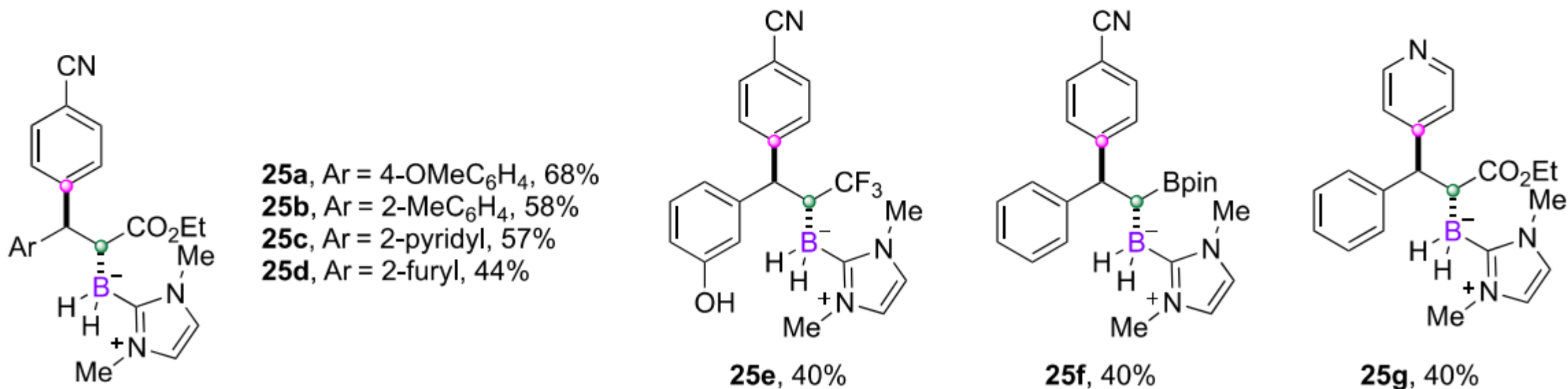


不同 NHC-BH<sub>3</sub> 均可参与反应, 证明 SET 生成 LBR 具有一定普适性。

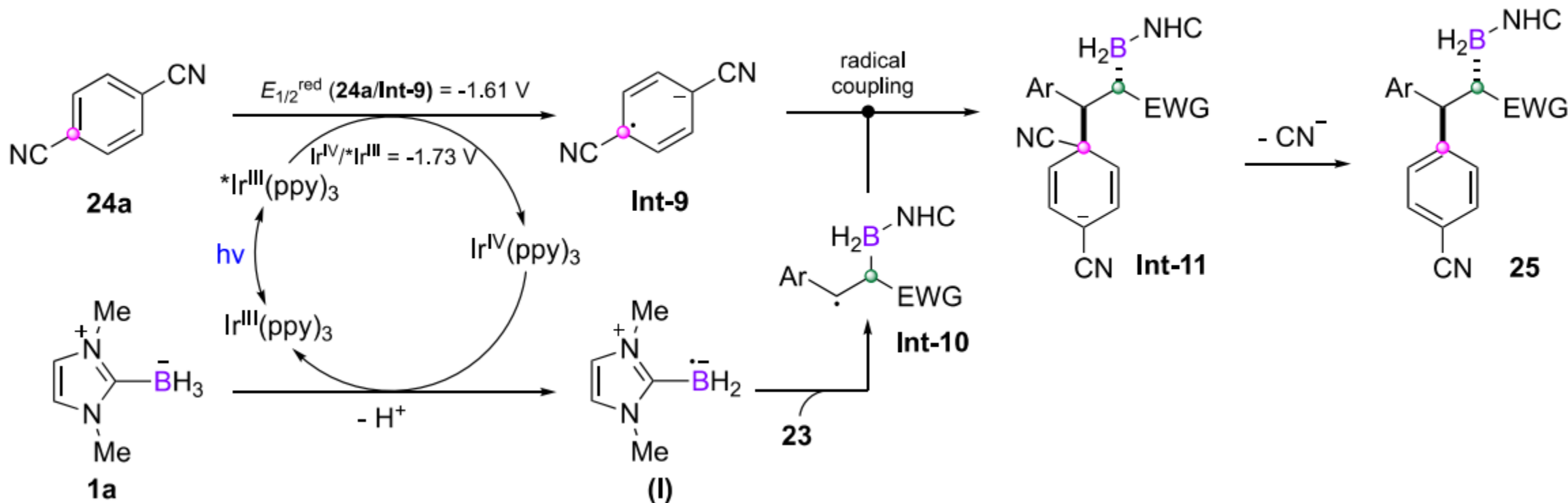
# 02 C-B 键构建



## (a) Representative products for radical arylboration

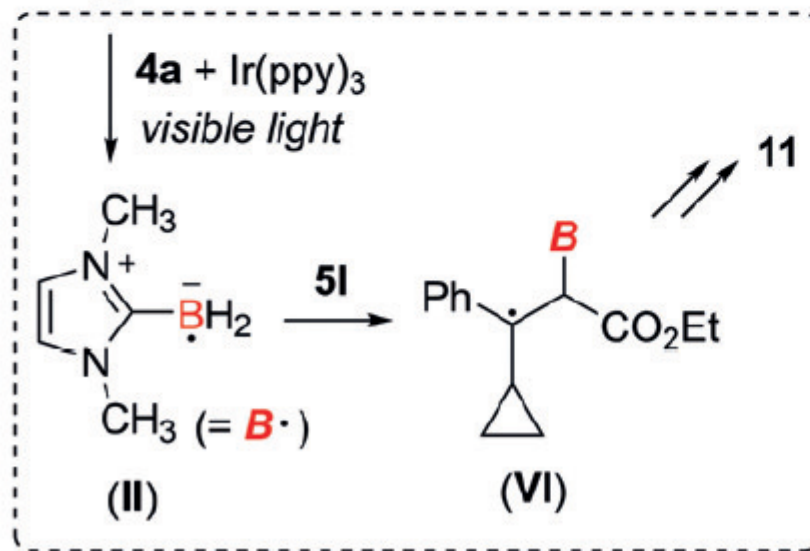
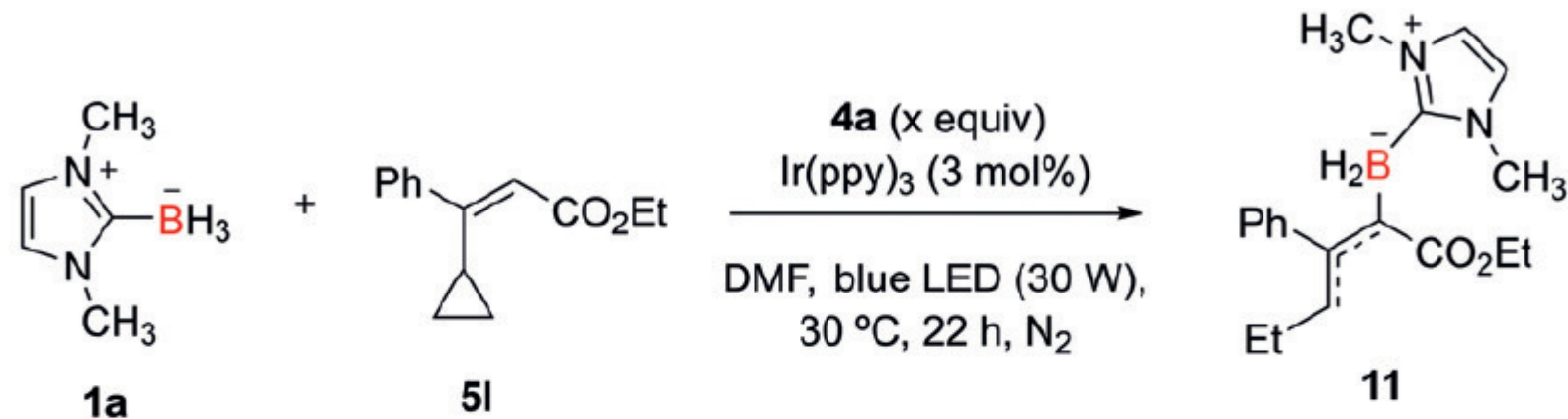


## (b) A proposed reaction mechanism



氰基芳烃生成自由基阴离子 → NHC-BH<sub>3</sub> 生成硼自由基 → 硼自由基加成烯烃  
 → 与芳烃自由基阴离子偶联 → 脱 CN<sup>-</sup> 得产物。

(c) A radical clock experiment verifying the oxidative generation of NHC-boryl radical





<b>4a</b> (x equiv)	<b>11</b> (yield)
—	not formed ( <b>1a</b> : 95%, <b>5I</b> : 98%)
0.2	39%

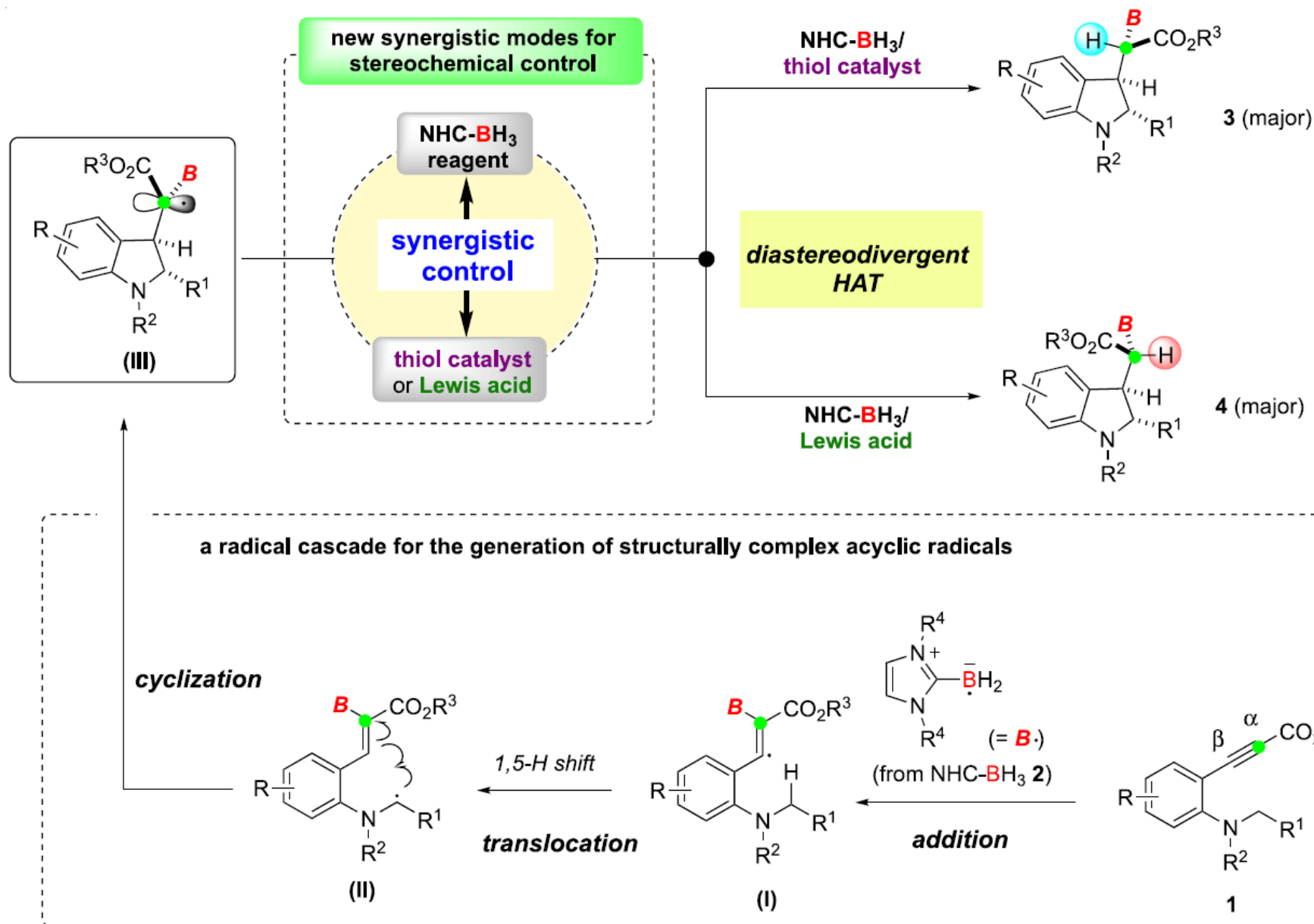
ARTICLE

<https://doi.org/10.1038/s41467-022-28071-8>

OPEN

# Stereoselective hydrogen atom transfer to acyclic radicals: a switch enabling diastereodivergent borylative radical cascades

Tian Ye<sup>1,4</sup>, Feng-Lian Zhang<sup>1,4</sup>, Hui-Min Xia<sup>1</sup>, Xi Zhou<sup>1</sup>, Zhi-Xiang Yu <sup>2</sup>✉ & Yi-Feng Wang <sup>1,3</sup>✉



关键：调控 HAT 面选择性，  
实现非对映发散合成。

硫醇弱相互作用 → 3

ZnI<sub>2</sub> 配位调控 → 4

01

研究背景

02

C-B 键构建

03

C-X键活化

04

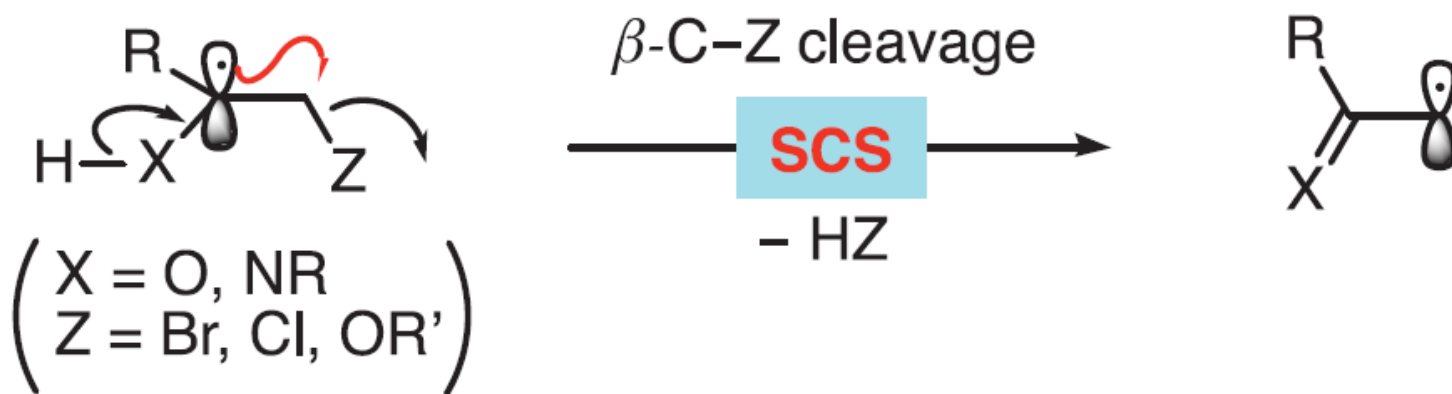
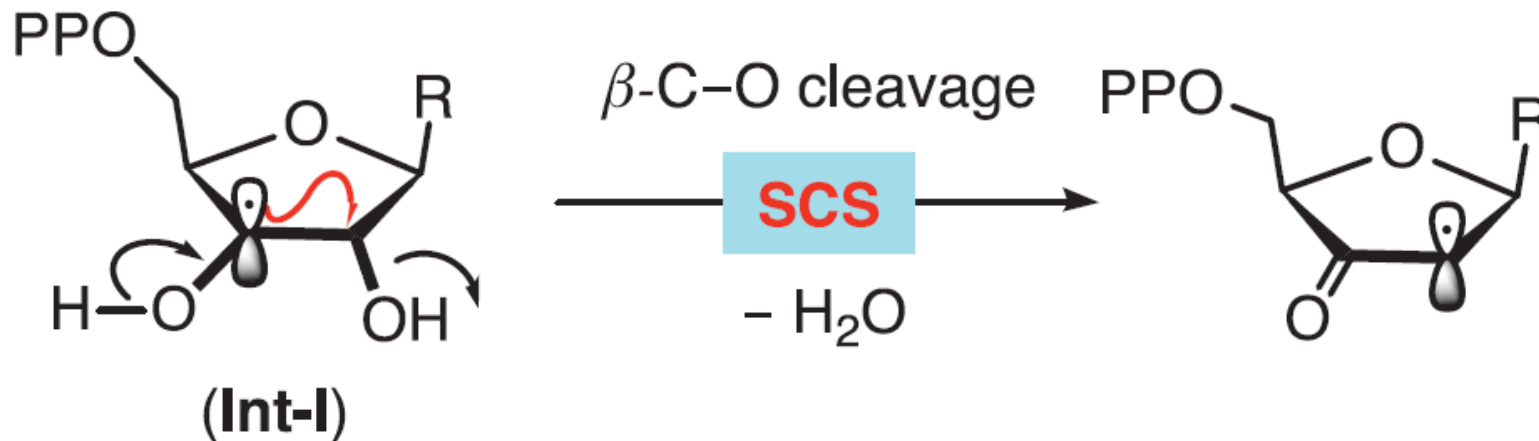
不对称催化

## ORGANIC CHEMISTRY

# Sequential C-F bond functionalizations of trifluoroacetamides and acetates via spin-center shifts

You-Jie Yu<sup>1\*</sup>, Feng-Lian Zhang<sup>1\*</sup>, Tian-Yu Peng<sup>1</sup>, Chang-Ling Wang<sup>1</sup>, Jie Cheng<sup>1</sup>, Chen Chen<sup>1</sup>, Kendall N. Houk<sup>2†</sup>, Yi-Feng Wang<sup>1,3,4†</sup>

## Spin-Center Shift



自由基中心转移

过程:

