Photoinduced C–N cross coupling reaction developed by G. C. Fu's group

2018. 1. 11. LS

Tsukasa Shimakawa

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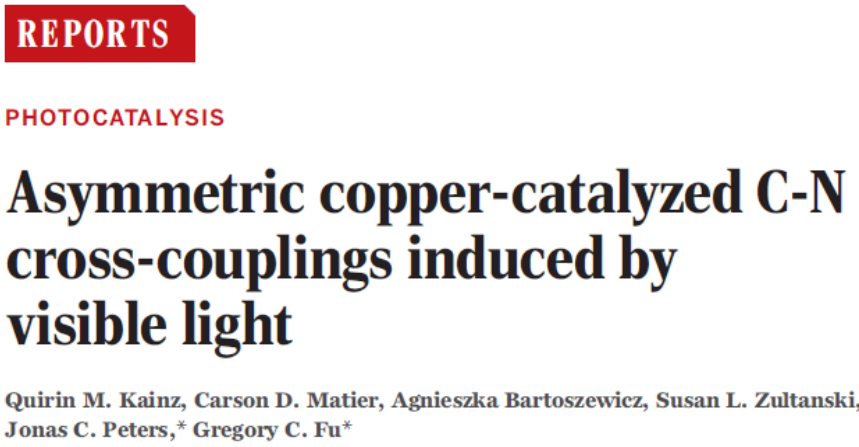
2. Asymmetric cross coupling of carbazoles induced by visible light (Fu, 2016)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Asymmetric copper-catalyzed C-N cross-couplings induced by visible light

Quirin M. Kainz, Carson D. Matier, Agnieszka Bartoszewicz, Susan L. Zultanski, Jonas C. Peters,* Gregory C. Fu*

3. Alkylation of aliphatic amine induced by visible light (Fu, 2017)


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Communication

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Copper-Catalyzed Alkylation of Aliphatic Amines Induced by Visible Light

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Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, California 91125, United States

Prof. Gregory, C. Fu

Education and Professional Appointments:
1984 - 1985 : MIT (BS: Prof. Sharpless, K. B.)

1985 - 1991 : Harvard University (Ph. D: Prof. Evans, D. A.)

1991 - 1993 : Caltech (Posdoc: Prof. Grubbs, R. H.)

1993 - 1999 : MIT (Assistant professor, Associate professor)

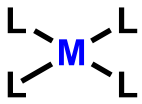
1999 - 2012 : MIT (Professor of chemistry)

2012 - : Caltech (Professor of chemistry)

Research area:
1. Development of Nickel catalyzed cross coupling reaction

2. Development of Copper catalyzed carbon-heteroatom coupling reaction induced by light (collaboration with Peters group at Caltech)

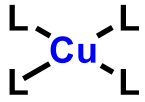
Common photoredox catalyst



M : high cost (Ir, Ru)

transition metal complex only serves as
1. Photo excitation
2. Site for redox chemistry

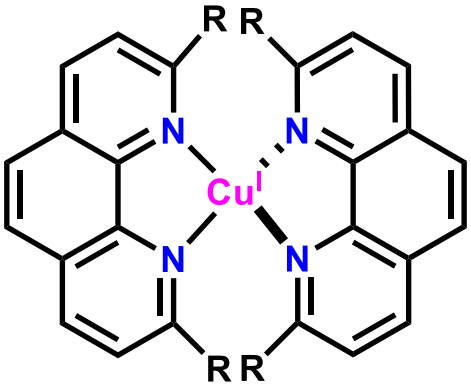
Fu's approach



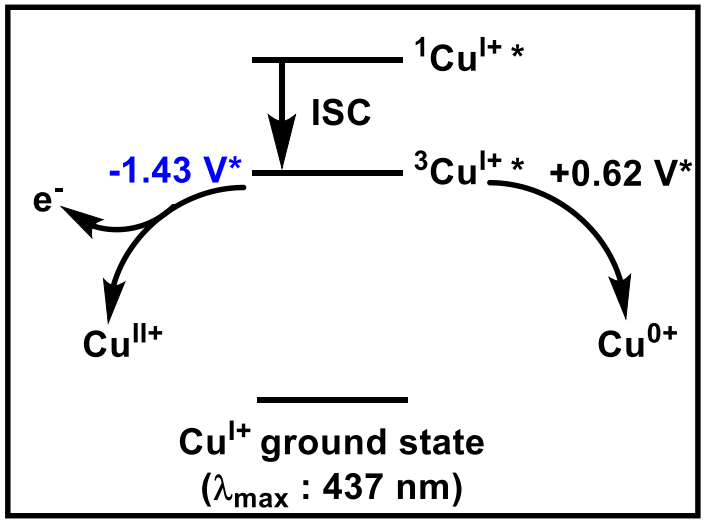
Cu: *low* cost

transition metal complex serves as
1. Photo excitation
2. Site for redox chemistry
3. Site for key bond formation

Copper in photocatalyst



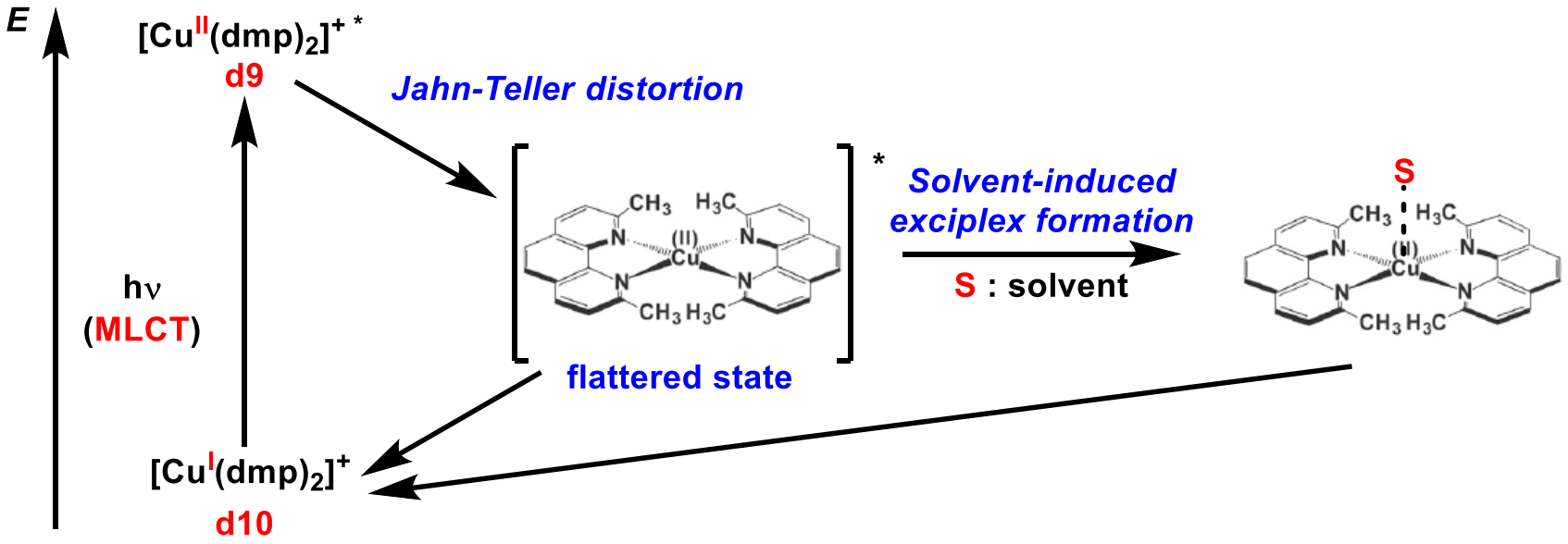
$[Cu(dap)_2]^+$
R = 4-methoxyphenyl



1. **strong reductant**
cf. $[Ru(bpy)_3]^{2+}$: -0.81 V*

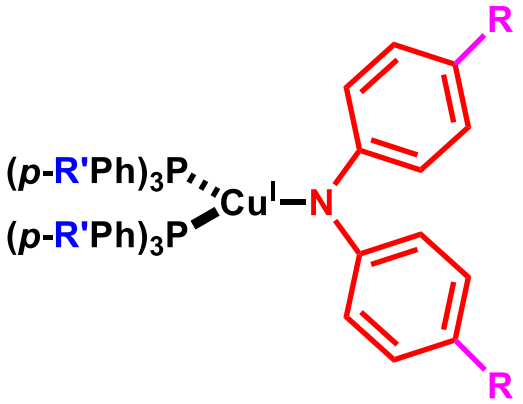
2. **short excited state lifetime**
(270 ns)
cf. $[Ru(bpy)_3]^{2+}$: 1100 ns

* vs SCE in MeCN

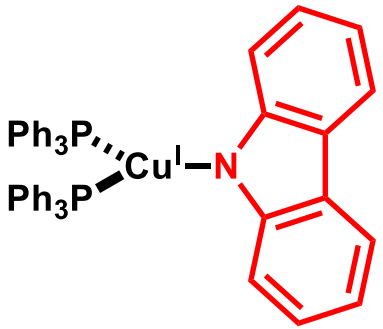


1) Sauvage, J-P. Kern, J-M. *J. Chem. Soc. Chem. Commun*. **1987**, 546. 2) Paria, S. and Reiser, O. *ChemCatChem* **2014**, *6*, 2477.
3) Lavie-Cambot, A.; Cantuel, M.; Leydet, Y.; Jonusauskas, G.; Bassani, D. M.; McClenaghan, N. D. *Coord. Chem. Rev*. **2008**, *252*, 2572.
4) Tsubomura, T.; Tsukuda, T.; Matsumoto, K. *Bull. Jpn. Soc. Coord. Chem*. **2008**, *52*, 29.

Cu(I)-arylamidophosphine complex



1 : R = Me, R' = H
2 : R = H, R' = Me
3 : R = H, R' = F



4

Table 1: Photophysical parameters of complex 1~4*

complex	λ_{em} (nm)[a]	ϕ[b]	τ (μs)[c]
1	546	0.22	3.17
2	509	0.13	2.5
3	535	0.11	2.71
4	461	0.24	11.7

*measured at room temperature in MeCy
[a]λ_{ex} = 390 nm, [b]ϕ= luminescence quantum yield
[c]τ (μs) = excited state lifetime

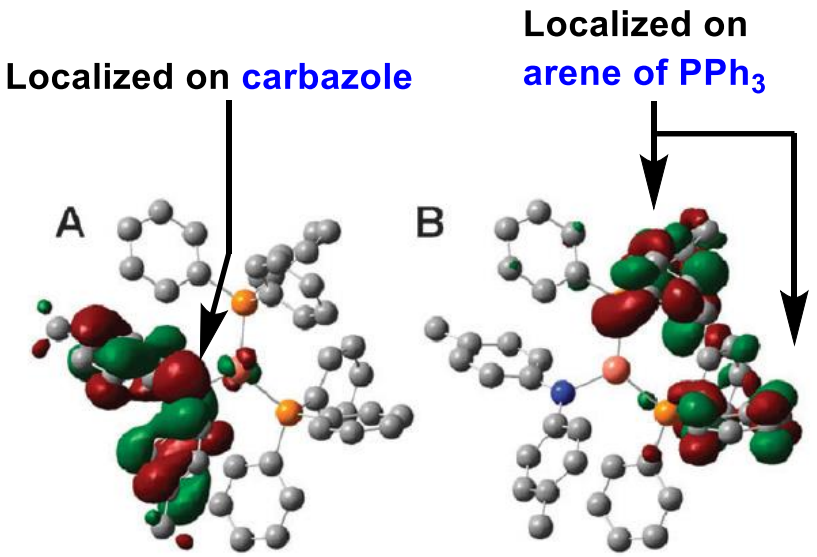
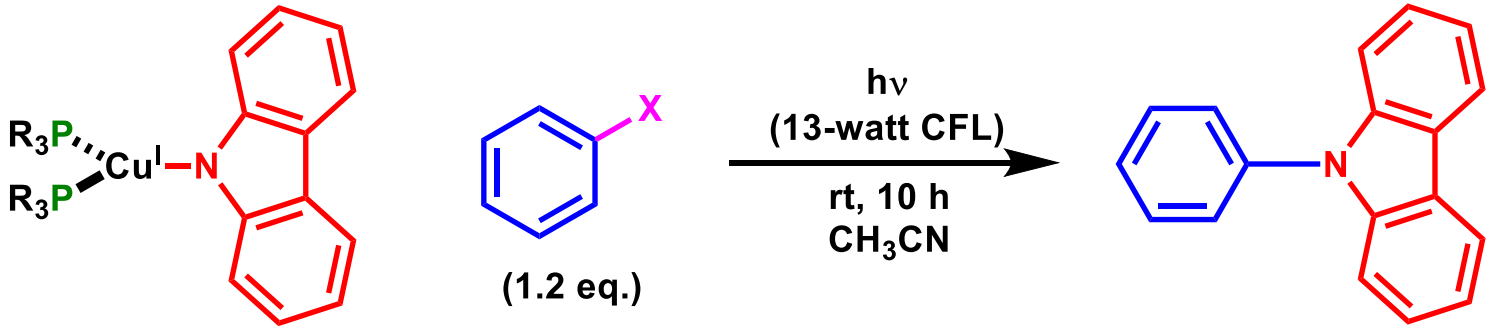


Fig 1. A) HOMO of 2 as calculated by DFT energy = -84.3 kcal/mol. B) LUMO of 2 as calculated by DFT energy = -23.4 kcal/mol

Lotino, K. J. and Peters, J. C. *Chem. Commun.* **2010**, *46*, 3690.
Miller, A. J. M.; Dempsey, J. L.; Peters, J. C. *Inorg. Chem.* **2007**, *46*, 7244.

Photoinduced Ullmann C-N coupling



R = *m*-tol

X = I
X = Br
X = Cl

77%
40%
5%

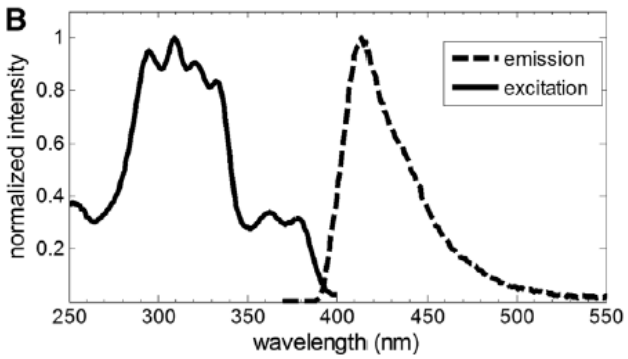
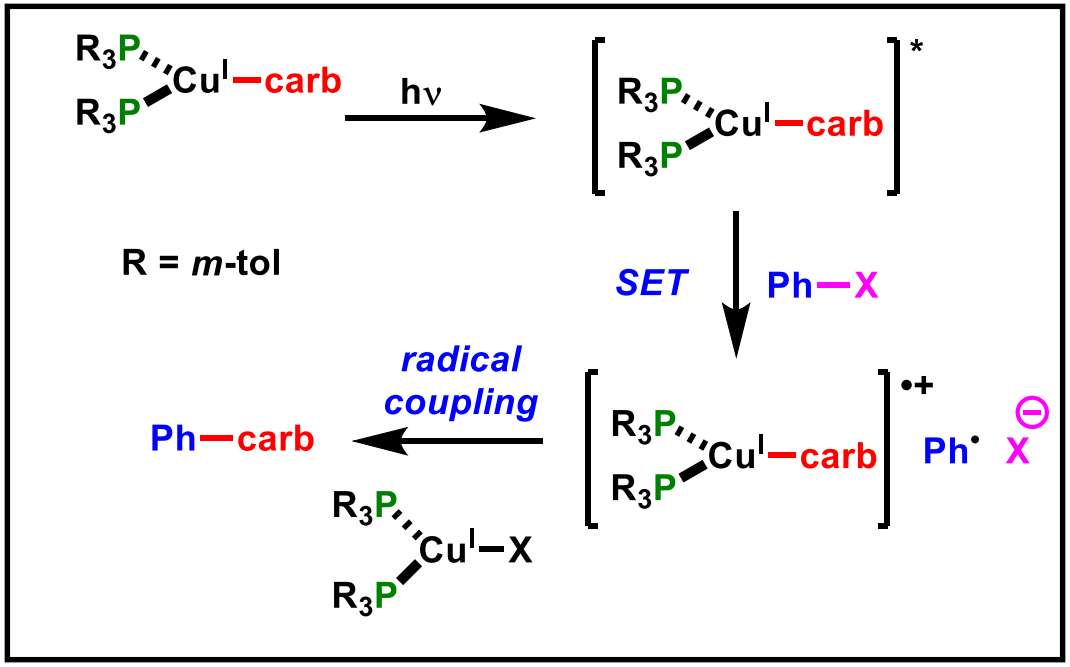


Fig 2. Emission and excitation spectra of $(PR_3)_2Cu$(carbazolide) (in CH_3CN, R = *m*-tol)