自由基形成

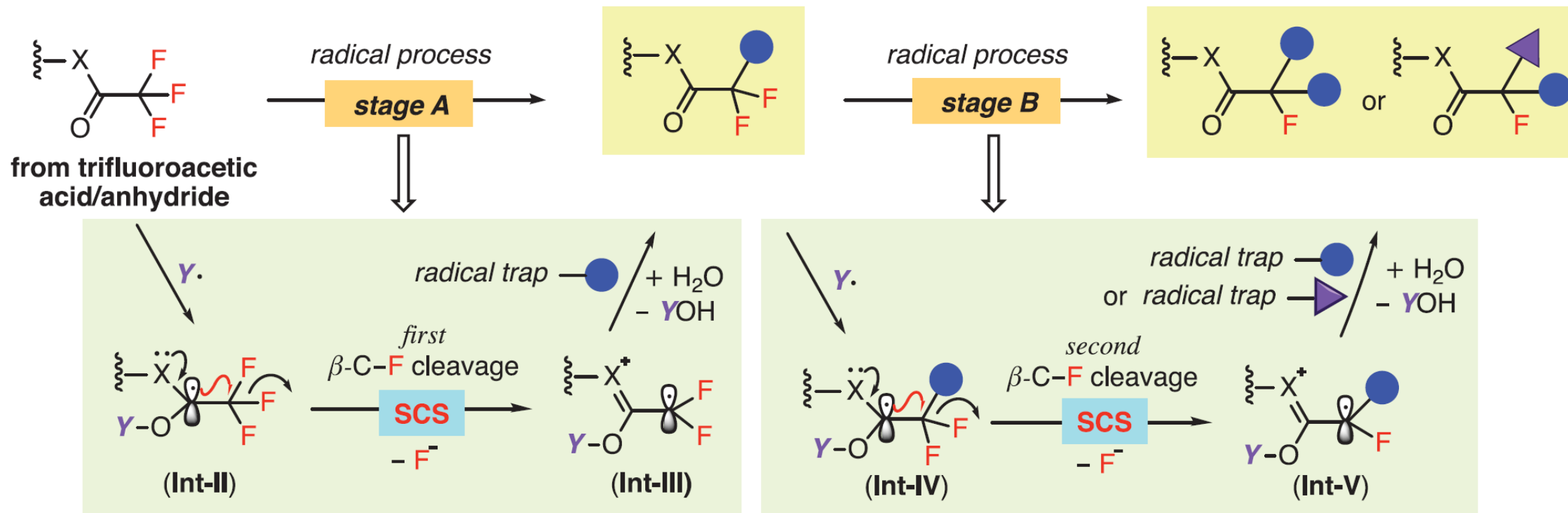
→ 电子重排

→  $\beta\text{-C-X}$  键断裂

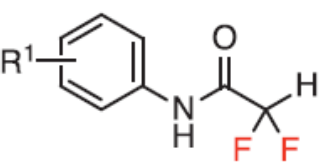
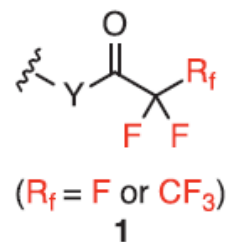
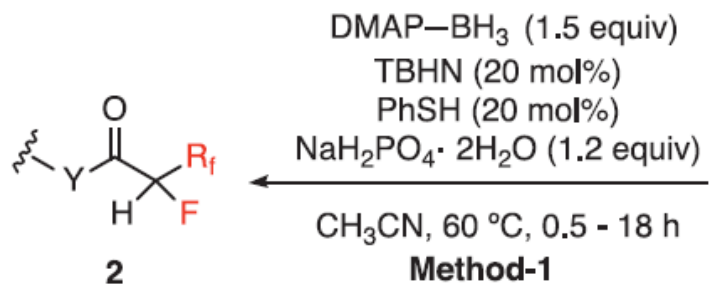
→ 自由基转移到新位置

结果:

实现 C-X 等键活化



先形成自由基中间体  $\rightarrow$  自由基中心转移  $\rightarrow$  C-X 键断裂  $\rightarrow$  生成新的自由基。



**2a** R<sup>1</sup> = H, 82%  
(gram-scale, 68%)

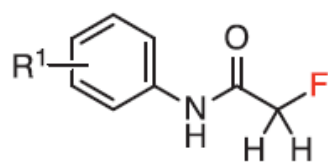
**2b** R<sup>1</sup> = 4-*i*-Pr, 74%

**2c** R<sup>1</sup> = 4-OMe, 77%

**2d** R<sup>1</sup> = 4-CF<sub>3</sub>, 58%\*

**2e** R<sup>1</sup> = 3-F, 62%\*

**2f** R<sup>1</sup> = 2-Cl, 64%\*



**3a** R<sup>1</sup> = H, 85%  
(gram-scale, 76%)

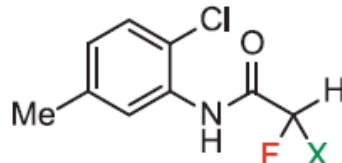
**3b** R<sup>1</sup> = 4-*i*-Pr, 94%

**3c** R<sup>1</sup> = 4-OMe, 85%

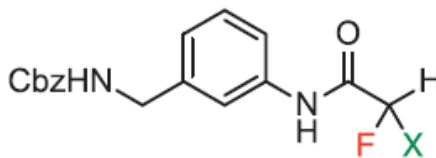
**3d** R<sup>1</sup> = 4-CF<sub>3</sub>, 73%†

**3e** R<sup>1</sup> = 3-F, 88%†

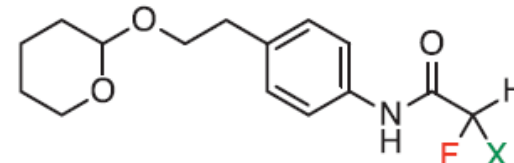
**3f** R<sup>1</sup> = 2-Cl, 71%†



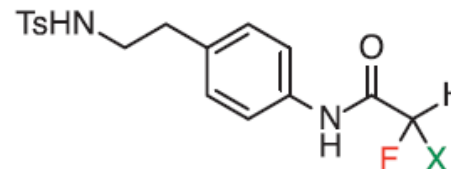
**2g**, X = F, 65%\*  
**3g**, X = H, 72%†



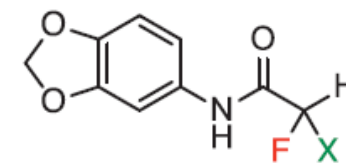
**2j**, X = F, 70%  
**3j**, X = H, 90%



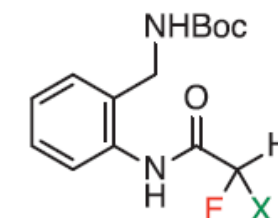
**2h**, X = F, 75%  
**3h**, X = H, 92%



**2k**, X = F, 84%  
**3k**, X = H, 92%

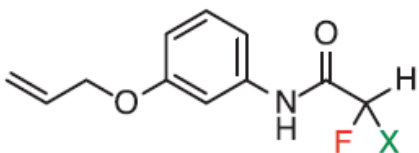


**2i**, X = F, 76%  
**3i**, X = H, 84%

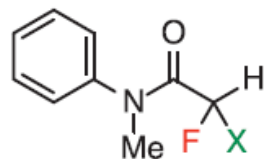


**2l**, X = F, 65%  
**3l**, X = H, 80%

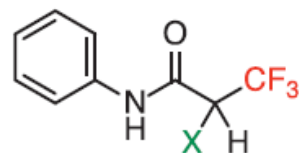
# 03 C-X 键活化



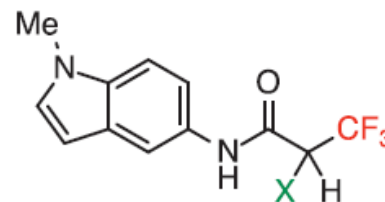
**2m**, X = F, 34%  
**3m**, X = H, 50%



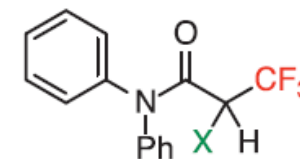
**2n**, X = F, 41%<sup>†</sup>  
**3n**, X = H, 51%



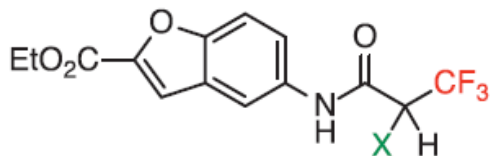
**2o**, X = F, 92%\*  
**3o**, X = H, 94%



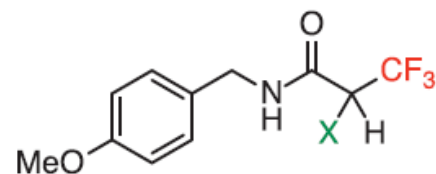
**2p**, X = F, 84%  
**3p**, X = H, 55%



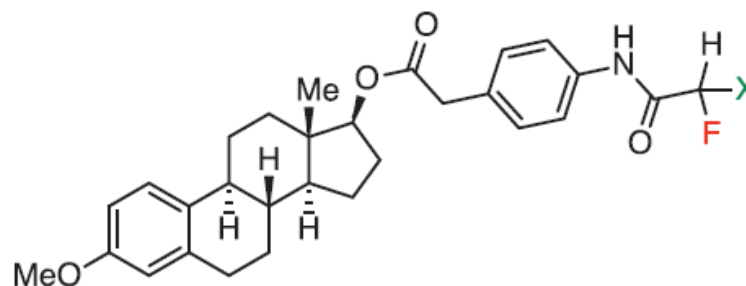
**2q**, X = F, 63%  
**3q**, X = H, 89%



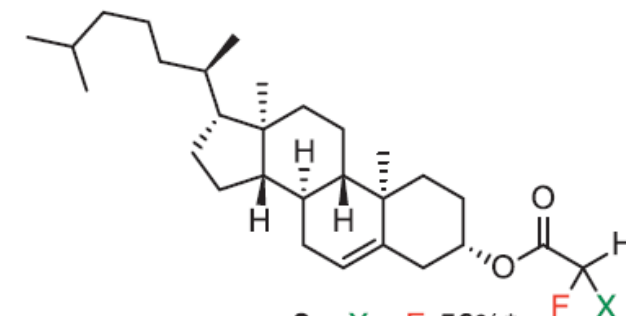
**2r**, X = F, 73%  
**3r**, X = H, 70%



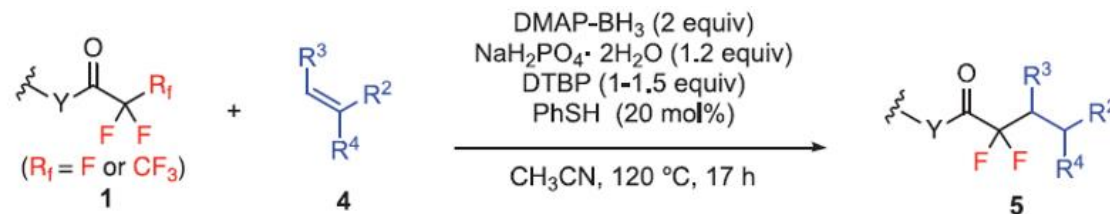
**2s**, X = F, 44%  
**3s**, X = H, trace (2s, 50%)



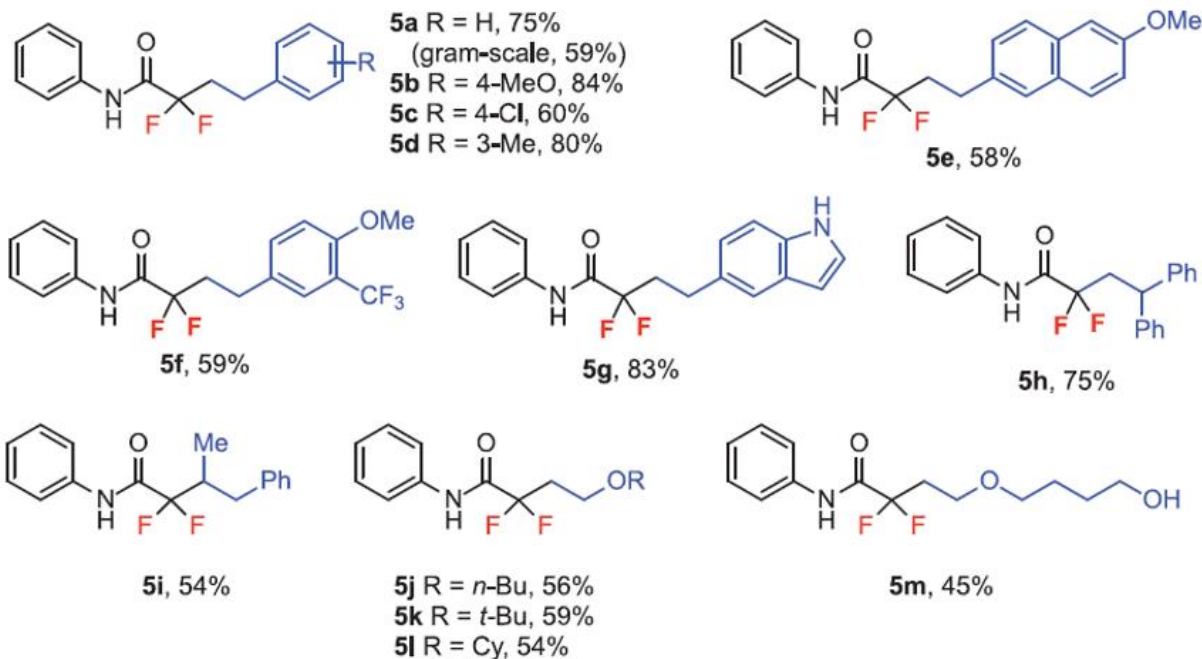
**2t**, X = F, 65%  
**3t**, X = H, 76%



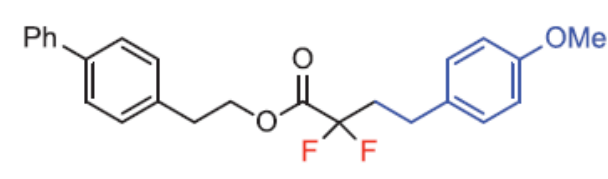
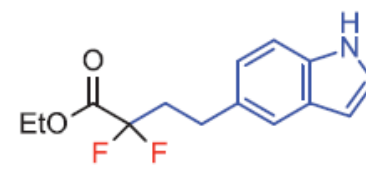
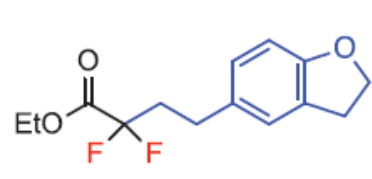
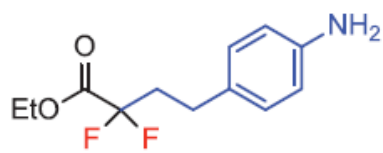
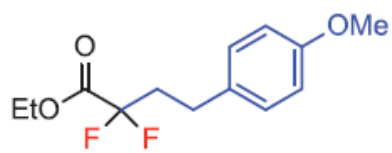
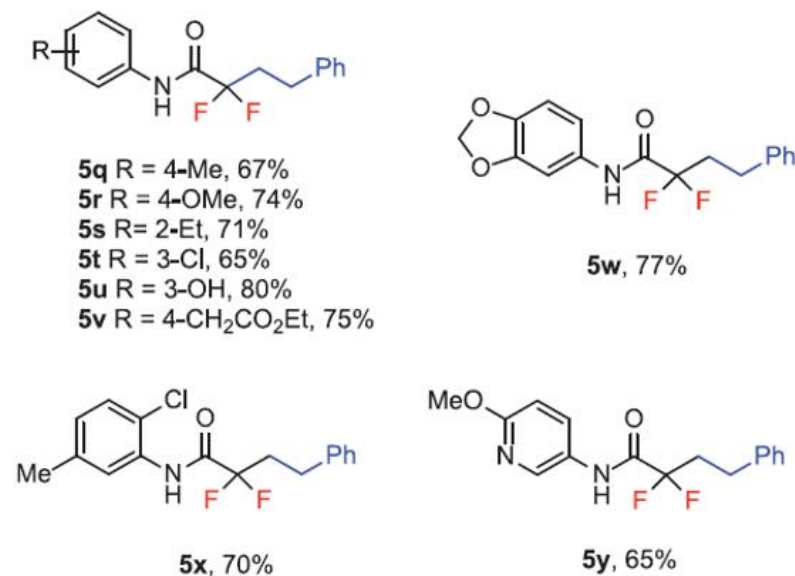
**2u**, X = F, 56%\*  
**3u**, X = H, trace



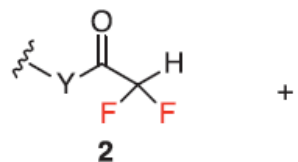
A



B



A



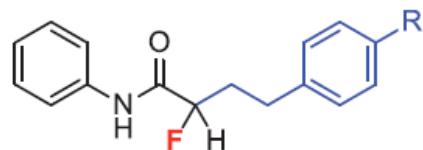
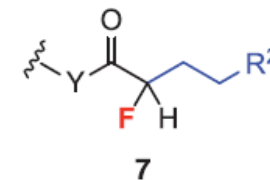
hydrodefluorination products  
from *stage A*



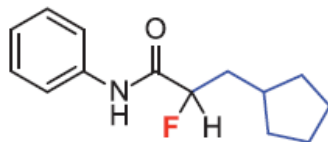
DMAP-BH<sub>3</sub> (3-4 equiv)  
NaH<sub>2</sub>PO<sub>4</sub> · 2H<sub>2</sub>O (3-4 equiv)  
DTBP (1.5 equiv)  
PhSH (20 mol%)

CH<sub>3</sub>CN, 120 °C, 12 h

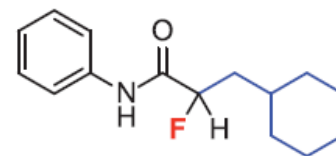
*stage B*



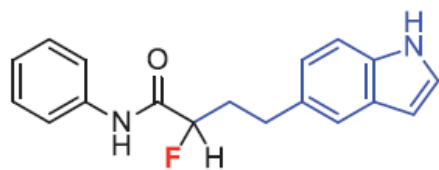
7a R = H, 70%  
(gram-scale, 77%)  
7b R = NH<sub>2</sub>, 79%  
7c R = OMe, 83%