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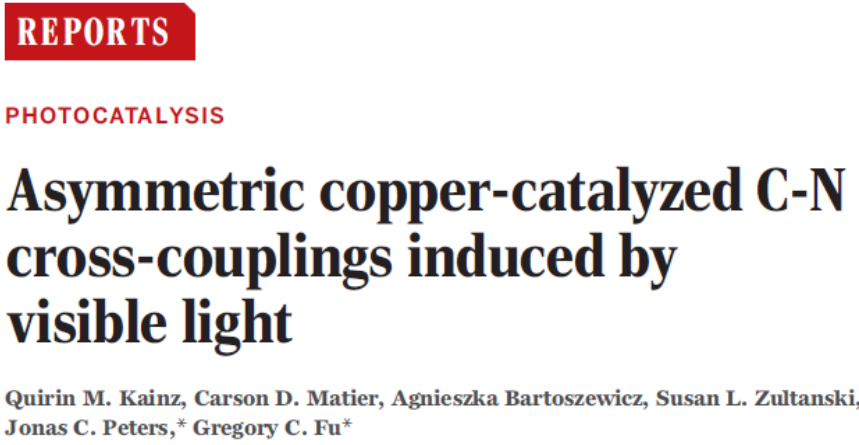
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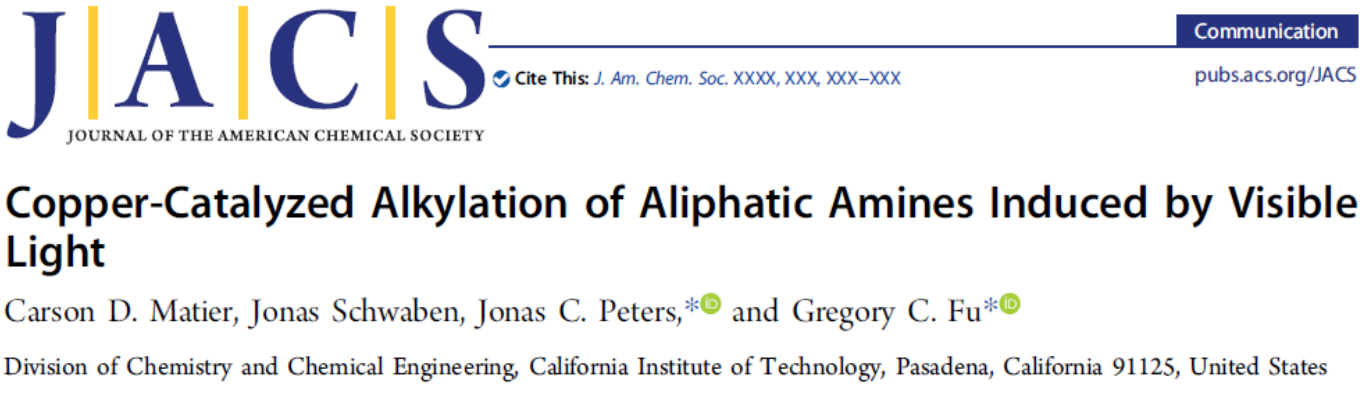
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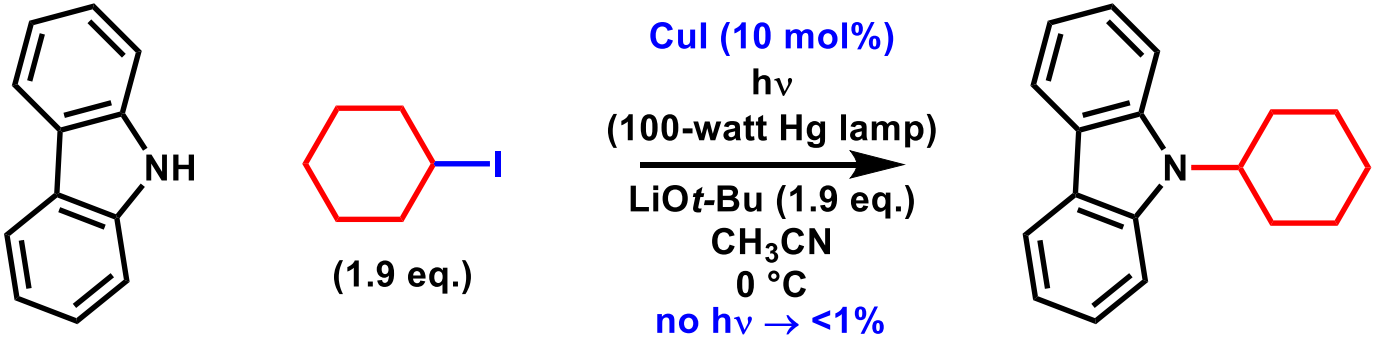
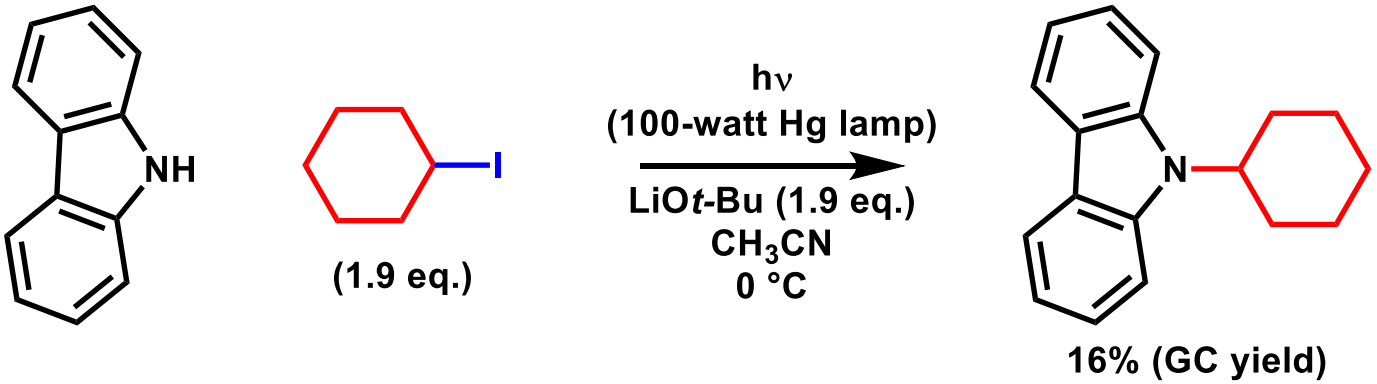
Carson D. Matier, Jonas Schwaben, Jonas C. Peters,* and Gregory C. Fu*

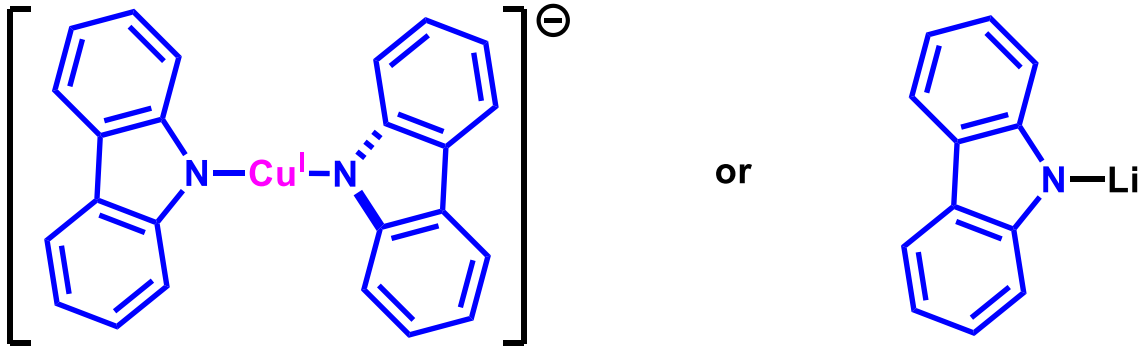
Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, California 91125, United States

Cu-catalyzed alkylation of carbazole

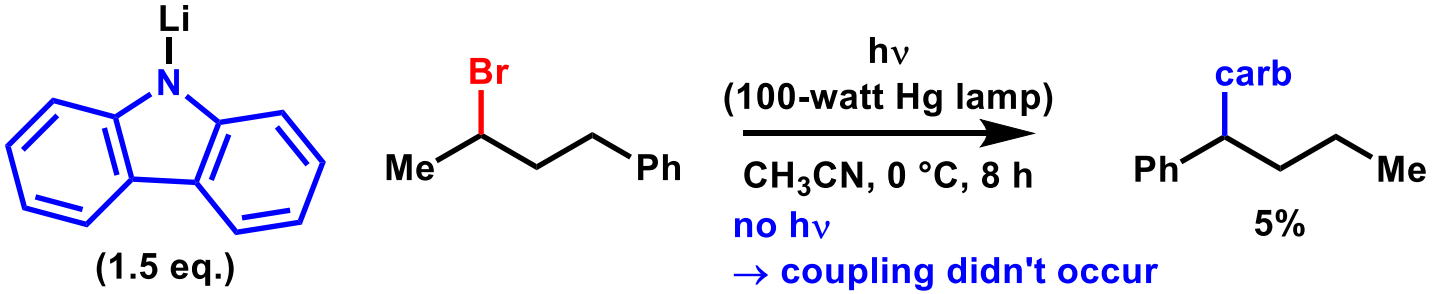




Candidate of photoreductant



Mechanistic study (1)



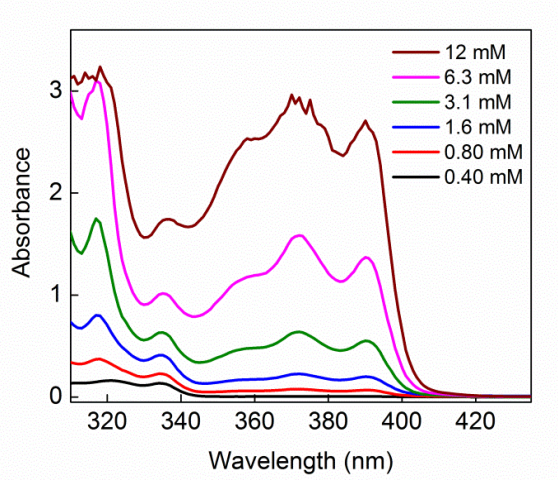


Fig 3. UV-vis spectra of Li(carb)
absorbance at 365 nm depends on concentration
(over 0.4 mM, ε = 2200 M^{-1} cm^{-1})

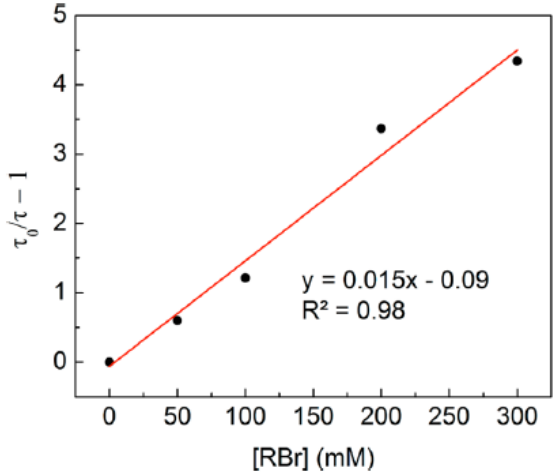
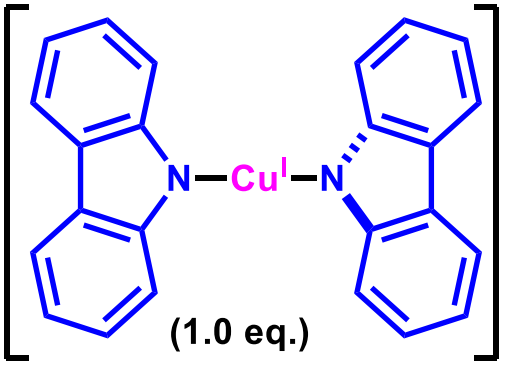


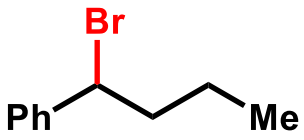
Fig 4. Stern-Volmer Plot of [Li(carb)]*
K_{sv} = 0.015 mM^{-1}
rate const. = 4.9 x 10^8 M^{-1} s^{-1}

Mechanistic study (2)



(1.0 eq.)

[Cu(carb)$_2$]Li

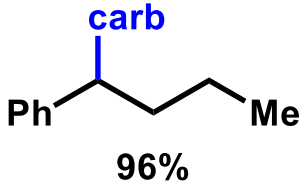


hν
(100-watt Hg lamp)

CH_3CN, 0 °C, 8 h

no hν

→ coupling didn't occur



96%

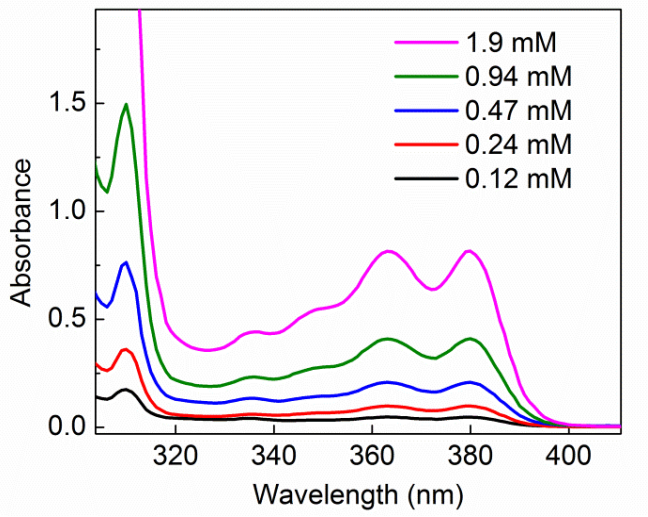


Fig 5. UV-vis spectra of [Cu(carb)$_2$]Li

absorption at 365 nm with ε = 4300 M^{-1} cm^{-1}

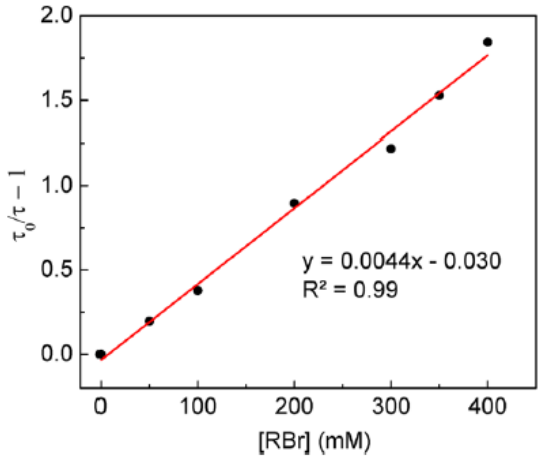


Fig 6. Stern-Volmer plot of [Cu(carb)$_2$]Li*

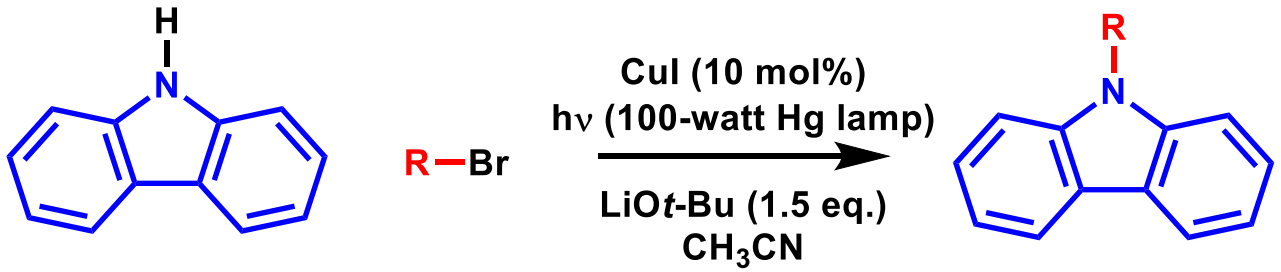
K_{sv} : 0.0044 mM^{-1}

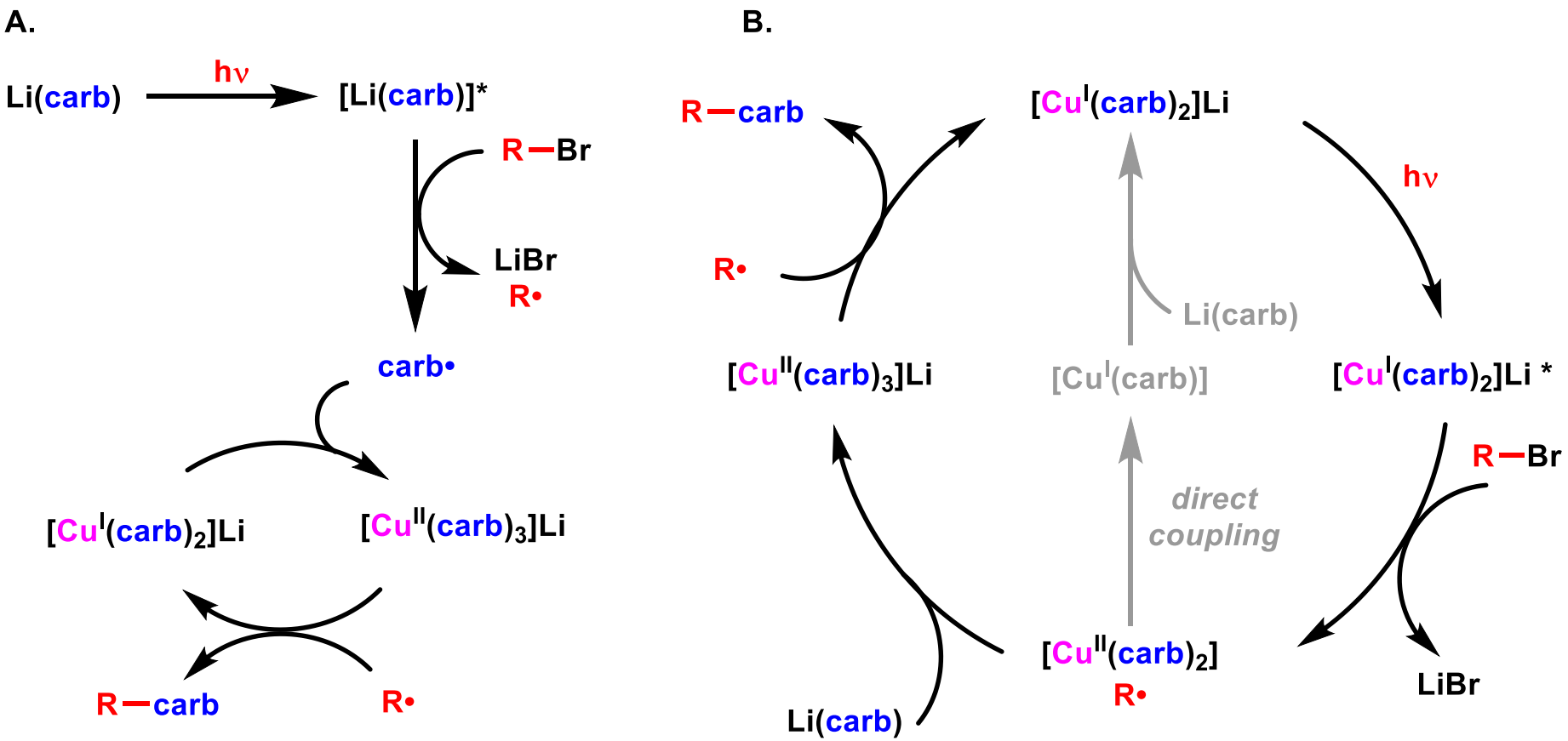
rate const. : k = 4.8 x 10^6 M^{-1} s^{-1}

[Li(carb)]* may be the primary photoreductant.

Ahn, J. M.; Ratani, T. S.; Hannoun, K. I.; Fu, G. C.; Peters, J. C. *J. Am. Chem. Soc.* **2017**, *139*, 12716.

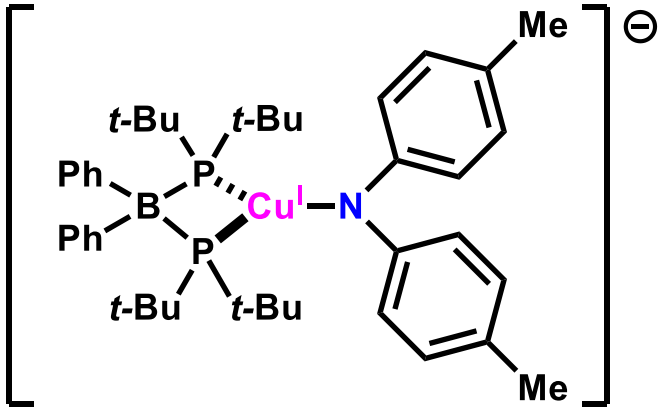
Proposed reaction mechanism by author





Ahn, J. M.; Ratani, T. S.; Hannoun, K. I.; Fu, G. C.; Peters, J. C. *J. Am. Chem. Soc.* **2017**, *139*, 12716.
Johnson, M. W.; Hannoun, K. I.; Tan, Y.; Fu, G. C.; Peters, J. C. *Chem. Sci.* **2016**, *7*, 4091.