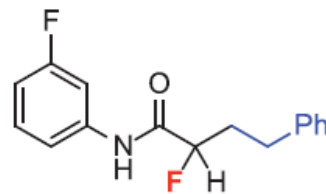
7d, 64%



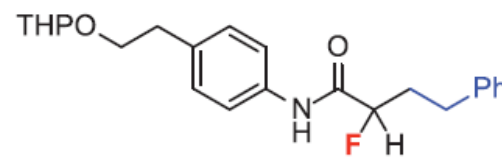
7e, 61%



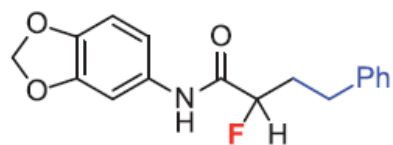
7f, 82%



7g, 68%



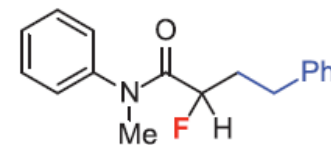
7h, 61%



7i, 53%

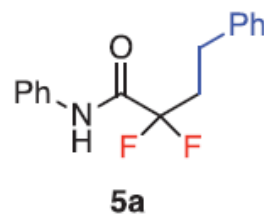


7j, 63%

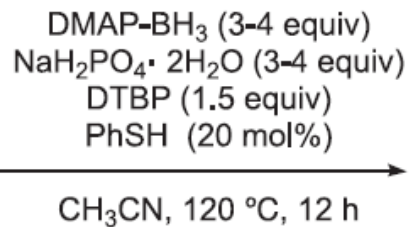


7k, 39%

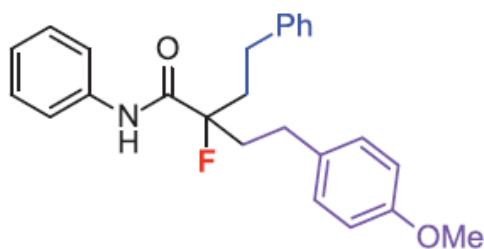
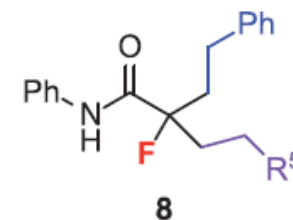
B



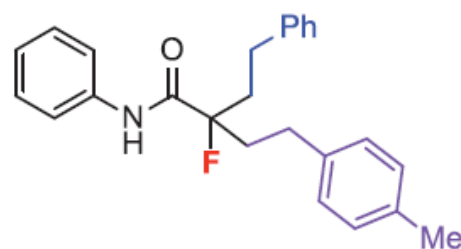
a coupling product  
from *stage A*



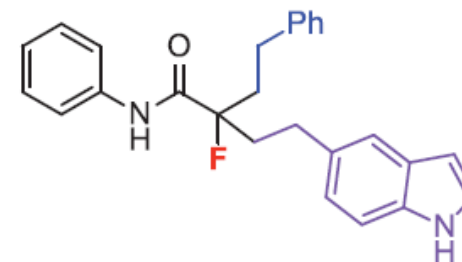
*stage B*



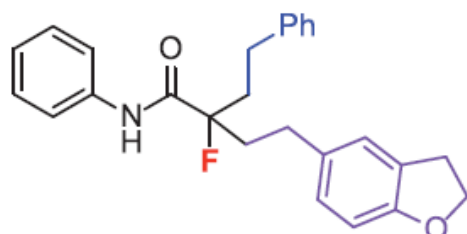
**8a**, 60% (**5a**, 38% recovery)



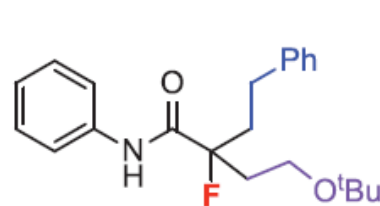
**8b**, 62% (**5a**, 35% recovery)



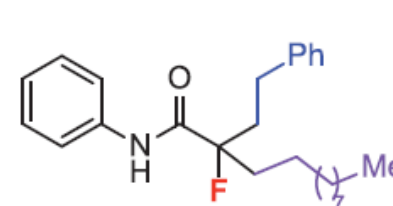
**8c**, 55% (**5a**, 42% recovery)



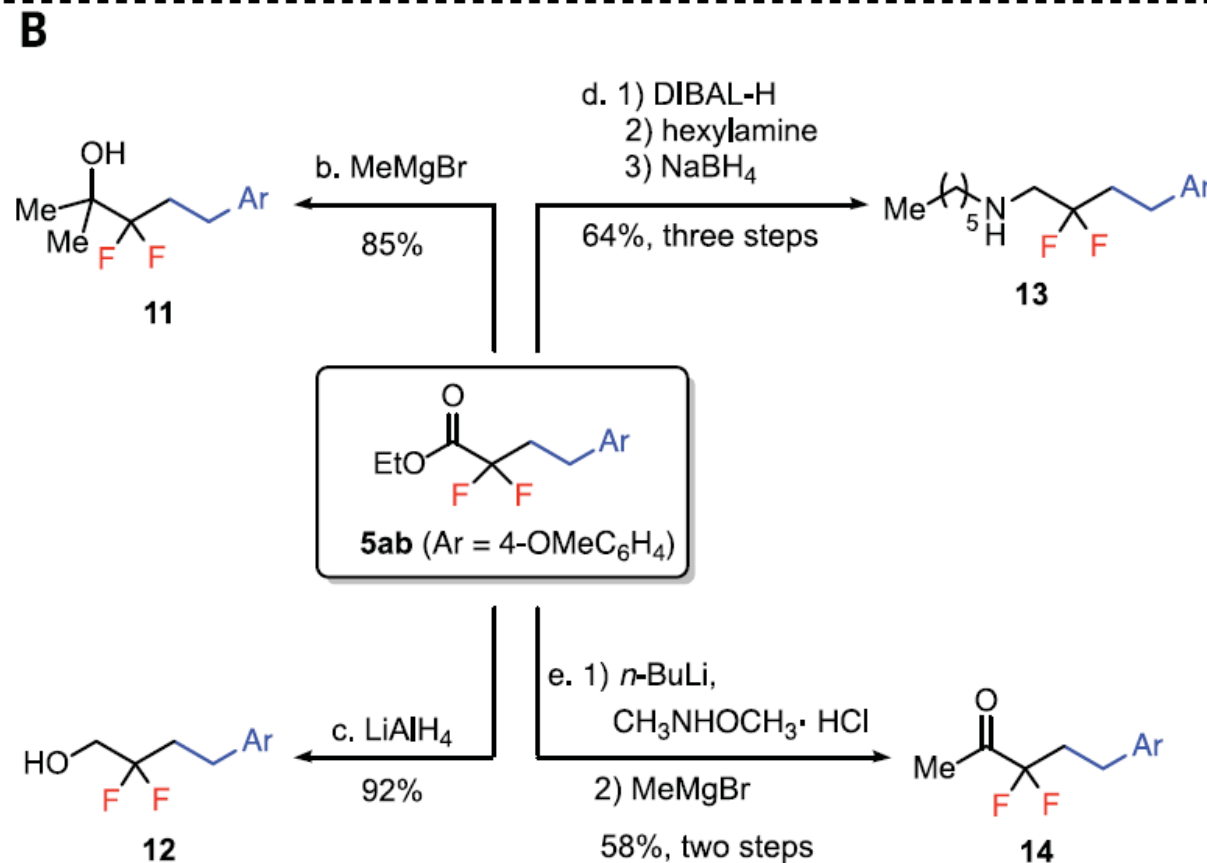
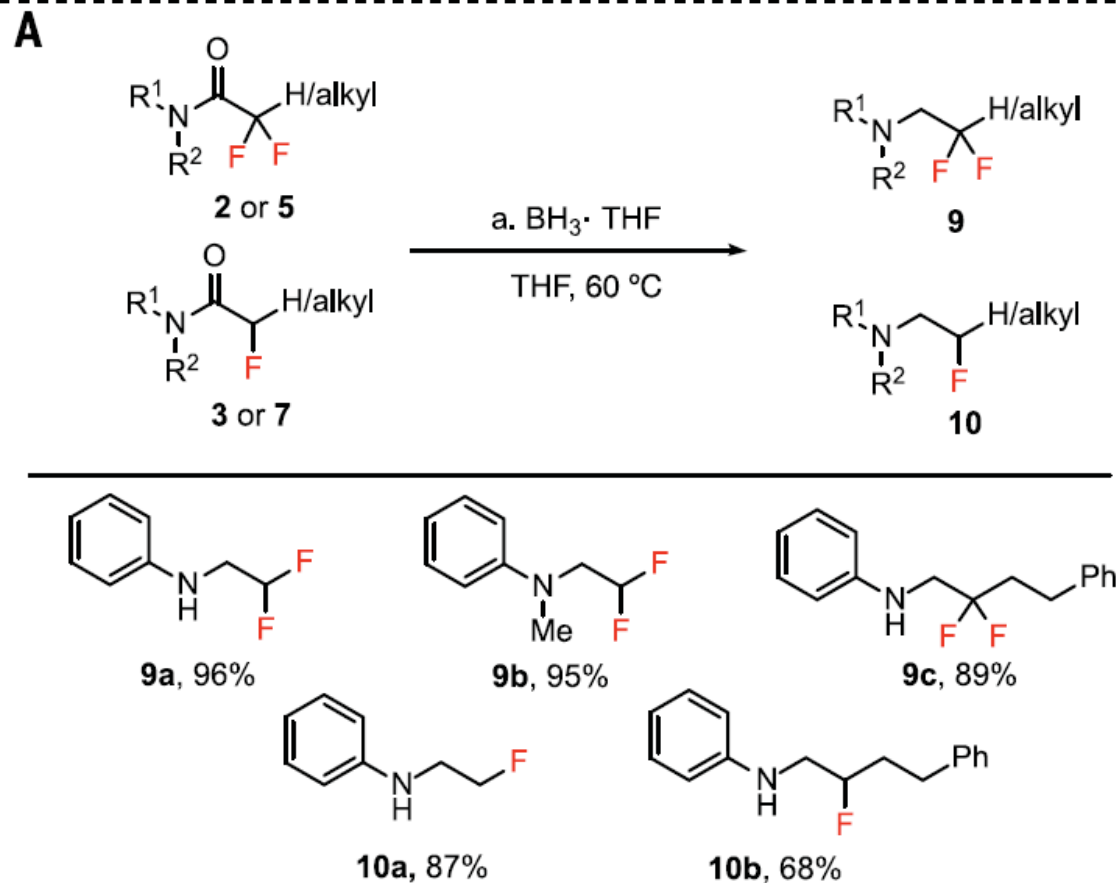
**8d**, 42% (**5a**, 50% recovery)



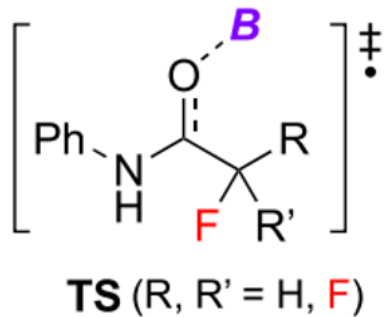
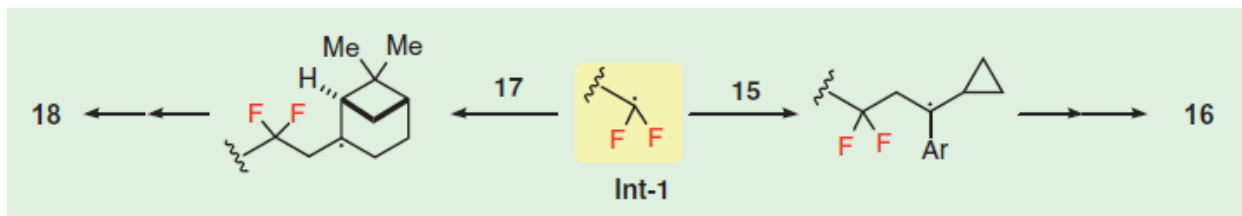
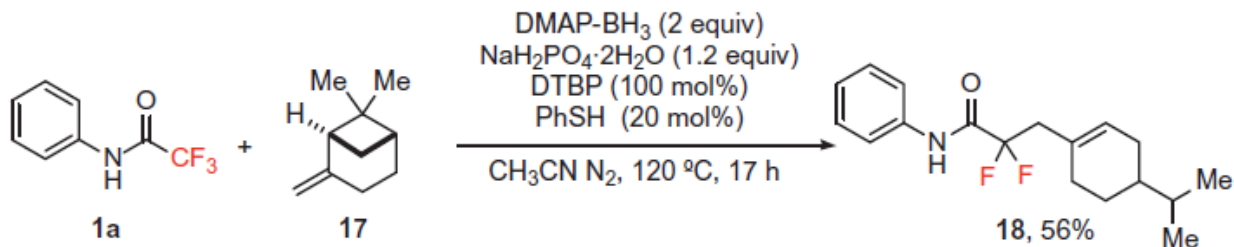
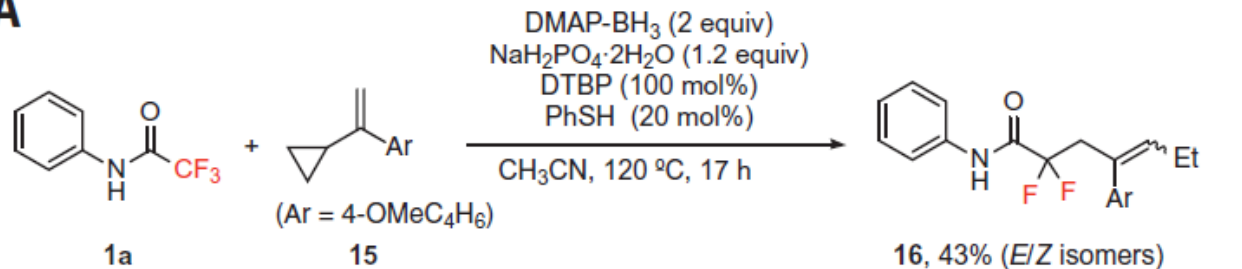
**8e**, 46% (**5a**: 30% recovery)



**8f**, 30% (**5a**: 25% recovery)

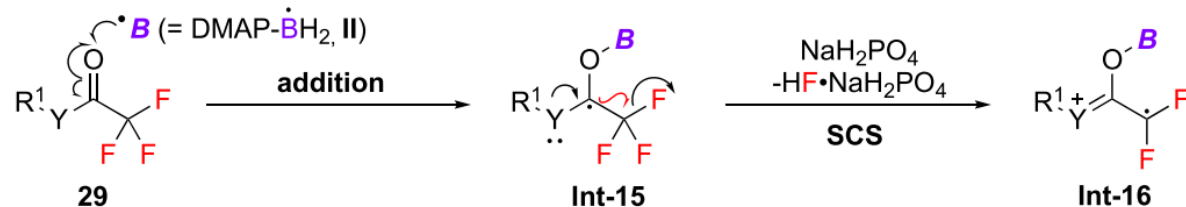


A

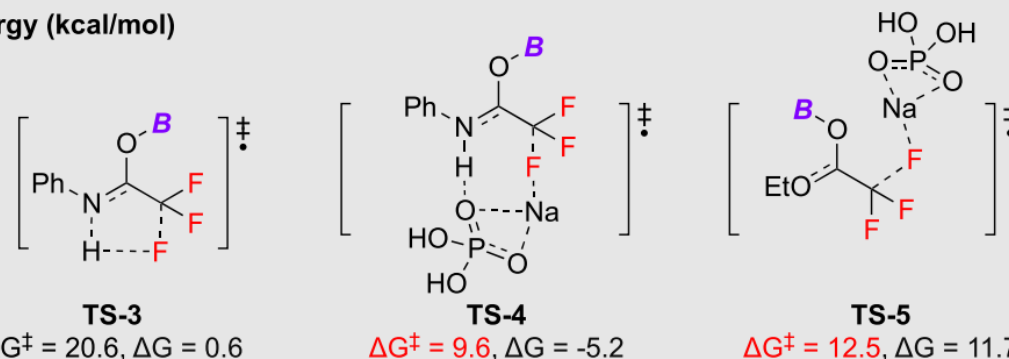


TS	$\Delta G^\ddagger$
TS-6 (29a, CF <sub>3</sub> )	7.9 kcal/mol
TS-7 (30a, CF <sub>2</sub> H)	9.2 kcal/mol
TS-8 (31a, CFH <sub>2</sub> )	11.1 kcal/mol

Mechanistic insights into SCS defluorination

The effect of NaH<sub>2</sub>PO<sub>4</sub> in SCS defluorination

Energy (kcal/mol)

 $\Delta G^\ddagger = 20.6, \Delta G = 0.6$  $\Delta G^\ddagger = 9.6, \Delta G = -5.2$  $\Delta G^\ddagger = 12.5, \Delta G = 11.7$ 

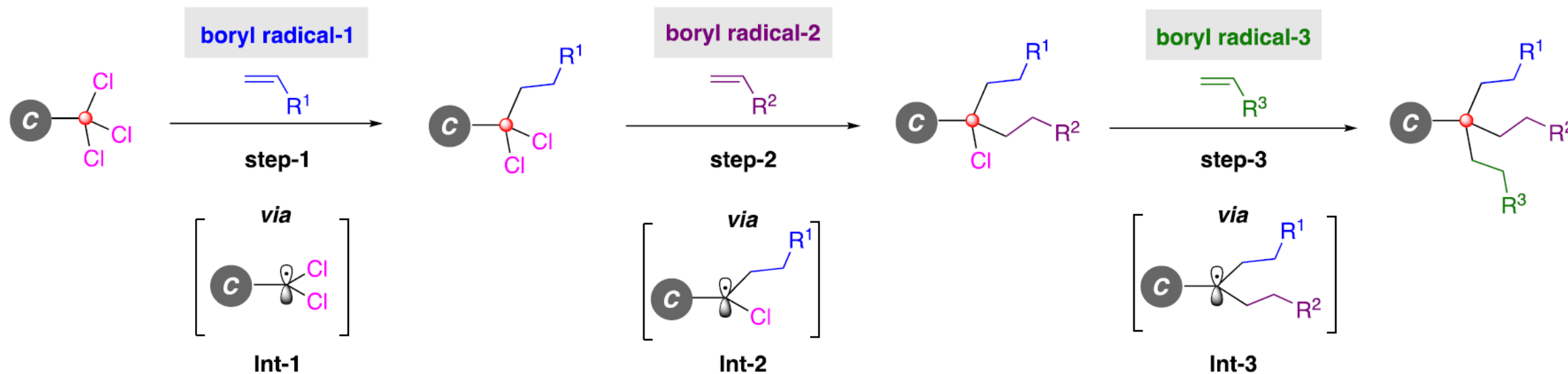
1. 自由基钟实验支持二氟烷基自由基中间体的存在。
2. Na<sup>+</sup> 协助 F<sup>-</sup> 离去, 显著降低 SCS 脱氟能垒
3. F 原子减少 → 羰基亲电性降低 → B 自由基加成变难 → 避免过度脱氟

# Boryl Radicals Enabled a Three-Step Sequence to Assemble All-Carbon Quaternary Centers from Activated Trichloromethyl Groups

Qiang Zhao,<sup>||</sup> Bin Li,<sup>||</sup> Xi Zhou, Zhao Wang, Feng-Lian Zhang,<sup>\*</sup> Yuanming Li, Xiaoguo Zhou, Yao Fu,<sup>\*</sup> and Yi-Feng Wang<sup>\*</sup>

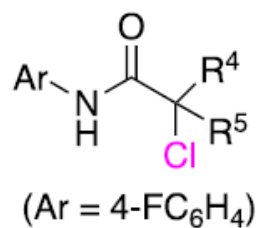
*J. Am. Chem. Soc.* **2022**, *144*, 15275.