Character of $[Cu^{II}(carb)_3]Li$ species



Spin density

Cu : 13%

N : 49% (0.49e$^-$)

(*p*-tol)$_2$: 20%

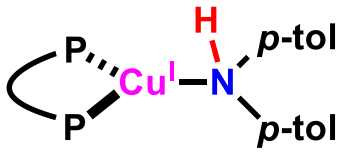
P*t*-Bu$_2$: 15%

BPh$_2$: 2%

n-Bu$_3$SnH

KIE

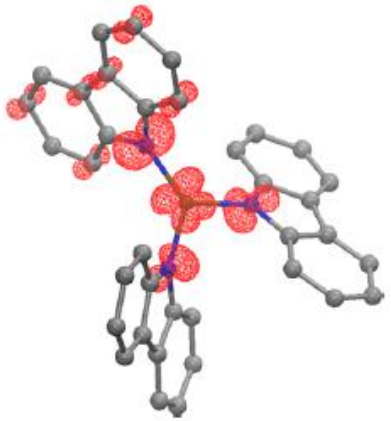
k_H/k_D = 4.8



+ *n*Bu$_3$Sn—Sn*n*Bu$_3$

Character of $[Cu^{II}(carb)_3][K(THF)_6]$ species

(b)



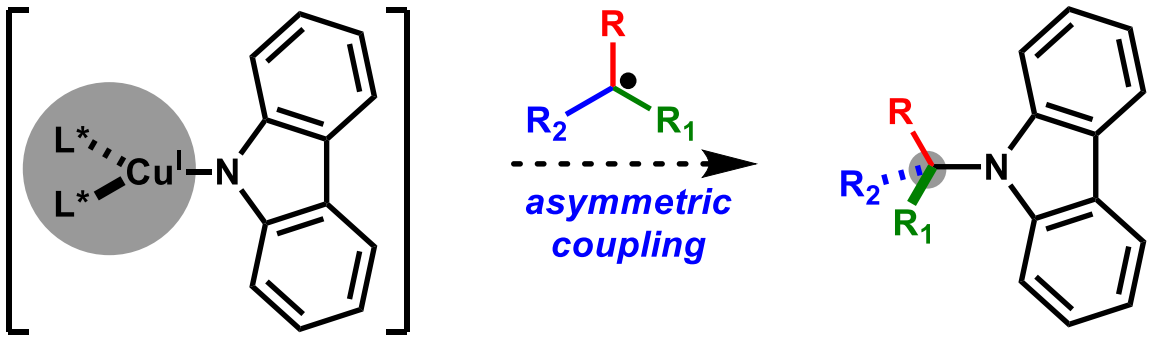
Cu : 43% (0.43e$^-$)

N : 27% (0.27e$^-$)

Fig 7. Spin-density plot of $[Cu^{II}(carb)_3]^-$ (counter cation was omitted)

Direct coupling of radical and carbazyl ligand

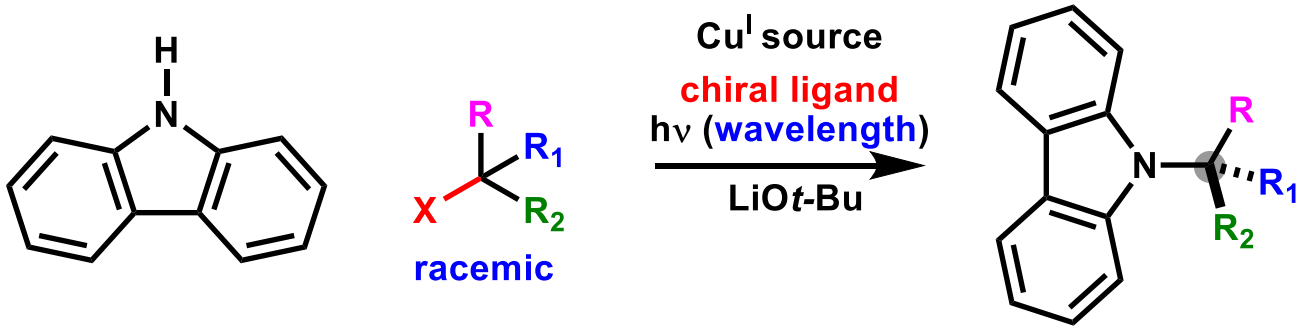
To achieve asymmetric coupling of carbazole and alkyl halide,,,



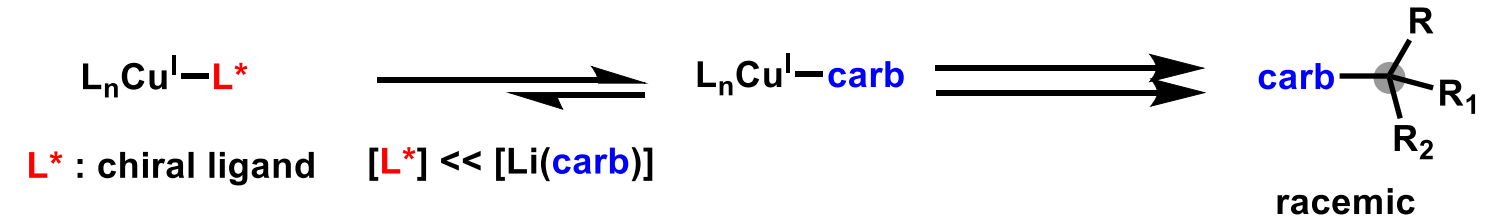
Mankad, N. P.; Autholine, W. E.; Szilagyi, R. K.; Peters, J. C. *J. Am. Chem. Soc.* **2009**, *131*, 3878.

Ahn, J. M.; Ratani, T. S.; Hannoun, K. I.; Fu, G. C.; Peters, J. C. *J. Am. Chem. Soc.* **2017**, *139*, 12716.

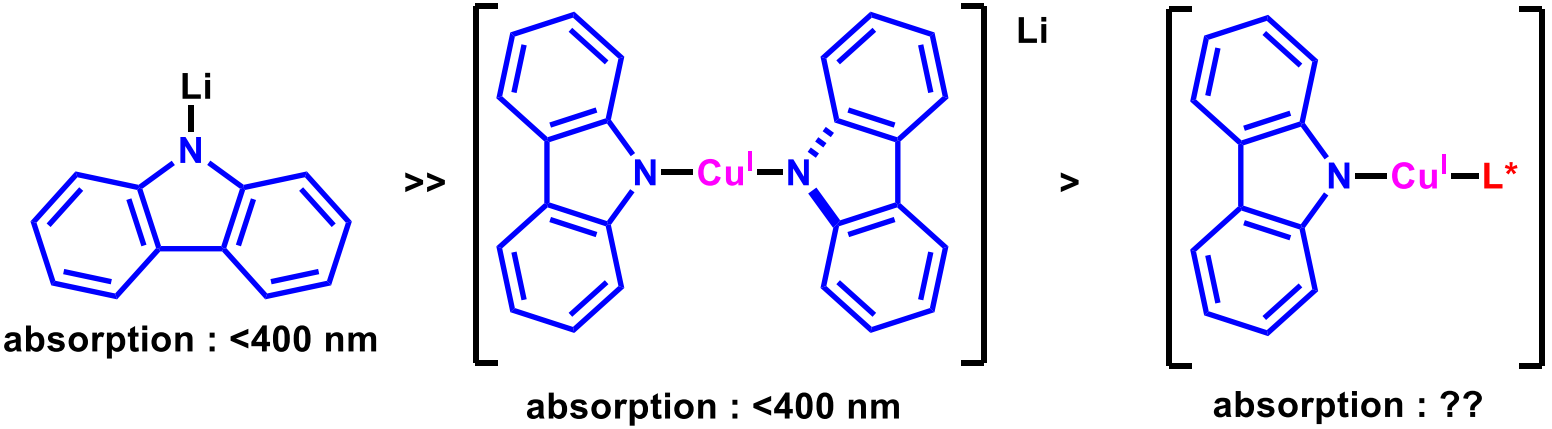
Difficulty of asymmetric C-N cross coupling



- chiral ligand vs carbazole

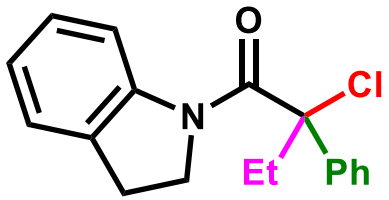


- limitation of wavelength

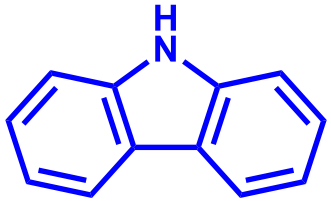


1. Bulky chiral ligand
2. Tuning of photoreductant of alkyl halide (absorption : over 400 nm)

Asymmetric C-N cross coupling reaction



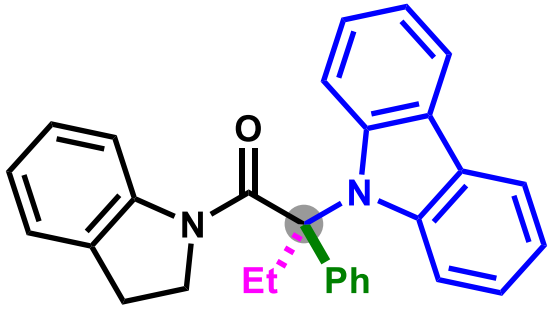
racemic
(1.2 eq.)