This work: boryl radical enabled a three-step sequence to assemble all-carbon quaternary centers from activated  $\text{CCl}_3$  groups



通过分阶段选择合适的硼自由基，实现  $\text{CCl}_3$  中三个 C-Cl 键的逐步、可控官能团化。

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

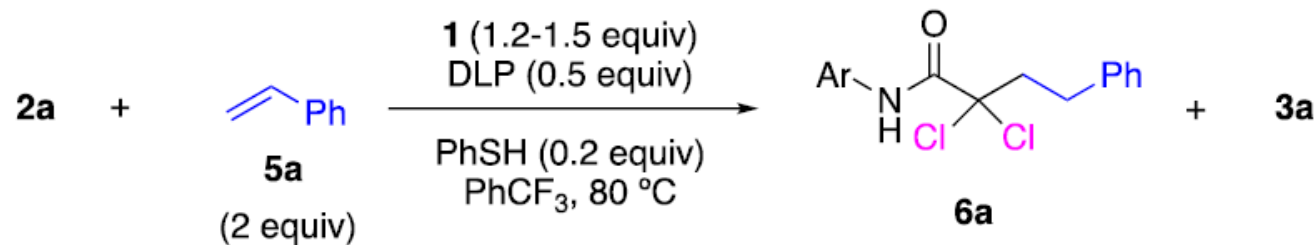


2a R<sup>4</sup> = R<sup>5</sup> = Cl  
 3a R<sup>4</sup> = H, R<sup>5</sup> = Cl  
 4a R<sup>4</sup> = R<sup>5</sup> = H

2a

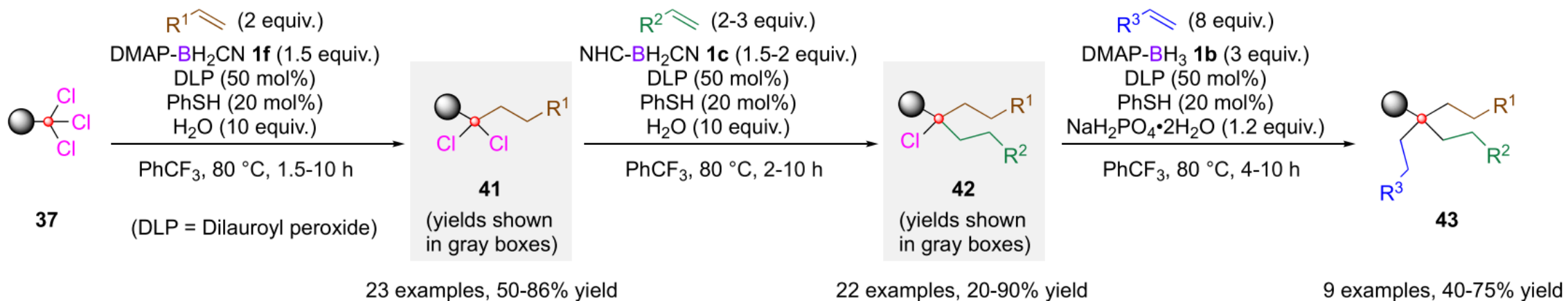
3a

boryl radical (B <sup>•</sup> )	$k_q$ (M <sup>-1</sup> s <sup>-1</sup> ) at 25 °C	$k_q$ (M <sup>-1</sup> s <sup>-1</sup> ) at 25 °C
DMAP-BH <sub>2</sub> (I)	$3.9(3) \times 10^8$	$3.7(9) \times 10^7$
NHC-BH <sub>2</sub> (II)	$2.5(5) \times 10^8$	$4.2(8) \times 10^7$
DMAP-BH <sub>2</sub> CN (III)	$2.9(4) \times 10^8$	$1.3(3) \times 10^7$
NHC-BH <sub>2</sub> CN (IV)	$8.4(13) \times 10^6$	$2.1(6) \times 10^5$

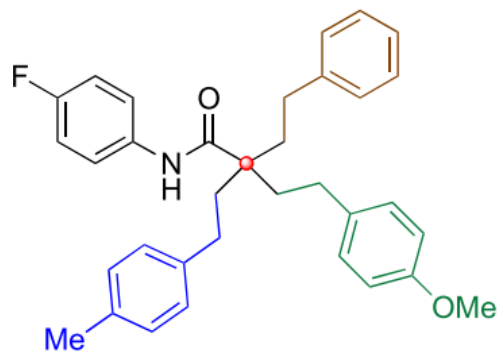
(b) Identification of boryl radical precursors for dechlorinative coupling reactions of 2a<sup>a</sup>

entry	radical precursor	yield of 6a	yield of 3a	$\Delta G^\ddagger$ (TS-2) (kcal/mol)	$\Delta\Delta G^\ddagger$ (TS-2 vs. TS-1) (kcal/mol)
1	DMAP-BH <sub>3</sub> (1a)	40%	47%	7.7	-0.7
2	NHC-BH <sub>3</sub> (1b)	21%	66%	8.5	0.1
3	DMAP-BH <sub>2</sub> CN (1c)	67% (76%) <sup>c</sup>	trace	12.6	4.2
4	NHC-BH <sub>2</sub> CN (1d)	63%	10%	9.7	1.3

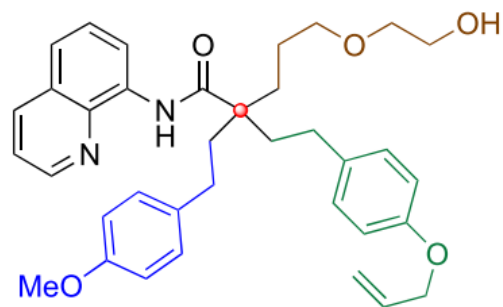
三氯底物 2a 和硼自由基反应的速度大约比二氯底物 3a 快一个数量级  
 调节 LBR 电子性质, 抑制 HAT 还原, 促进脱氯自由基与烯烃偶联。



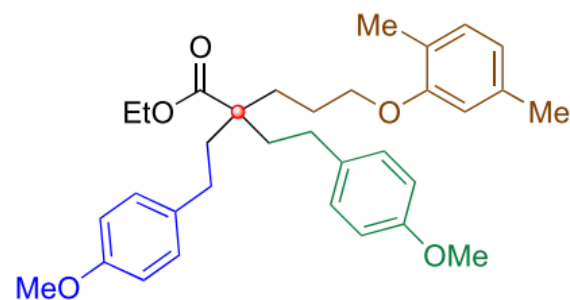
## representative all-carbon quaternary centers tethering three alkyl chains



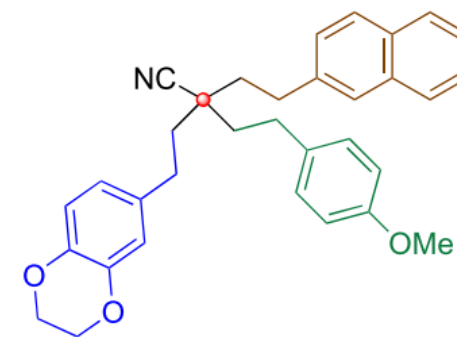
**37a**→**41a** : 76%  
**41a**→**42a** : 85%      **43a**, 65%



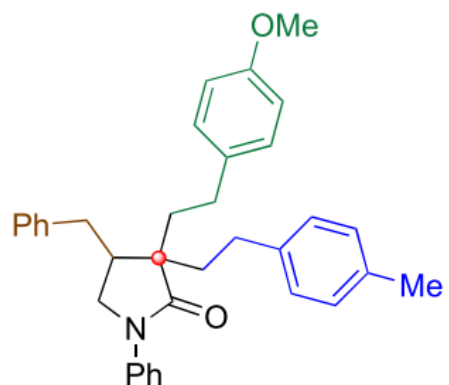
**37b**→**41b** : 52%  
**41b**→**42b** : 55%      **43b**, 40%



**37c**→**41c** : 60%  
**41c**→**42c** : 72%      **43c**, 75%

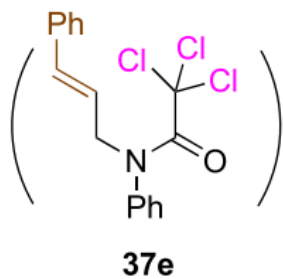


**37d**→**41d** : 60%  
**41d**→**42d** : 48%      **43d**, 47%

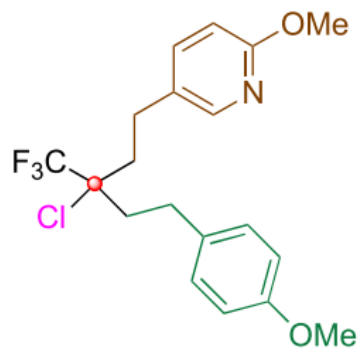


**37e**→**41e** : 75%  
**41e**→**42e** : 67%

**43e**, 50%

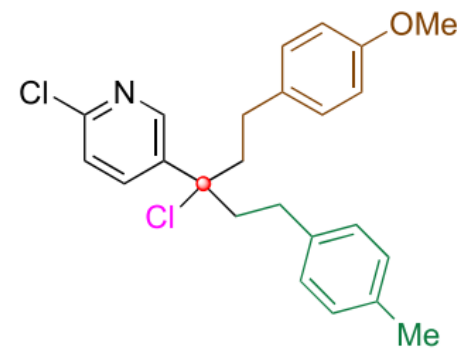


other CCl<sub>3</sub> groups for two successive dechlorination



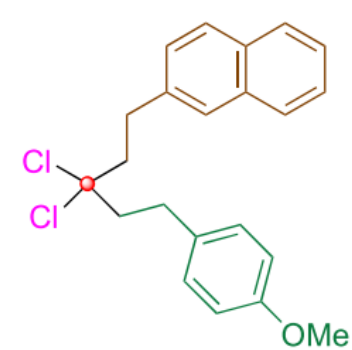
**42f**

**37f**→**41f** : 85%  
**41f**→**42f** : 43%



**42g**

**37g**→**41g** : 66%  
**41g**→**42g** : 52%



**42h**

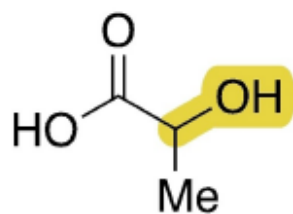
**37h**→**41h** : 86%  
**41h**→**42h** : 71%

**Synthetic Methods** Hot PaperHow to cite: *Angew. Chem. Int. Ed.* **2022**, 61, e202201329International Edition: [doi.org/10.1002/anie.202201329](https://doi.org/10.1002/anie.202201329)German Edition: [doi.org/10.1002/ange.202201329](https://doi.org/10.1002/ange.202201329)

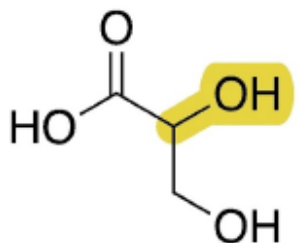
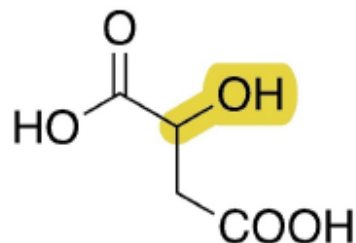
# Dehydroxylative Alkylation of $\alpha$ -Hydroxy Carboxylic Acid Derivatives via a Spin-Center Shift

*Tian-Yu Peng<sup>+</sup>, Zhe-Yuan Xu<sup>+</sup>, Feng-Lian Zhang,\* Bin Li, Wen-Ping Xu, Yao Fu,\* and Yi-Feng Wang\**

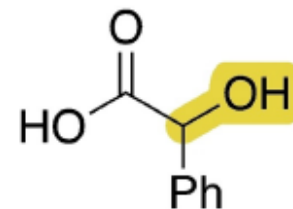
*Angew. Chem. Int. Ed.* **2022**, 61, e202201329.

(a) Examples of naturally occurring and important  $\alpha$ -hydroxy carboxylic acids and derivatives

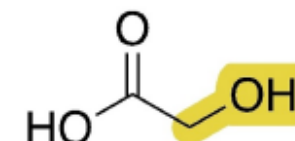
lactic acid

glyceric acid  
(from glycerol)

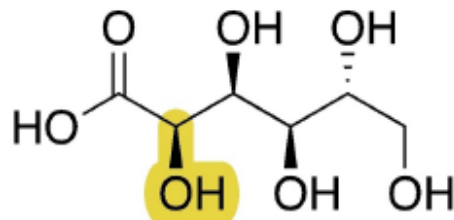
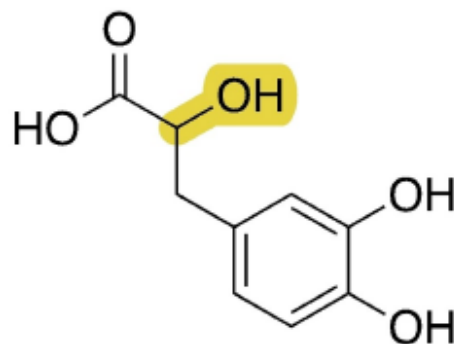
malic acid



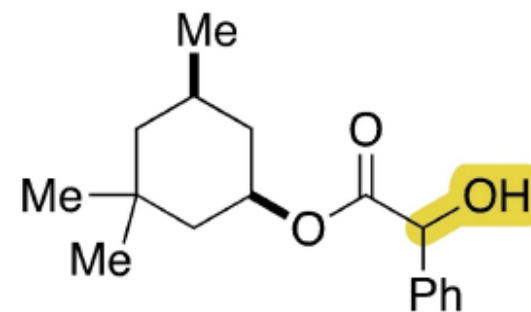
mandelic acid



glycolic acid

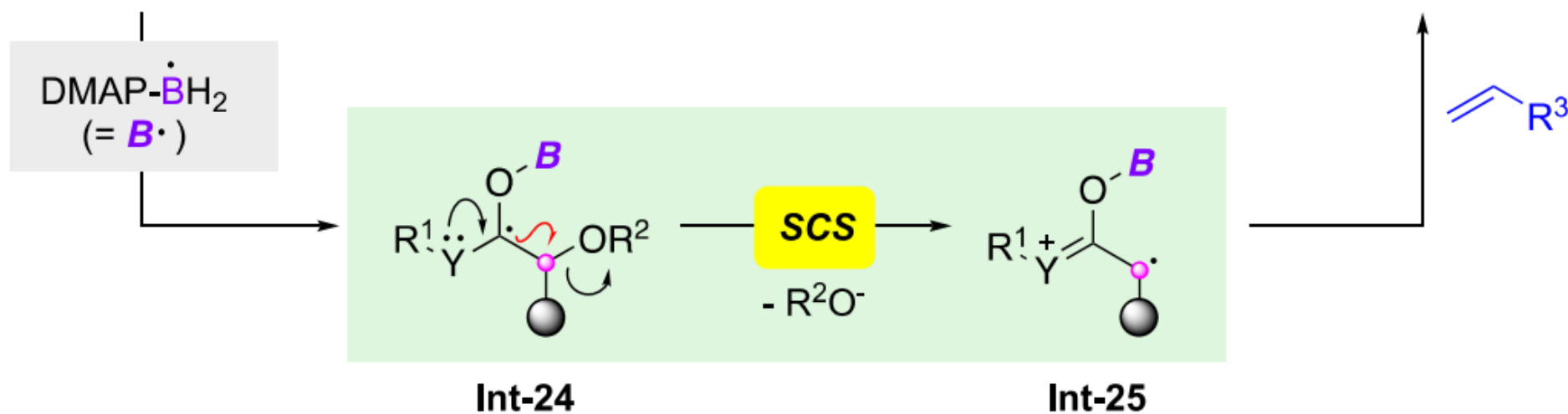
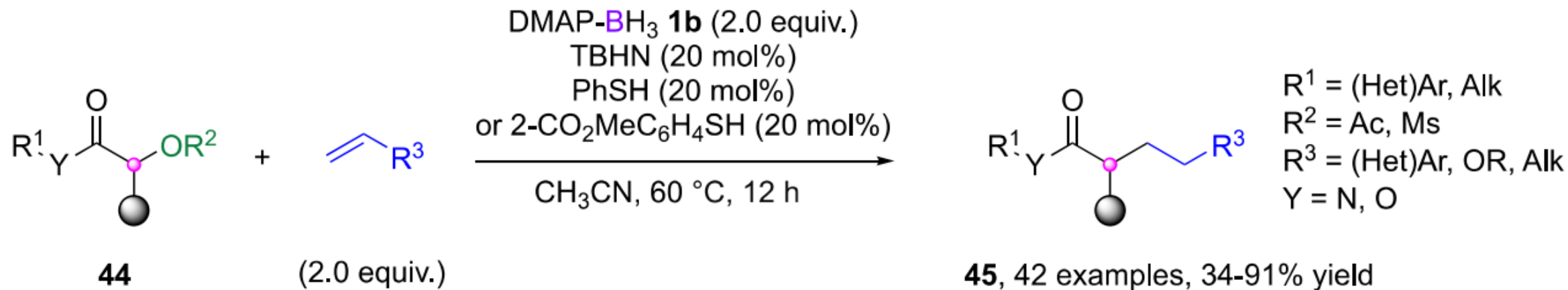
gluconic acid  
(from glucose)