CuCl (1.0 mol%)
(*S*)-L* (1.2 mol%)
hν (blue LED)

LiO*t*-Bu (1.5 eq.)
toluene, -40 °C, 16 h

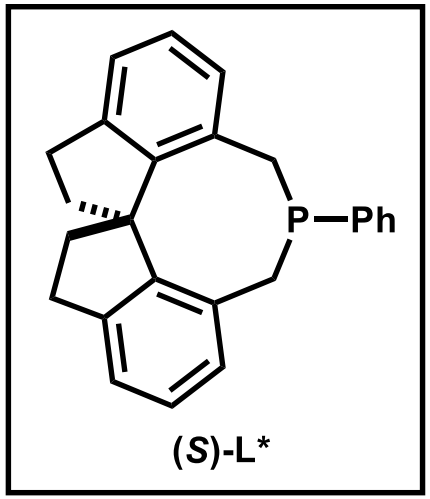
"standard conditions"



95%, 95% *ee*

Table 2. Effect of changes in reaction parameters

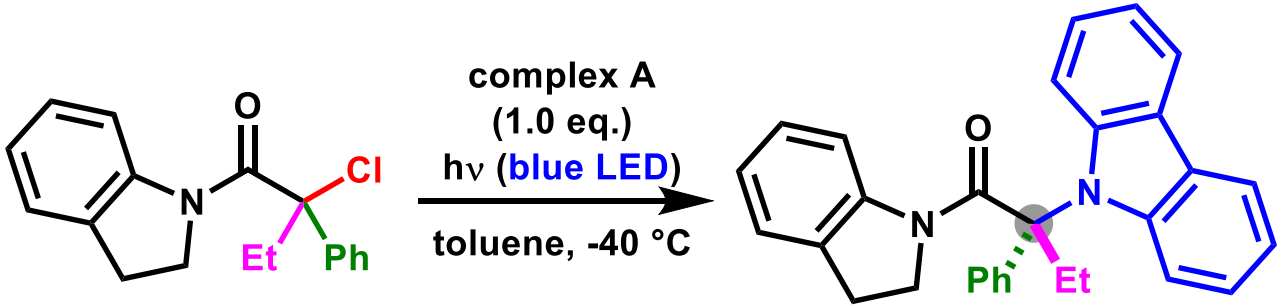
entry	change from standard conditions	result
1	none	95% (95% ee)
2	no CuCl	<1%
3	no hν	<1%
4	no (*S*)-L*	3% (racemic)

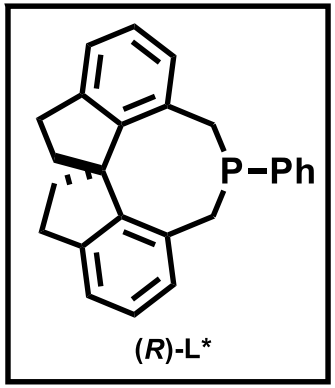


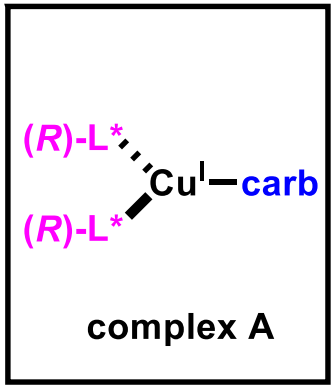
(*S*)-L*

entry 2 → [Li(carb)] was not excited. **entry 4 → Cu complex including chiral ligand was excited.**

Plausible intermediate







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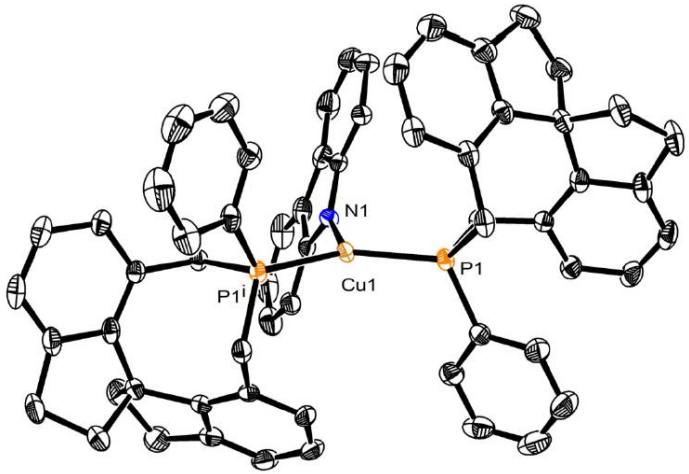
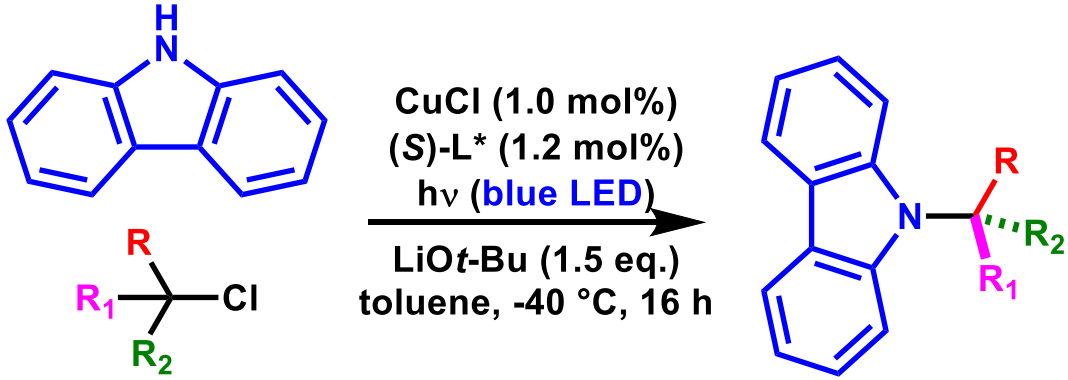
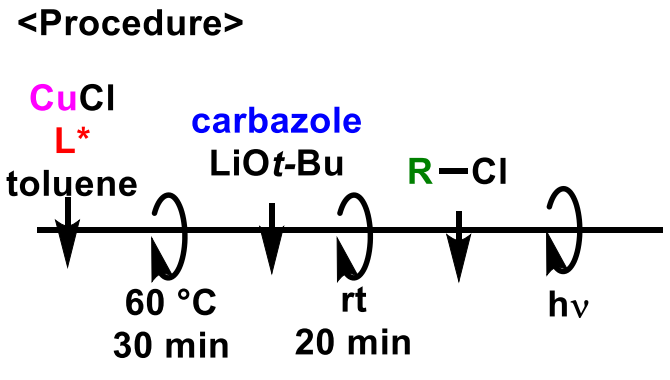


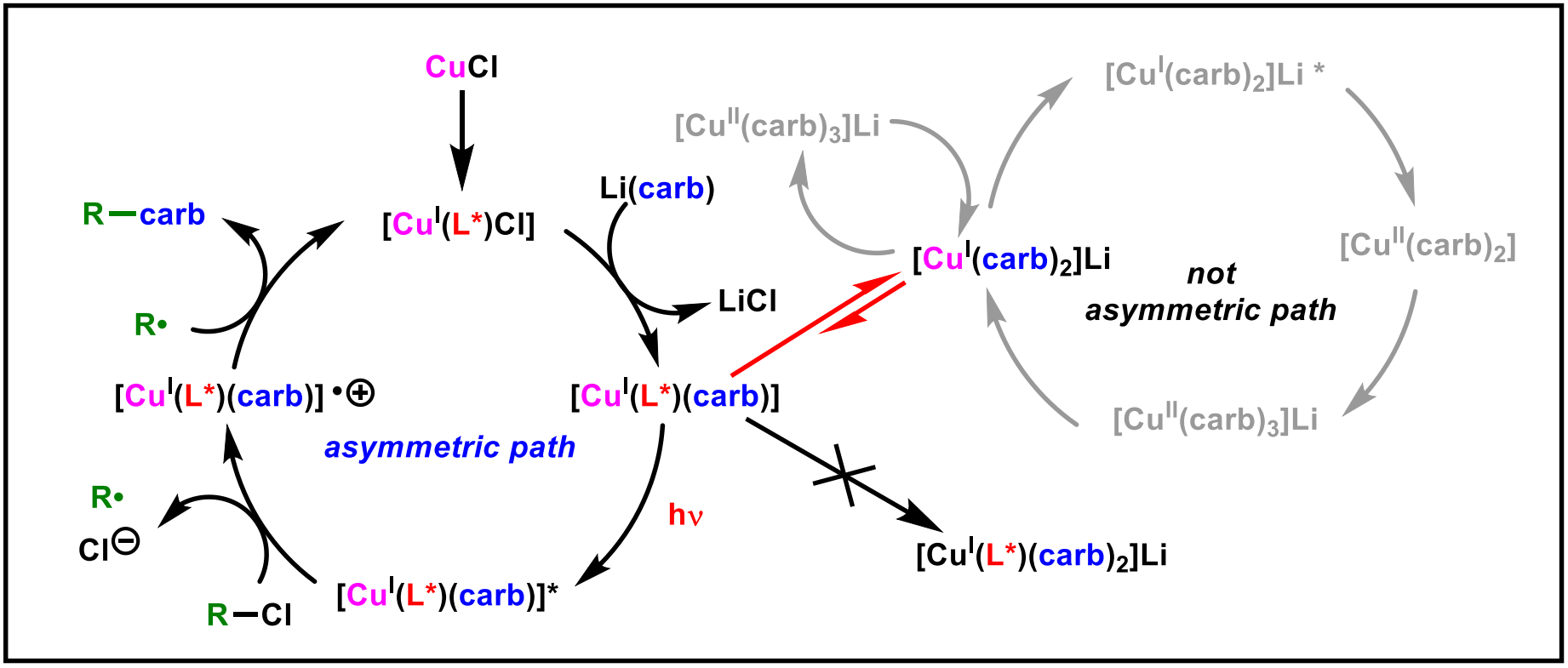
Complex A or [Cu^{I}(L*)(carb)] was plausible intermediate of this reaction.

Kainz, K. M.; Matier, C. D.; Bartoszewicz, A.; Zultanski, S. L.; Peters, J. C.; Fu, G. C. *Science* **2016**, *351*, 681.

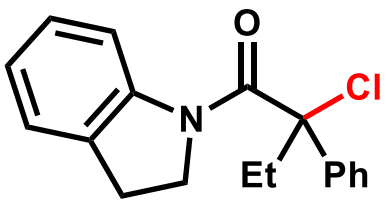
Proposed catalytic cycle (my proposal)



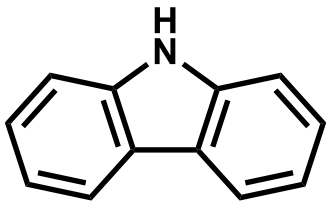




Subsrate scope of nucleophile

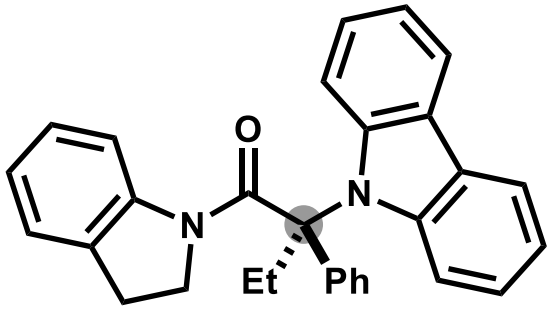


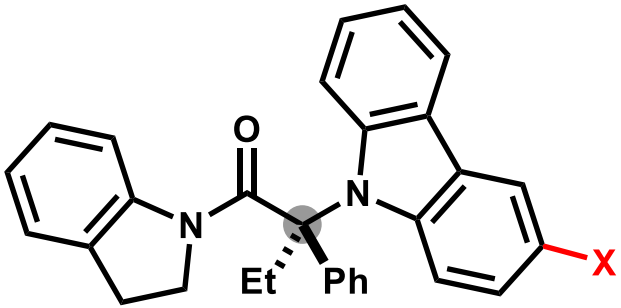
racemic
(1.2 eq.)



CuCl (1.0-5.0 mol%)
(*S*)-L* (1.2-6.0 mol%)
hν (blue LED)

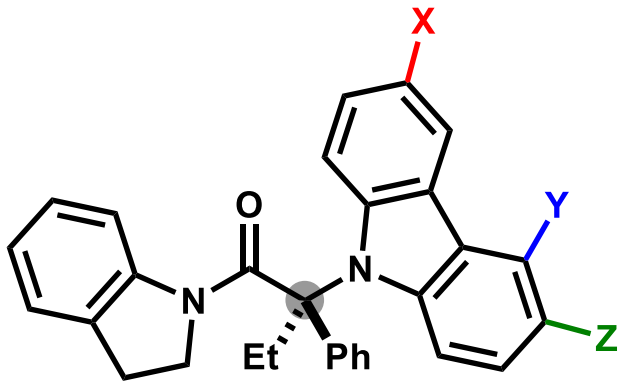
LiO*t*-Bu (1.5 eq.)
toluene, -40 °C





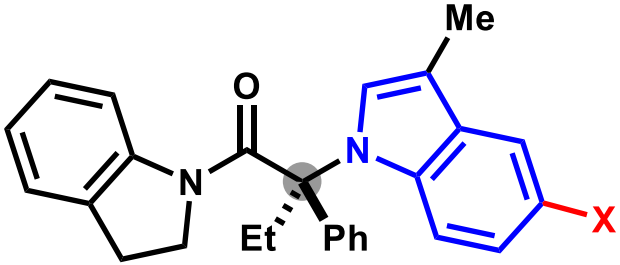
X = OMe (92%, 89% *ee*)

X = Br (82%, 92% *ee*)



X = Ph, Y = H, Z = Ph (98%, 90% *ee*)

X = H, Y = OMe, Z = H (87%, 92% *ee*)



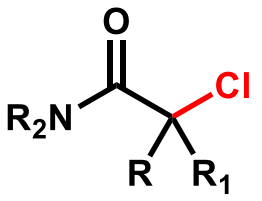
X = H (79%, 92% ee)

X = OMe (86%, 88% ee)

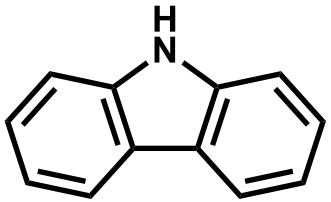
X = F (98%, 94% ee)

Kainz, K. M.; Matier, C. D.; Bartoszewicz, A.; Zultanski, S. L.; Peters, J. C.; Fu, G. C. *Science* **2016**, *351*, 681.

Subsrate scope of electrophile

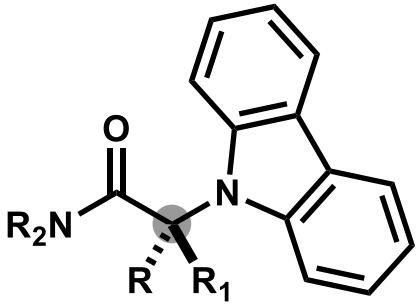


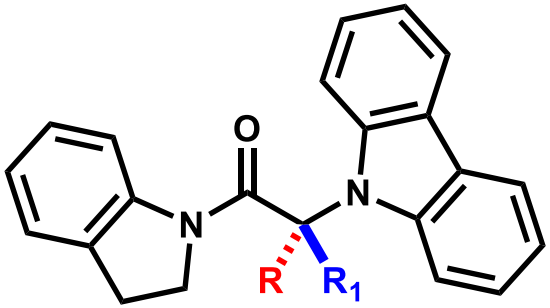
racemic
(1.2 eq.)



CuCl (1.0-5.0 mol%)
(*S*)-L* (1.2-6.0 mol%)
hν (blue LED)

LiO*t*-Bu (1.5 eq.)
toluene, -40 °C

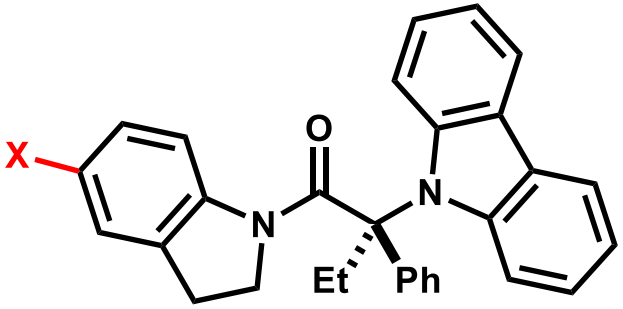




R = *i*-Bu, R_1 = Ph (82%, 92% ee)

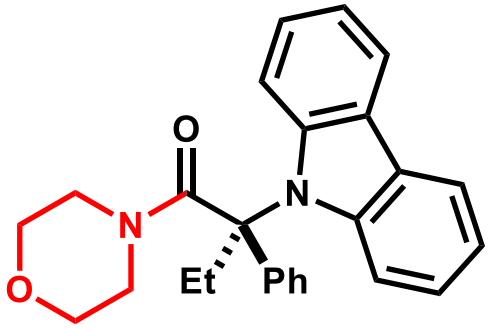
R = *i*-Bu, R_1 = Me (90%, 87% ee)

R = cyclopentyl, R_1 = Me (84%, 98% ee)

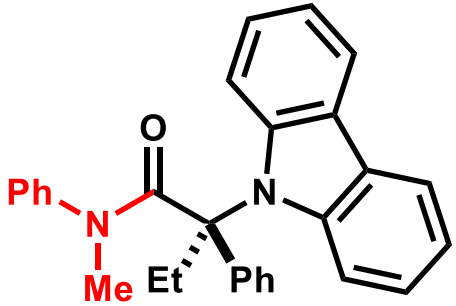


X = OMe (92%, 92% ee)

X = Cl (90%, 96% ee)