salvianic acid A



cyclandelate

$\alpha$ -羟基羧酸结构广泛存在于生物质平台分子和天然产物中，比如乳酸这类结构



SCS 策略拓展至 C-O 键活化, 实现脱羟基烷基化。

Article










<https://doi.org/10.1038/s41557-026-02137-2>

# Diverse radical C–F functionalizations of hexa- to difluoroarenes using boryl radicals as link-and-lose mediators

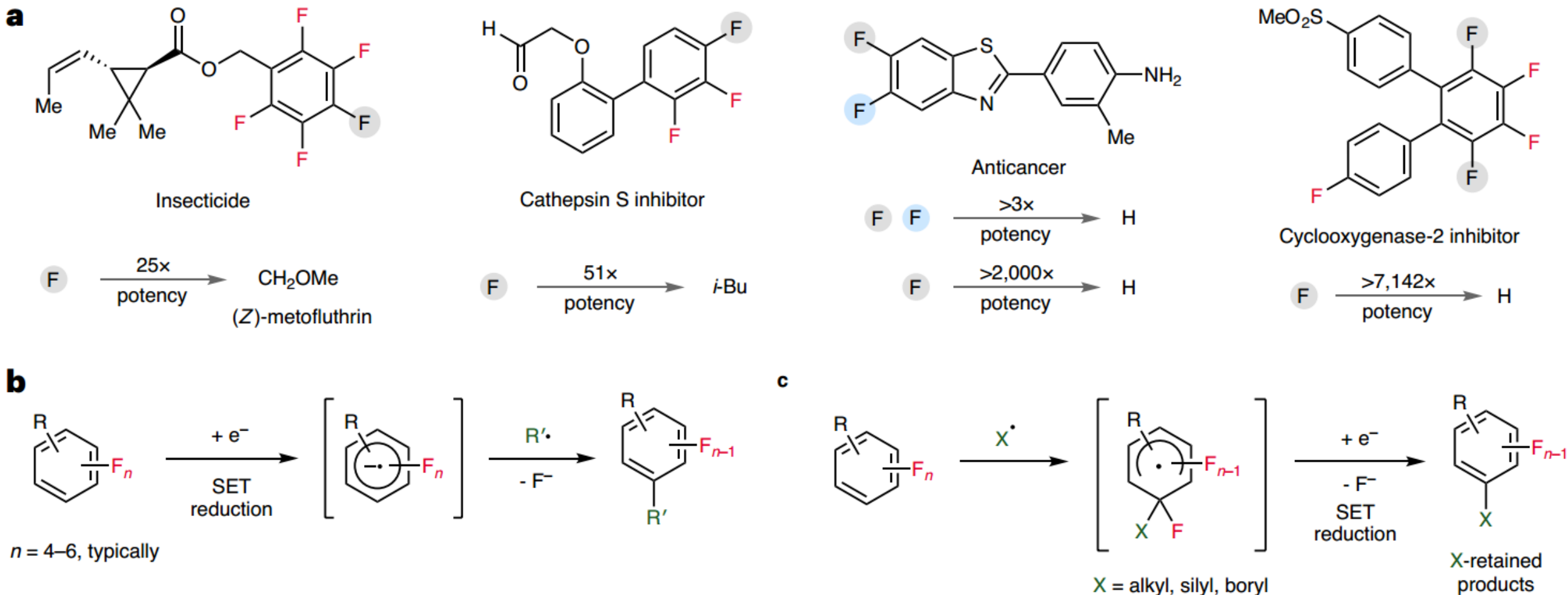
Received: 7 March 2025

Accepted: 24 March 2026

Published online: 22 April 2026

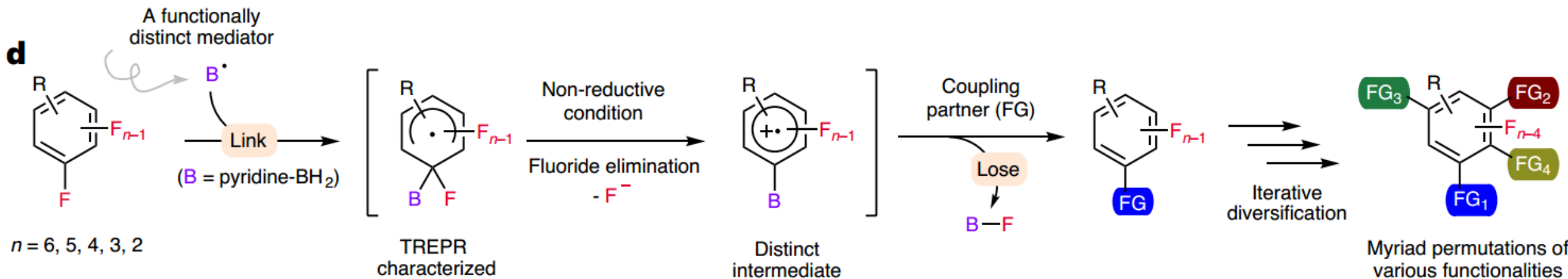
Tian Ye<sup>1,6</sup>, Fang-Song Zhang<sup>1,6</sup>, Zhe-Yuan Xu <sup>1,6</sup>, Sheng-Qi Zhou <sup>2,6</sup>,  
Yee Lin Phang<sup>1</sup>, Zhi-Qiang Ding<sup>1</sup>, Feng-Lian Zhang<sup>1</sup>, Wen-Chao Yang <sup>3</sup> ,  
Zhong-Ping Cai<sup>1</sup>, Yuan Peng<sup>1</sup>, Bing-Yi Zhou<sup>3</sup>, Wei-Qun Suo<sup>2</sup>, Xingwei Guo <sup>2,4</sup> ,  
Yao Fu <sup>1</sup>  & Yi-Feng Wang <sup>1,5</sup> 

*doi.org/10.1038/s41557-026-02137-2*

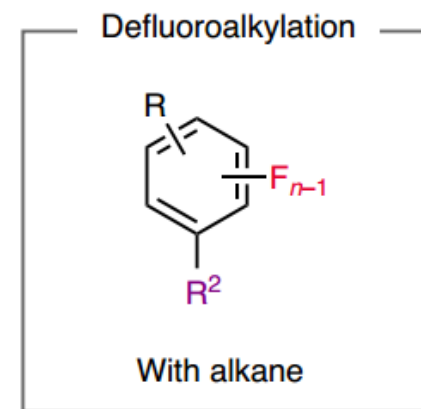
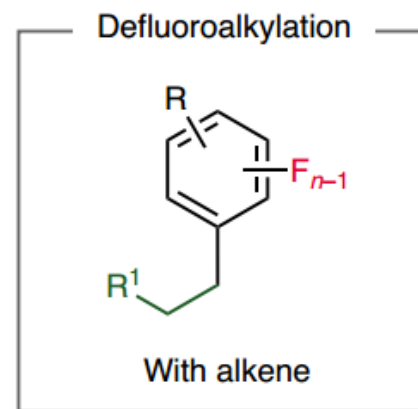
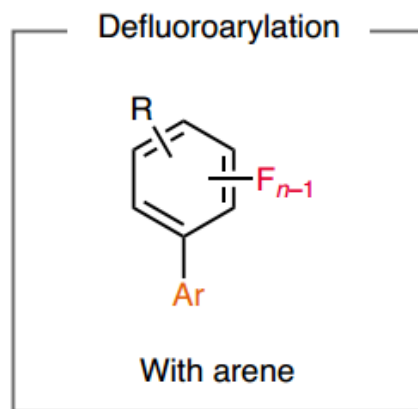
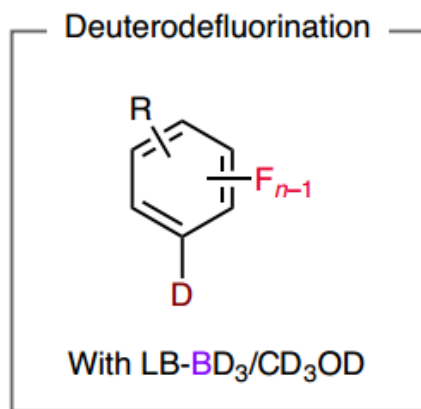
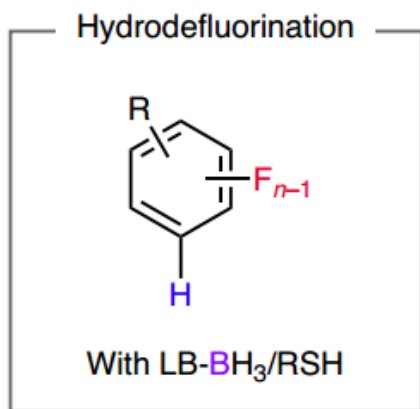


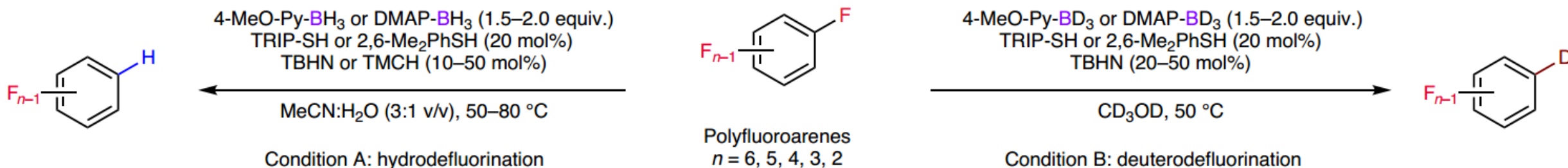
传统还原脱氟依赖底物电子性质高氟芳烃易反应，低氟芳烃较困难

已有自由基加成策略中 X 通常保留反应模式与产物多样性受限

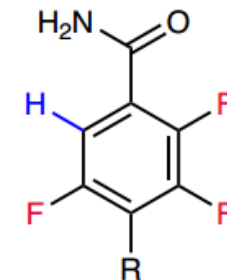
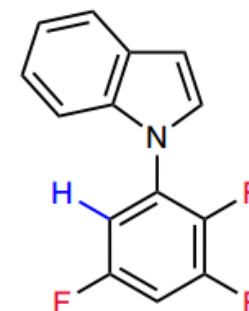
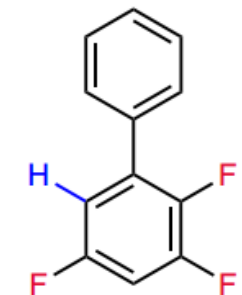
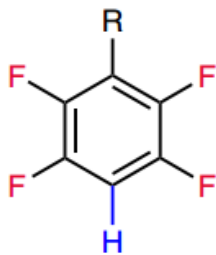
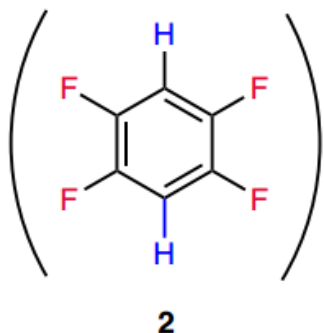
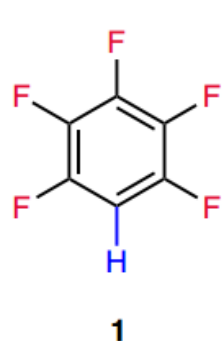


Each of multiple C-F transformations (FG<sub>1</sub>, FG<sub>2</sub>, FG<sub>3</sub> or FG<sub>4</sub>) could be:





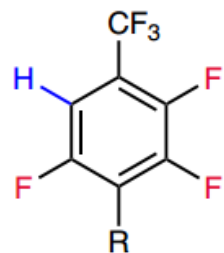
Condition A products:



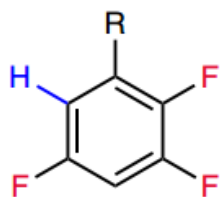
Standard conditions:

1, 89% + 2, trace<sup>b,c</sup>4-MeO-Py-BH<sub>3</sub> (5.0 equiv.)  
and TBHN (3.0 equiv.):1, 14% + 2, 82%<sup>b,c</sup>

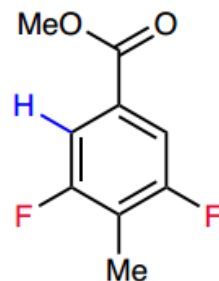
F 原子越多 → 芳环越缺电子 → 更易活化F 原子减少 → 芳环反应性降低 → 需更强亲核性 LBR



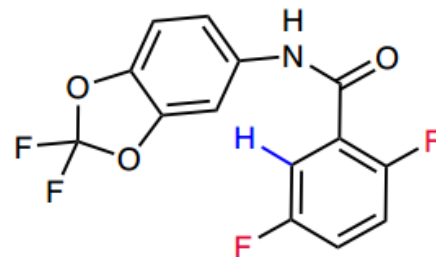
11, R = OPh, 82%<sup>b</sup>  
 12, R = NHPPh, 84%<sup>b</sup>



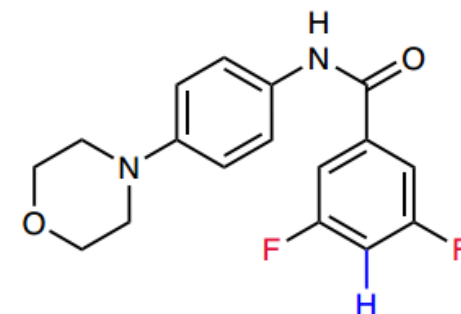
13, R = OMe, 30%<sup>c,d</sup>  
 14, R = NMe<sub>2</sub>, 14%<sup>c,d</sup>



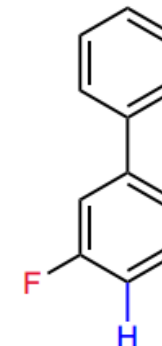
15, 70%<sup>d</sup>



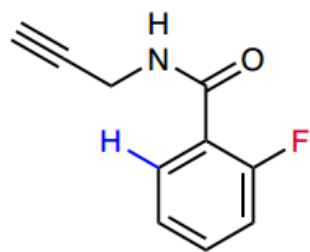
16, 92%<sup>d</sup>



17, 80%<sup>d</sup>

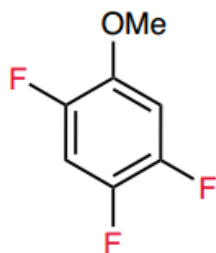


18, 46%<sup>d</sup>

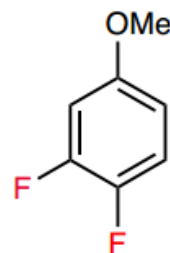


19, 66%<sup>d</sup>

Unsuccessful substrates

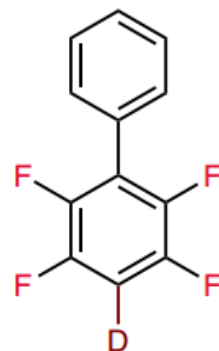


20, NR

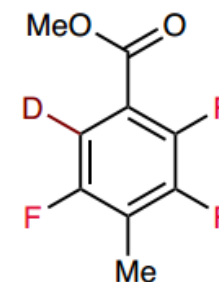


21, NR

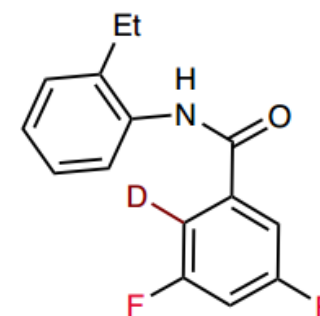
Condition B products:



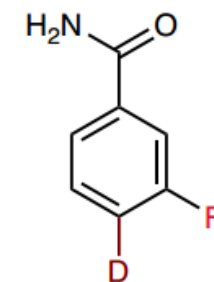
22, 58%<sup>b</sup> (97% D)



23, 87%<sup>b</sup> (98% D)

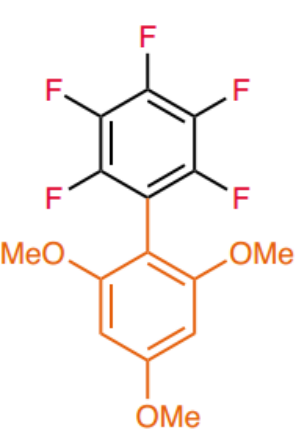
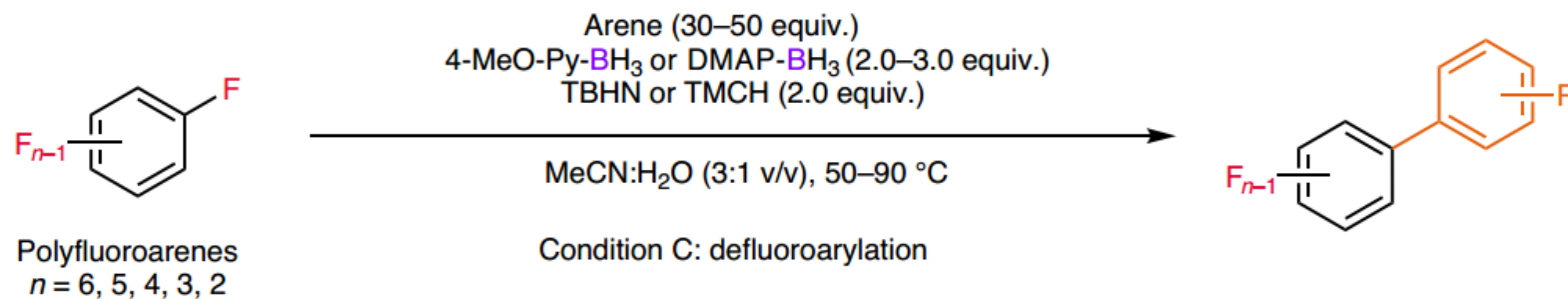
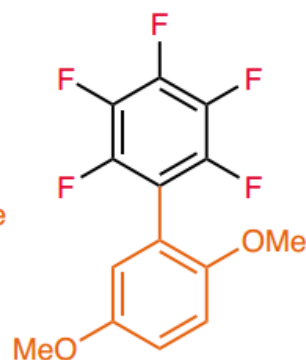
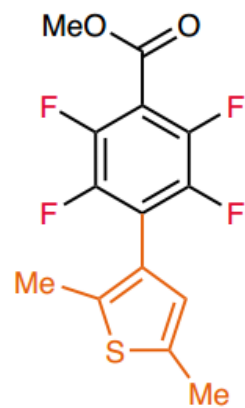
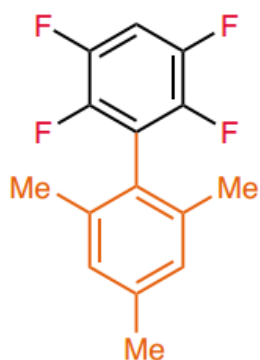
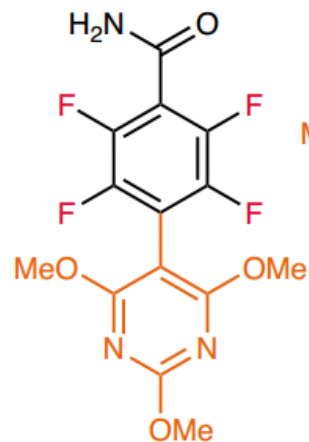
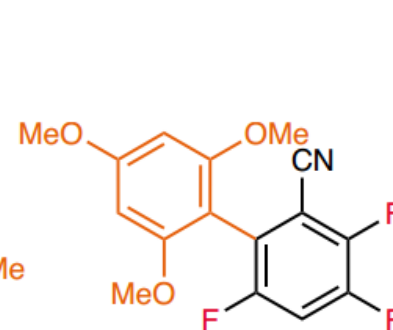
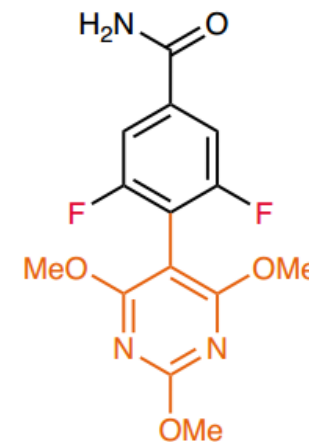
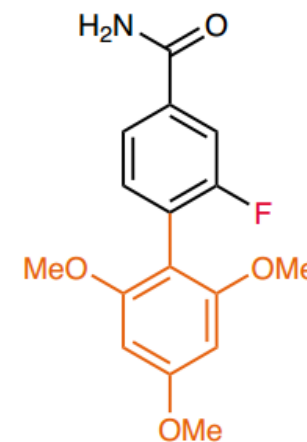


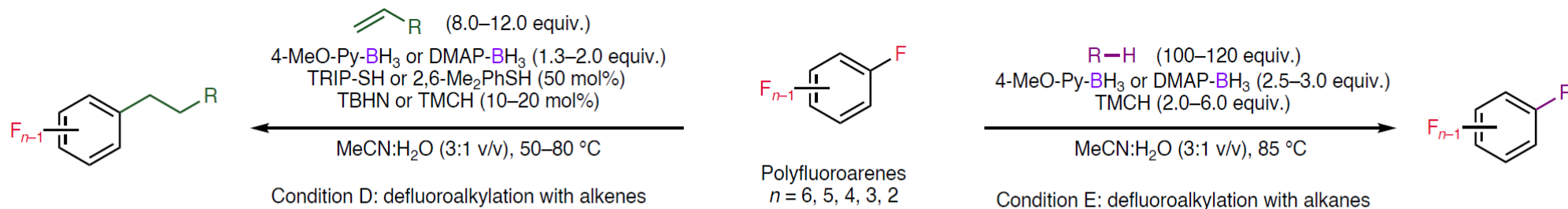
24, 84%<sup>d</sup> (93% D)



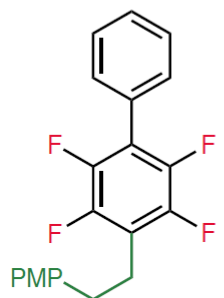
25, 45%<sup>d</sup> (92% D)

给电子基取代 → 初始 B· 加成困难可拓展至氘代脱氟，实现 C-D 键构建

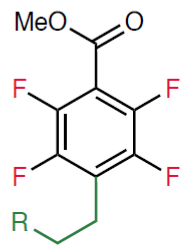
26, 71%<sup>b</sup>27, 45%<sup>b</sup>28, 38%<sup>b</sup> (9%)29, 44%<sup>c</sup> (20%)30, 62%<sup>b</sup> (11%)31, 54%<sup>b</sup> (22%)  
(CCDC: 2372239)32, 60%<sup>c</sup>33, 54%<sup>c</sup> (18%)**F → Ar**



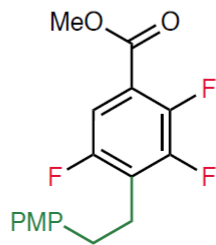
Condition D products:



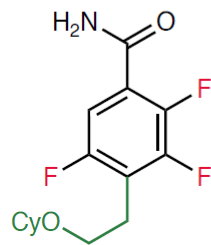
**34**, 55%<sup>b</sup>  
(17%)



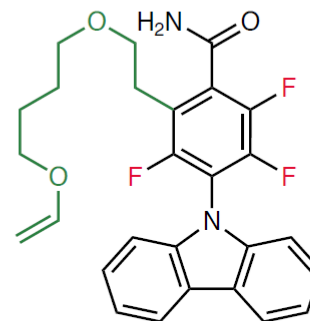
**35**, R = O(CH<sub>2</sub>)<sub>4</sub>OH,  
68%<sup>b</sup> (12%)  
**36**, R = OEt, 57%<sup>b</sup> (18%)



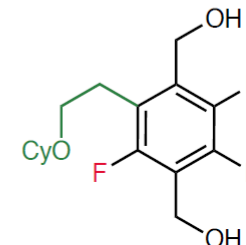
**37**, 52%<sup>b,c</sup> (10%)  
(CCDC: 2372236)



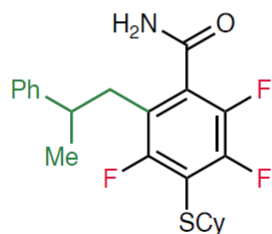
**38**, 59%<sup>b</sup> (10%)



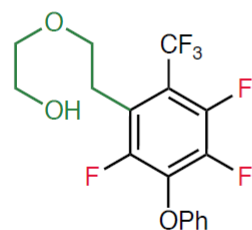
**39**, 71%<sup>b</sup> (25%) (CCDC: 2372238)  
Gram scale: 64%, 1.03 g<sup>b</sup>



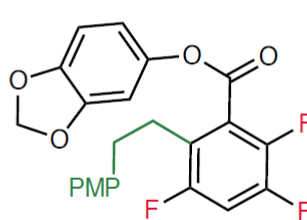
**40**, 65%<sup>d,e</sup> (15%)



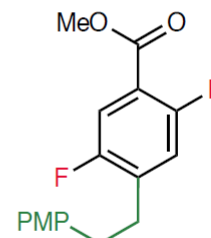
**41**, 67%<sup>b</sup> (14%)  
(CCDC: 2372244)



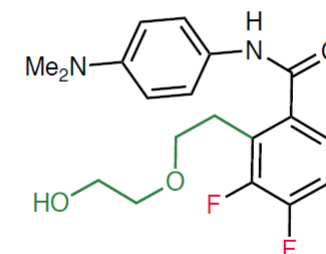
**42**, 70%<sup>b</sup> (15%)



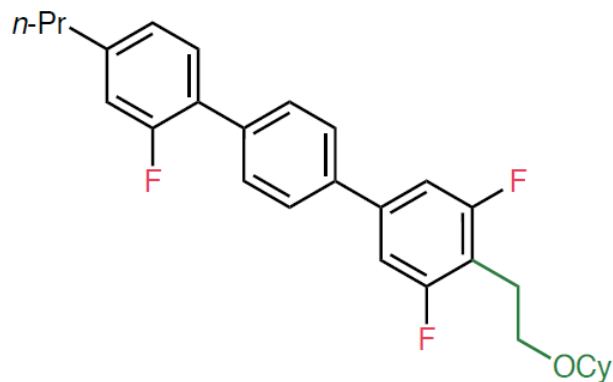
**43**, 50%<sup>b</sup> (15%)  
(CCDC: 2372237)



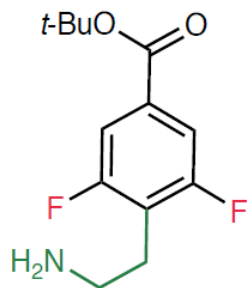
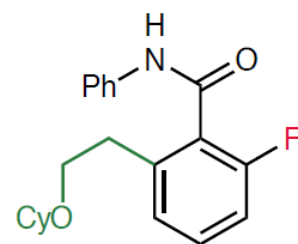
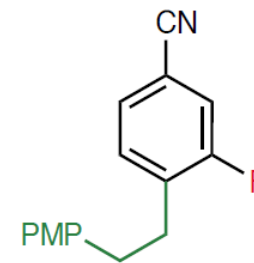
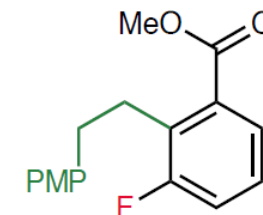
**44**, 76%<sup>d</sup> (18%)  
(CCDC: 2372240)



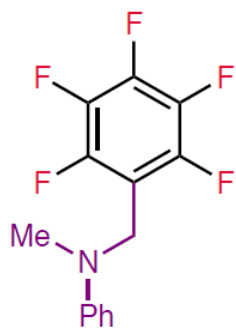
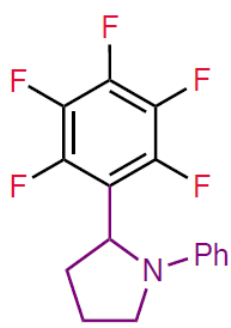
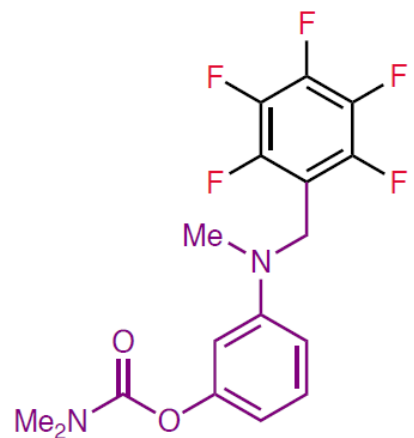
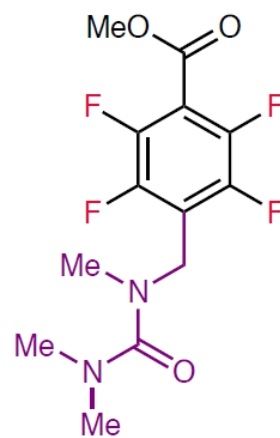
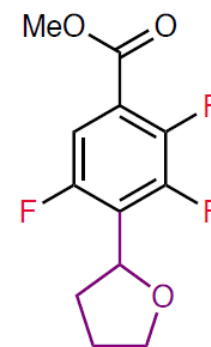
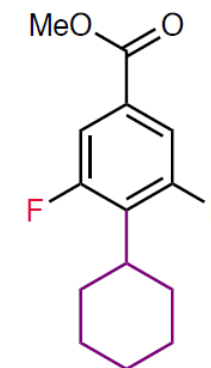
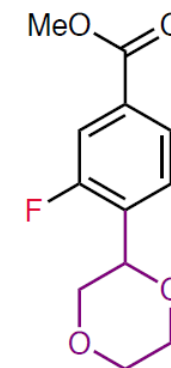
**45**, 60%<sup>d</sup> (32%)  
(CCDC: 2372241)

46, 76%<sup>d</sup>

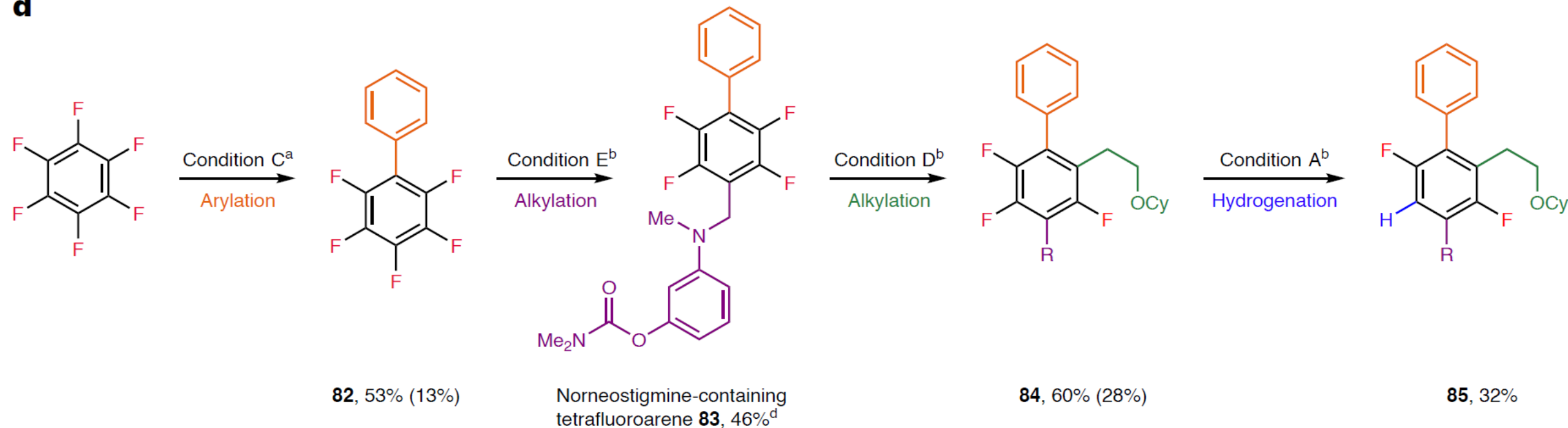
From 3PGUF (liquid crystal compound)

47, 51%<sup>d</sup> (one-pot two-step)Key intermediate towards HCV  
NS3 protease/NS4A inhibitor  
(Previously) Four steps48, 43%<sup>d</sup> (38%)49, 72%<sup>a,c</sup> (15%)50, 67%<sup>d</sup> (15%)

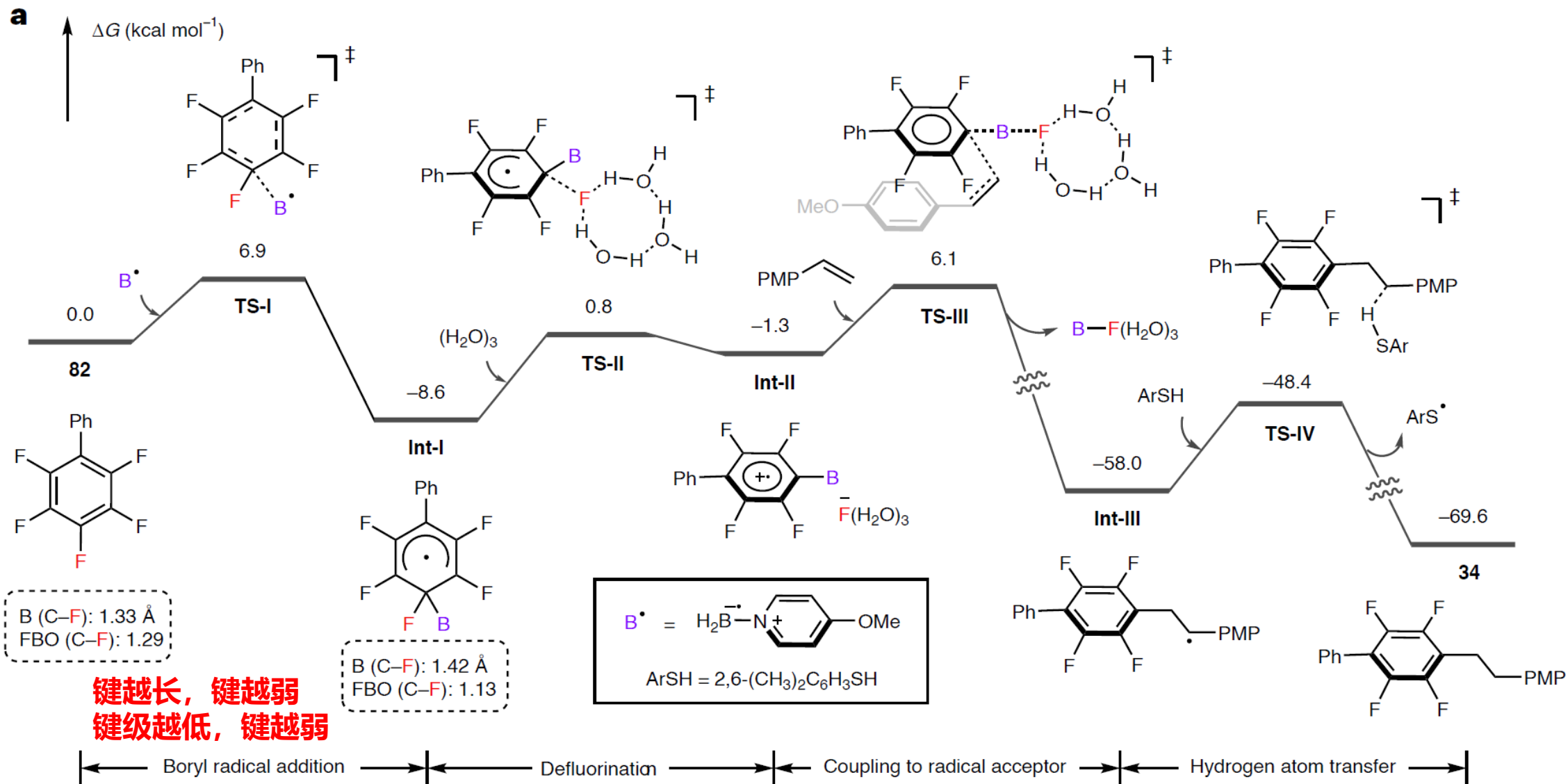
Condition E products:

51, 65%<sup>b,f</sup>52, 55%<sup>d</sup>53, 45%<sup>b</sup> (trace)<sup>g</sup>54, 34%<sup>b</sup> (15%)55, 36%<sup>b</sup>56, 40%<sup>d</sup> (14%)57, 45%<sup>d</sup>

d



不只是替换一个 C-F 键，而是可以继续替换第二个、第三个，甚至第四个 C-F 键

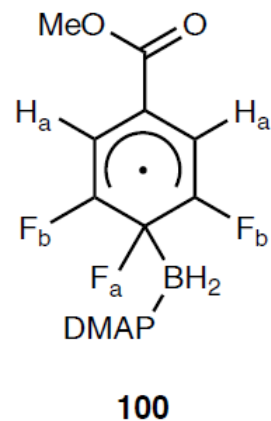
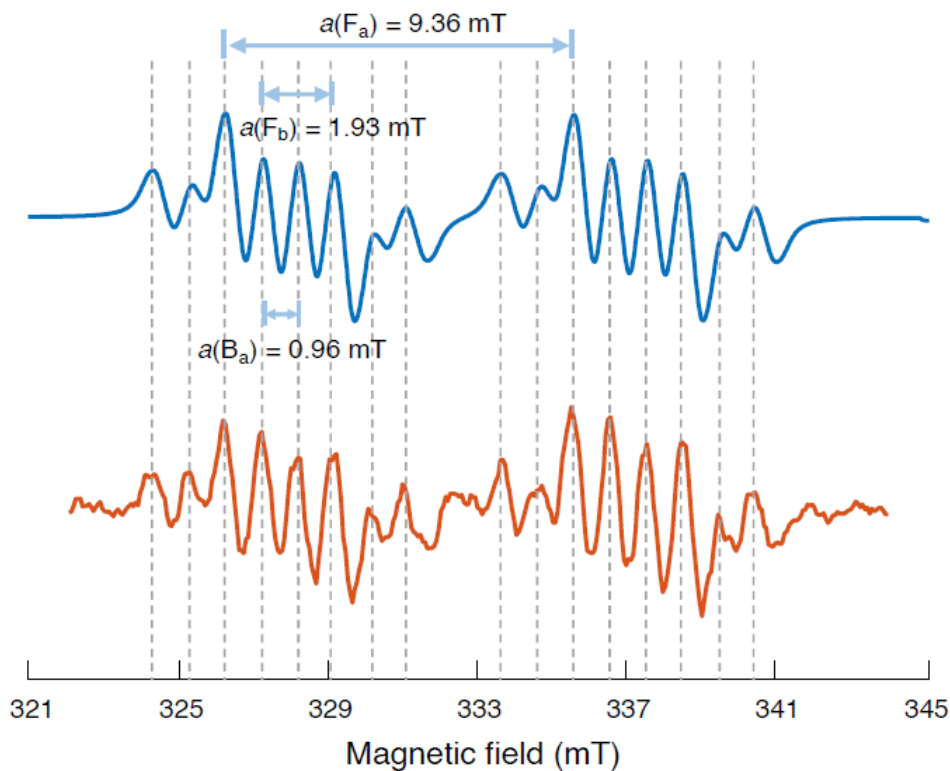


键越长, 键越弱  
键级越低, 键越弱

B• 加成削弱 C-F 键 → 异裂 F<sup>-</sup> 离去 → 烯烃捕获/B 离去 → HAT 得产物

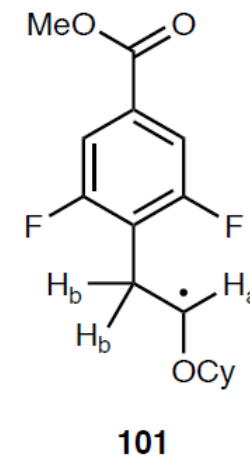
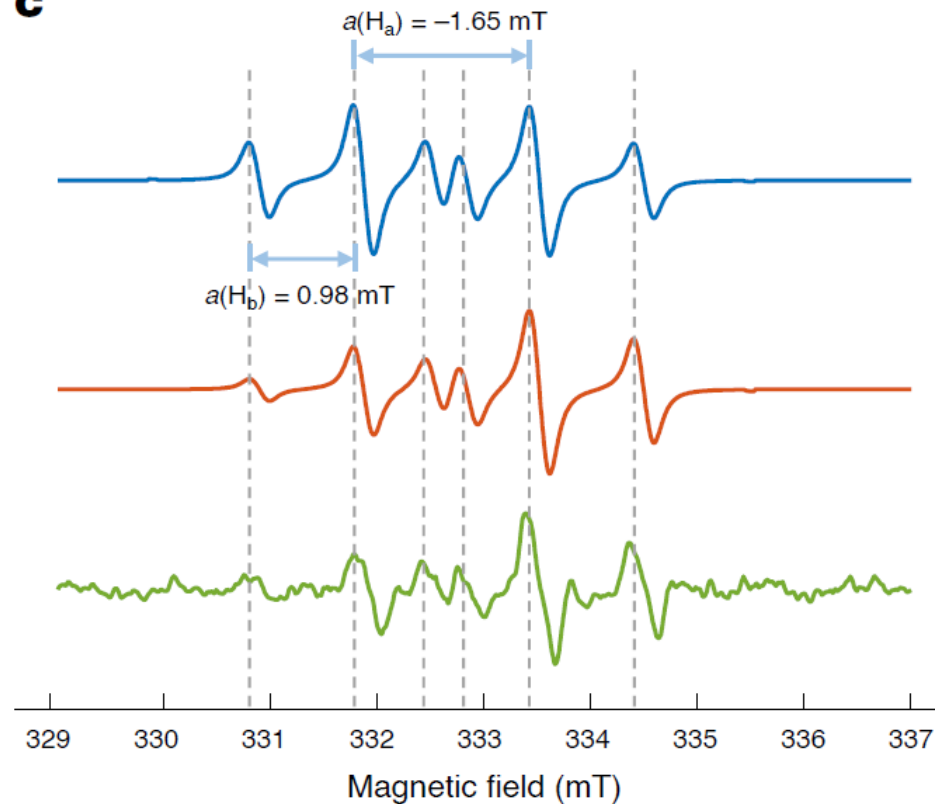
时间分辨电子顺磁共振：它适合检测反应中瞬间生成、寿命很短的自由基中间体，比如微秒级别存在的自由基。

b



- Simulation, Boltzmann distributed  
 $g = 2.0035$ ,  $lwpp = 0.34 \text{ mT}$ , modulation depth of  $0.5 \text{ mT}$
- Experiment, gate 0–300  $\mu\text{s}$

c



- Simulation, Boltzmann distributed  
 $g = 2.0036$ ,  $lwpp = 0.12 \text{ mT}$ , modulation depth of  $0.2 \text{ mT}$
- Simulation, polarized,  $\rho_{RP}(E/A) = 0.25$
- Experiment, gate 0–300  $\mu\text{s}$

模拟与实验匹配 → 自由基中间体 100与101 的存在

01

研究背景

02

C-B 键构建

03

C-X键活化

04

不对称催化

RESEARCH

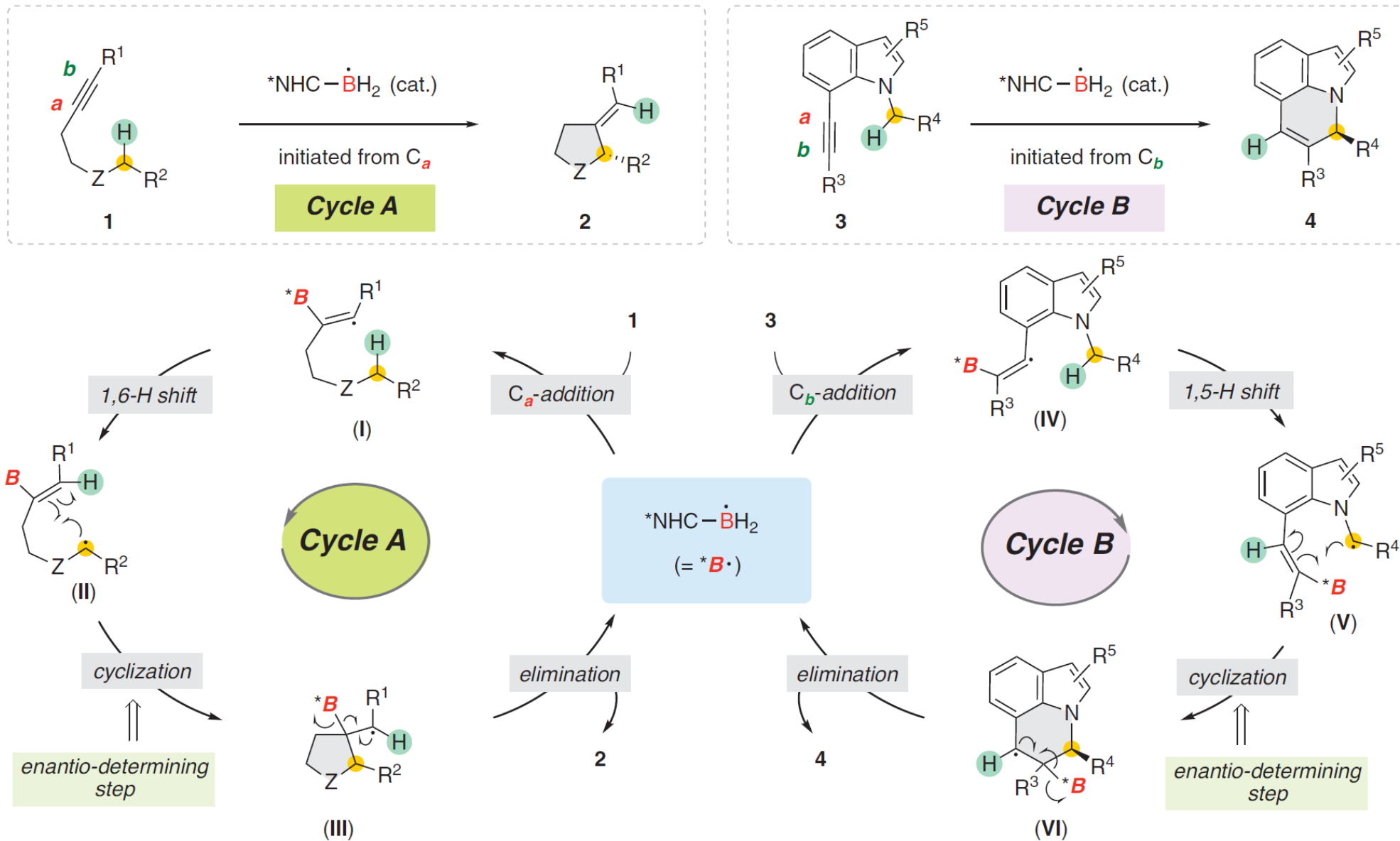
ORGANIC CHEMISTRY

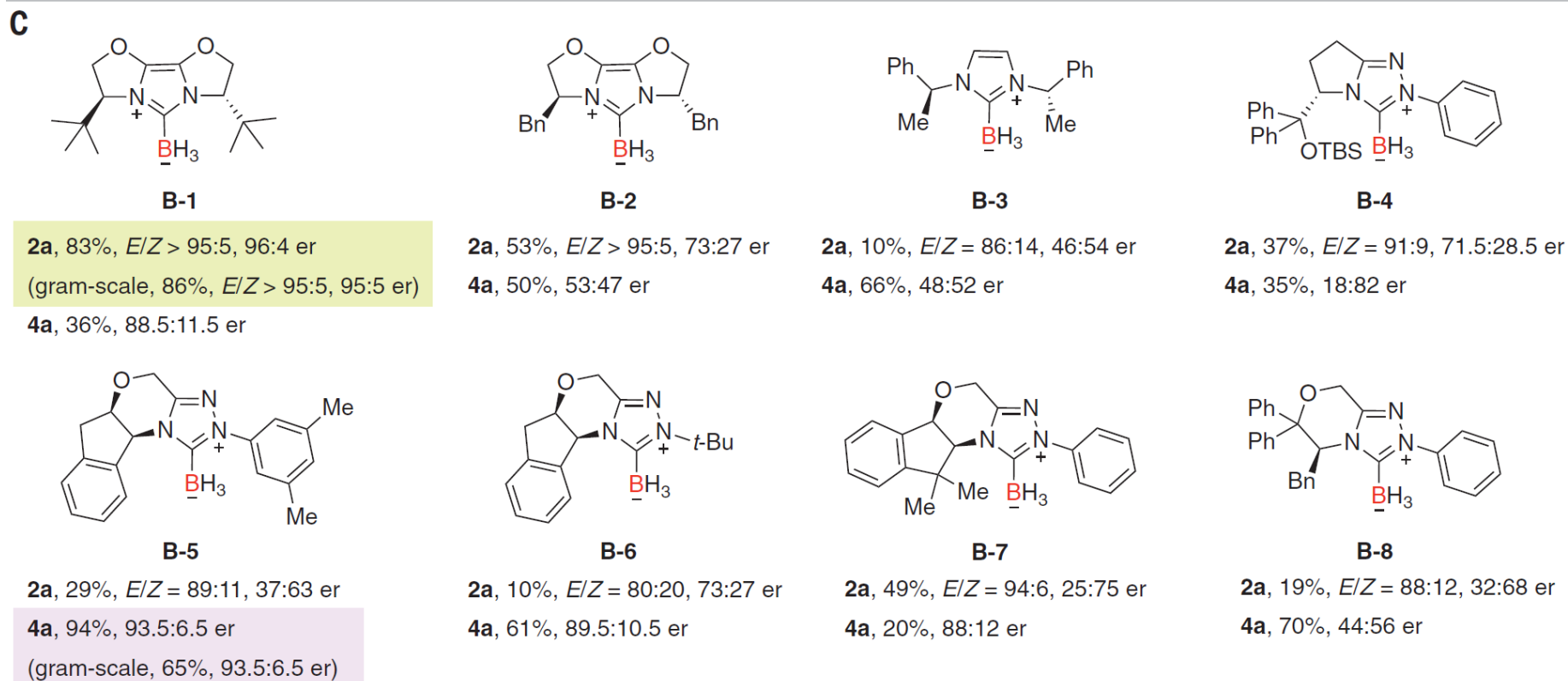
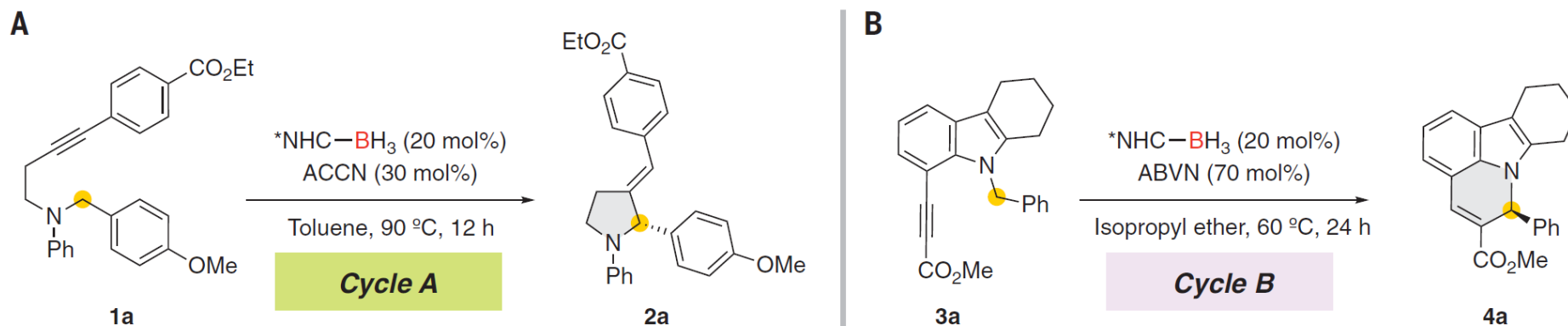
# Boryl radical catalysis enables asymmetric radical cycloisomerization reactions

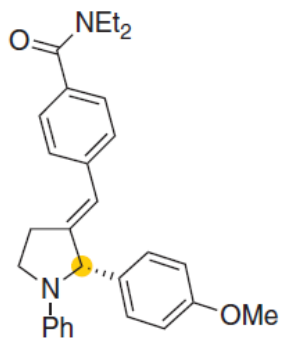
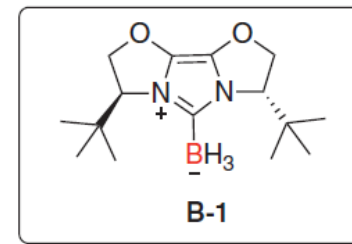
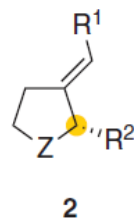
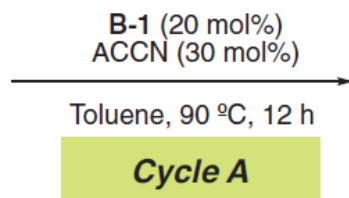
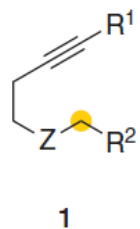
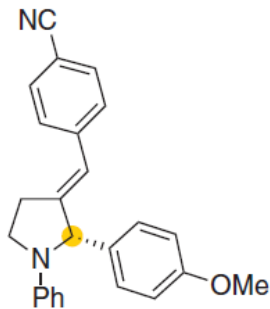
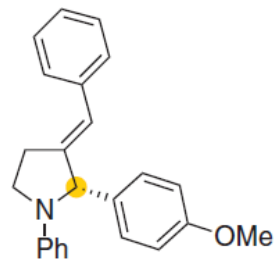
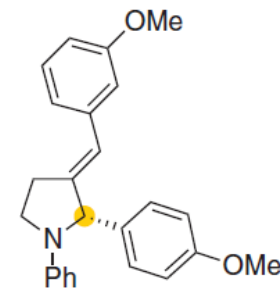
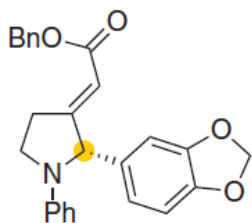
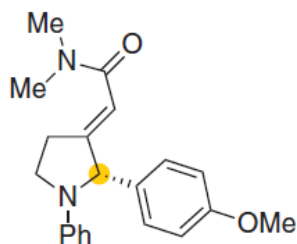
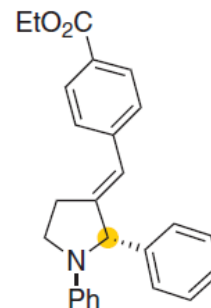
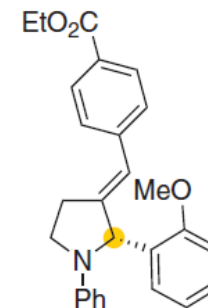
Chang-Ling Wang<sup>1†</sup>, Jie Wang<sup>1†</sup>, Ji-Kang Jin<sup>2†</sup>, Bin Li<sup>2</sup>, Yee Lin Phang<sup>1</sup>, Feng-Lian Zhang<sup>1\*</sup>, Tian Ye<sup>1</sup>, Hui-Min Xia<sup>1</sup>, Li-Wen Hui<sup>1</sup>, Ji-Hu Su<sup>3</sup>, Yao Fu<sup>1\*</sup>, Yi-Feng Wang<sup>1,4\*</sup>

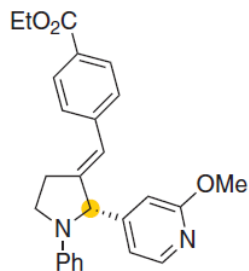
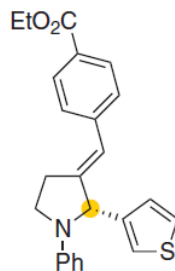
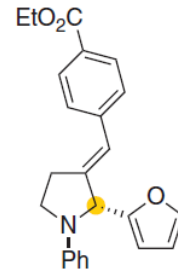
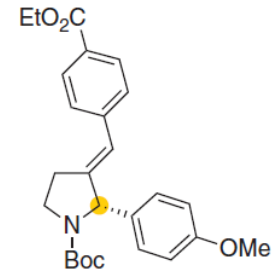
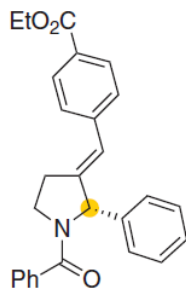
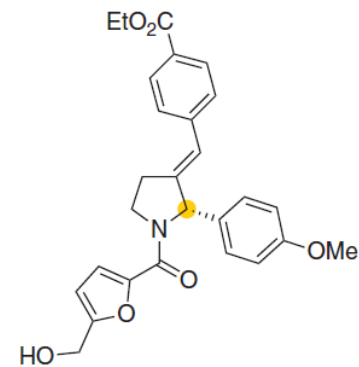
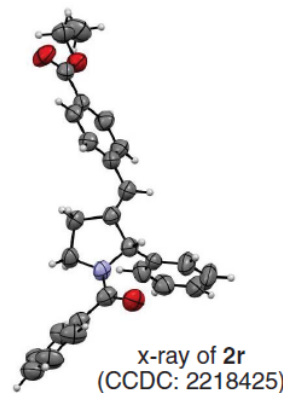
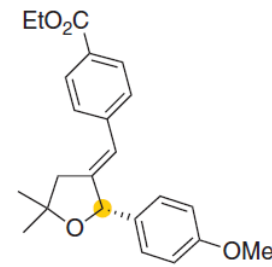
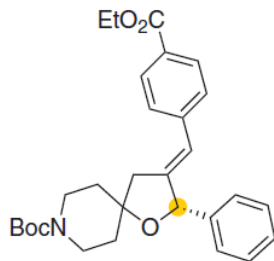
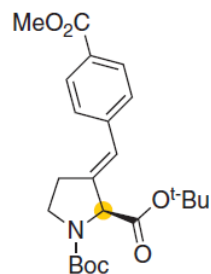
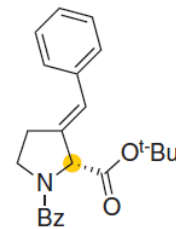
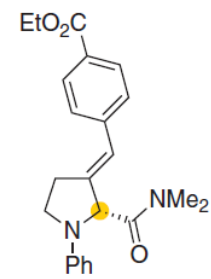
*Science* **2023**, 382, 1056.

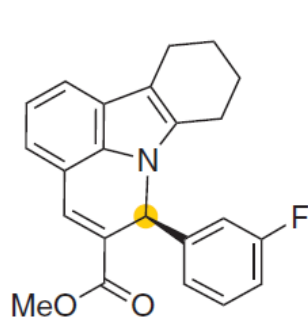
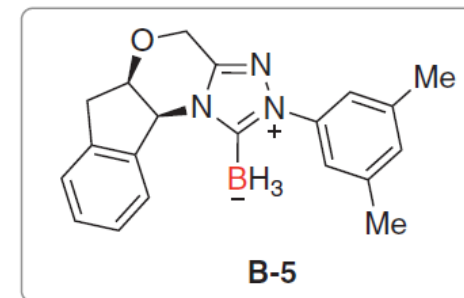
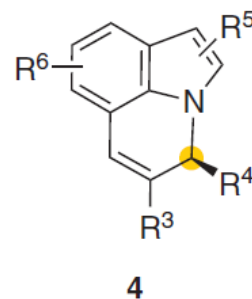
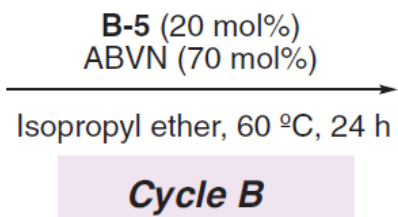
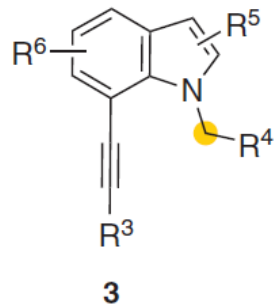
## 手性 NHC-boryl radical: 可逆加成/消除 + 手性环境控制自由基环化



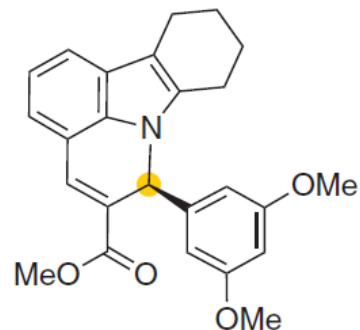


2b, 54%, *E/Z* > 95:5, 96.5:3.5 er2c, 90%, *E/Z* > 95:5, 92.5:7.5 er2d, 43%, *E/Z* > 95:5, 97:3 er2e, 38%, *E/Z* > 95:5, 94.5:5.5 er2f, 61%\*, *E/Z* = 88:12, 94:6 er2g, 55%\*, *E/Z* = 77:23, 93:7 er2h, 74%, *E/Z* > 95:5, 96:4 er2i, 52%, *E/Z* > 95:5, 95.5:4.5 er

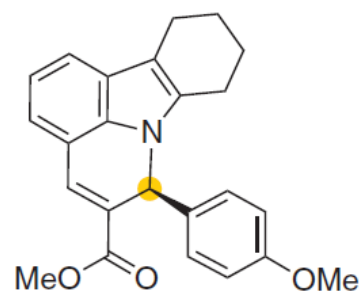
2n, 51%<sup>†</sup>, *E/Z* > 95:5, 95.5:4.5 er2o, 84%, *E/Z* = 91:9, 95:5 er2p, 51%, *E/Z* = 83:17, 94.5:5.5 er2q, 44%, *E/Z* > 95:5, 92.5:7.5 er2r, 43%, *E/Z* > 95:5, 94.5:5.5 er2s, 60%, *E/Z* = 92:8, 96:4 er2t, 85%, *E/Z* > 95:5, 87:13 er2u, 52%, *E/Z* > 95:5, 84:16 er2v, 36%<sup>‡</sup>, *E/Z* > 95:5, 91.5:8.5 er2w, 40%<sup>§</sup>, *E/Z* > 95:5, 94:6 er2x, 59%<sup>§</sup>, *E/Z* > 95:5, 85:15 er



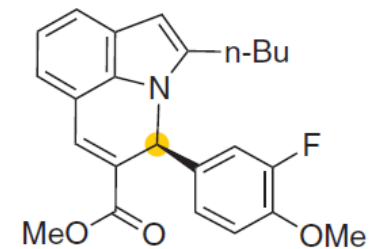
**4b**, 72%, 92:8 er



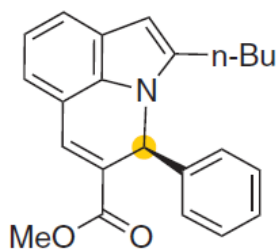
**4c**, 90%, 92:8 er



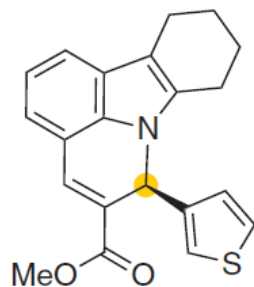
**4d**, 75%, 94:6 er



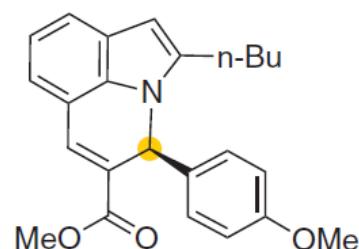
**4e**, 77%, 91:9 er



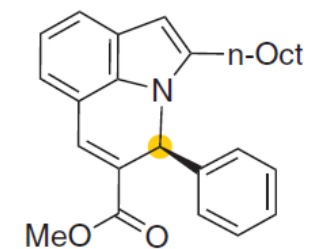
**4f**, 95%, 93.5:6.5 er



**4a**, 66%, 93:7 er

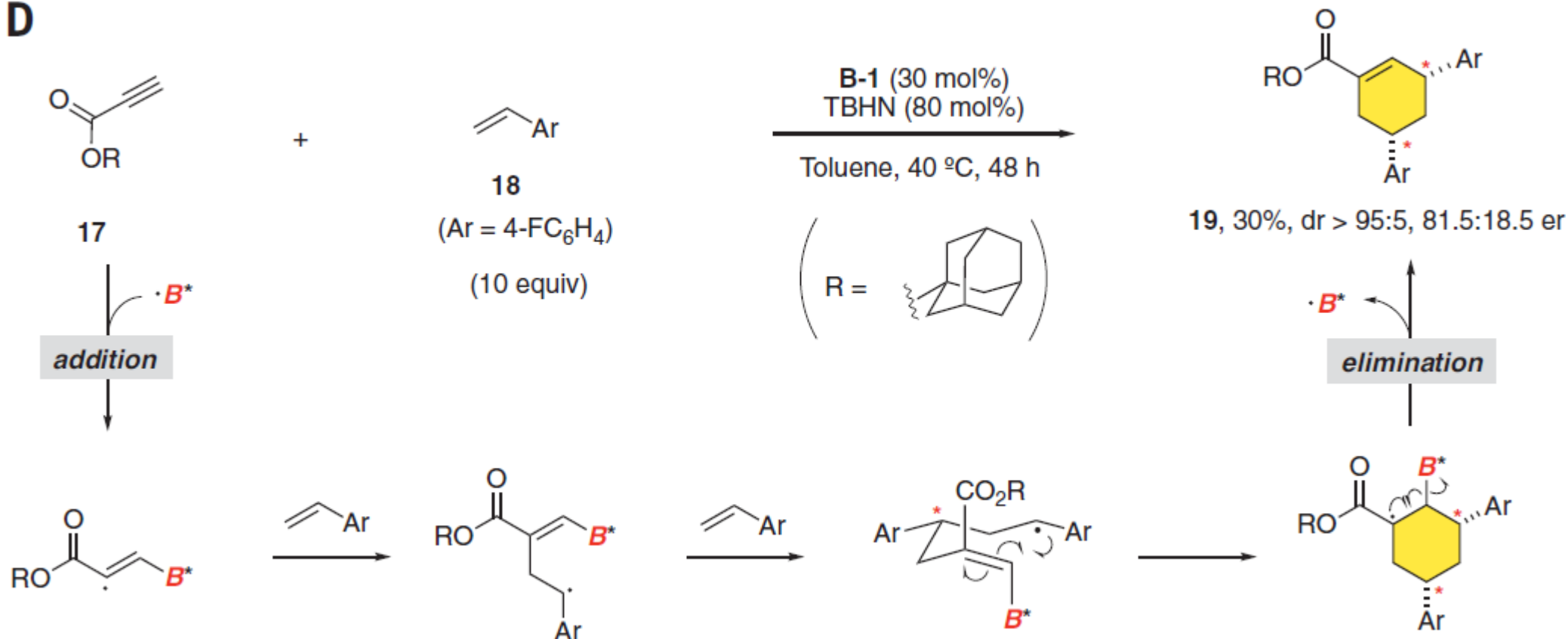


**4h**, 85%, 93.5:6.5 er



**4i**, 88%, 90:10 er

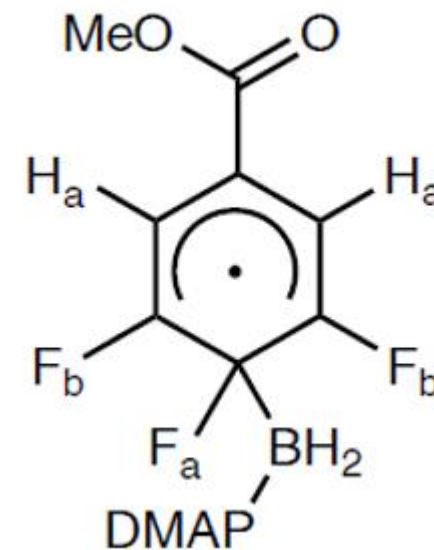
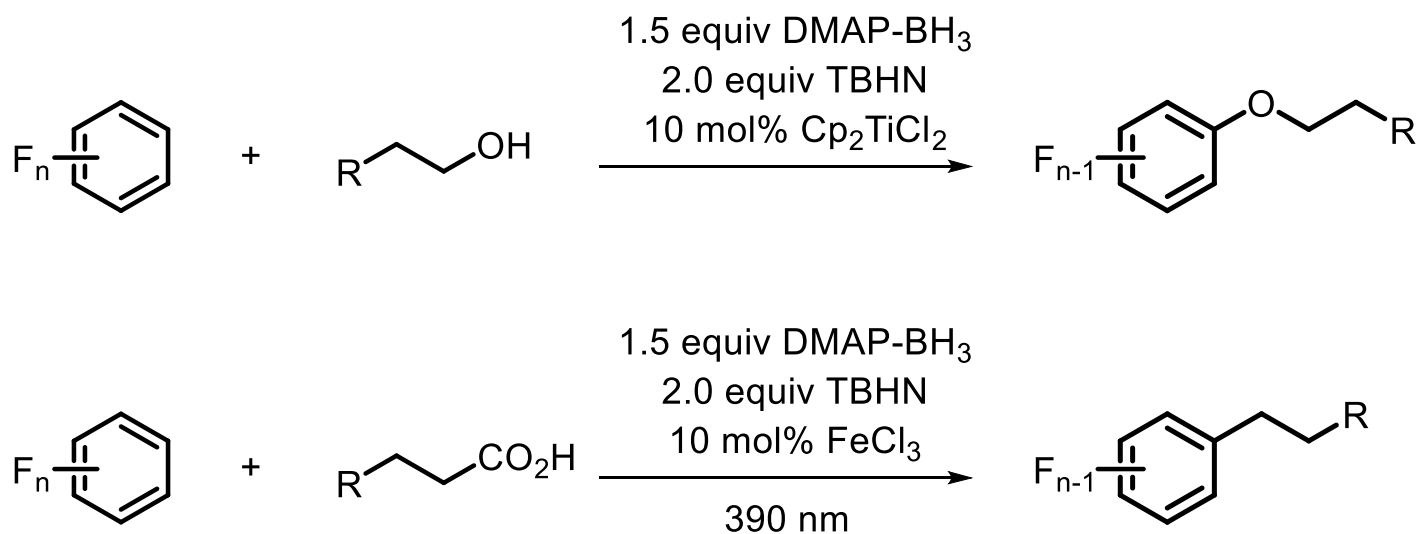
D



手性 NHC-B• 催化分子间 [2+2+2] 环化, 构建手性六元环

## 1. LBR/Ti 协同脱氟 C-O 键构筑

## 2. LBR/Fe-LMCT 协同脱氟脱羧烷基化



# 感谢各位同门的指导！ 敬请各位老师批评指正！

硼自由基催化的新反应—汪义丰

汇报人：李连杰

导师：杨泽鹏 教授

时间：2026. 05. 29