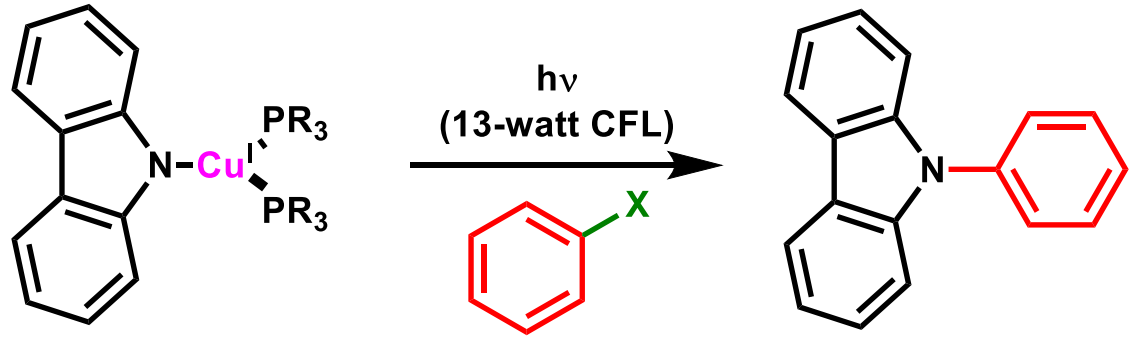
79%, 94% ee

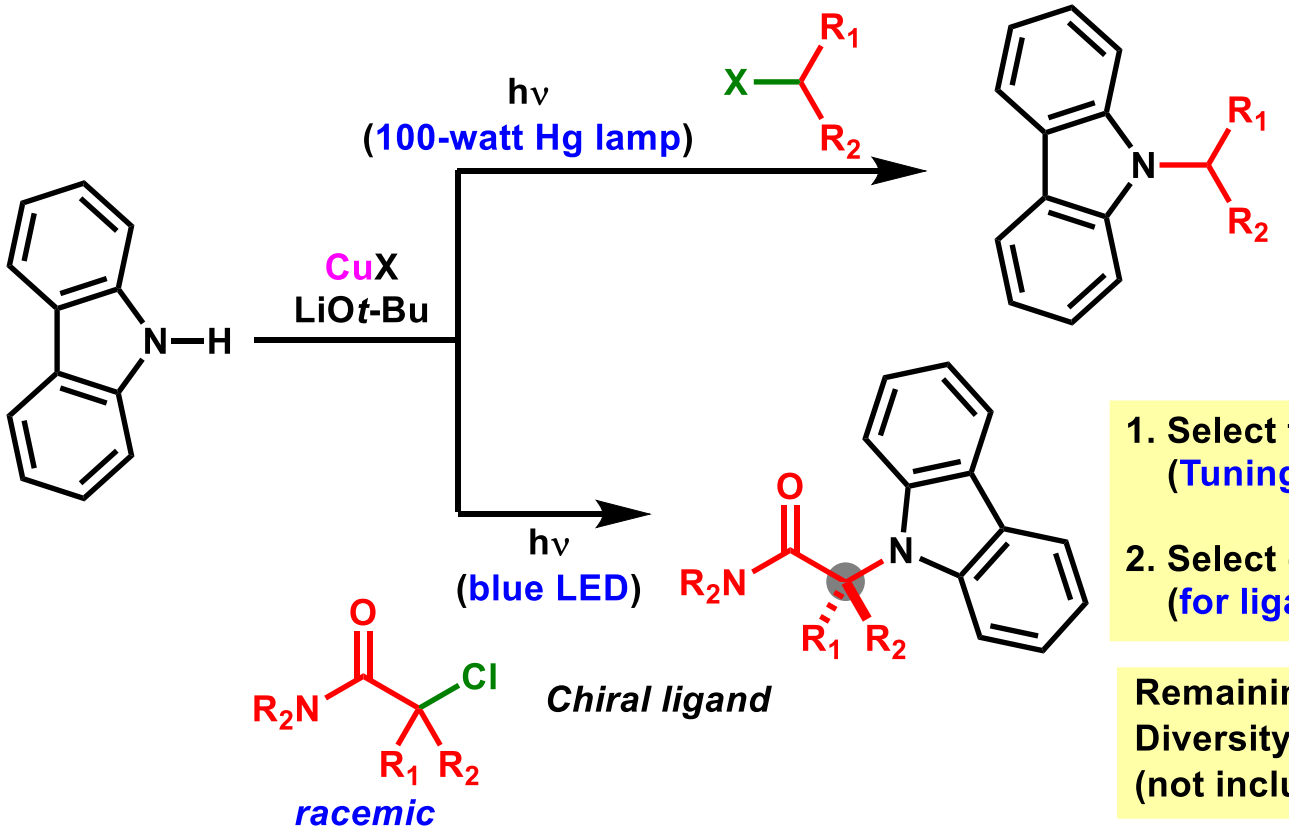


74%, 90% ee

Kainz, K. M.; Matier, C. D.; Bartoszewicz, A.; Zultanski, S. L.; Peters, J. C.; Fu, G. C. *Science* **2016**, *351*, 681.

Short summary and key to success





1. Select the chiral ligand, wavelength (Tuning of photoreductant)

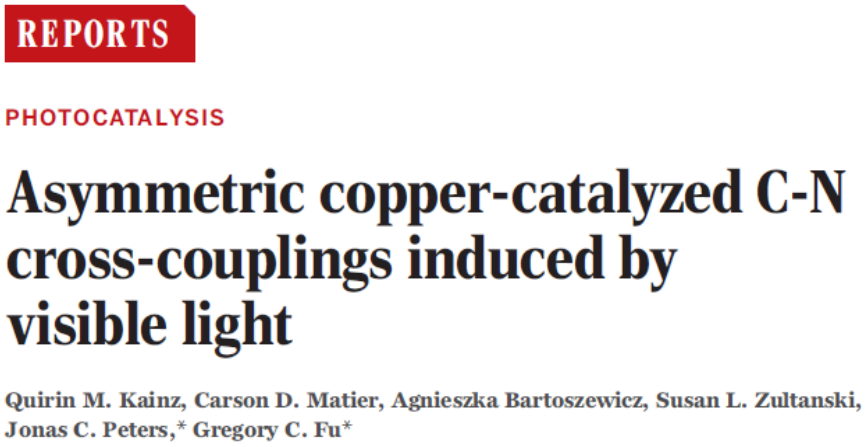
2. Select carbazole as amine source (for ligand exchange and excitaion)

Remaining tasks:
Diversity of amine unit
(not including π system)

Contents

1. Introduction

2. Asymmetric cross coupling of carbazoles induced by visible light (Fu, 2016)



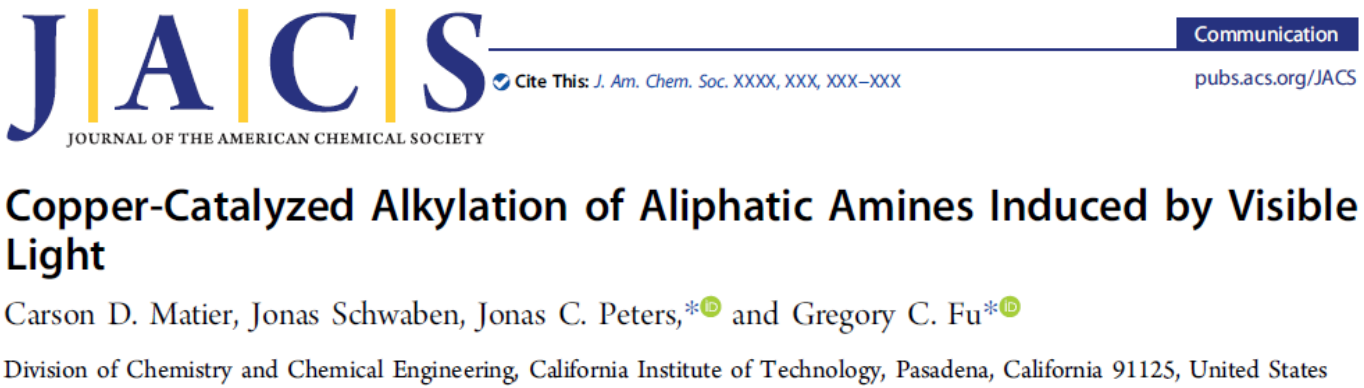
REPORTS

PHOTOCATALYSIS

Asymmetric copper-catalyzed C-N cross-couplings induced by visible light

Quirin M. Kainz, Carson D. Matier, Agnieszka Bartoszewicz, Susan L. Zultanski, Jonas C. Peters,* Gregory C. Fu*

3. Alkylation of aliphatic amine induced by visible light (Fu, 2017)



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Communication

Cite This: *J. Am. Chem. Soc.* XXXX, XXX, XXX–XXX

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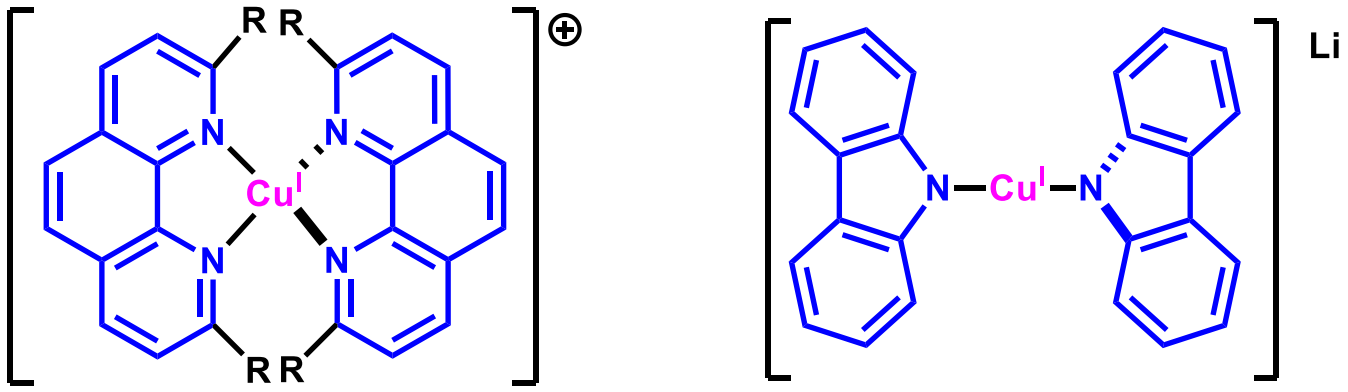
Copper-Catalyzed Alkylation of Aliphatic Amines Induced by Visible Light

Carson D. Matier, Jonas Schwaben, Jonas C. Peters,* and Gregory C. Fu*

Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, California 91125, United States

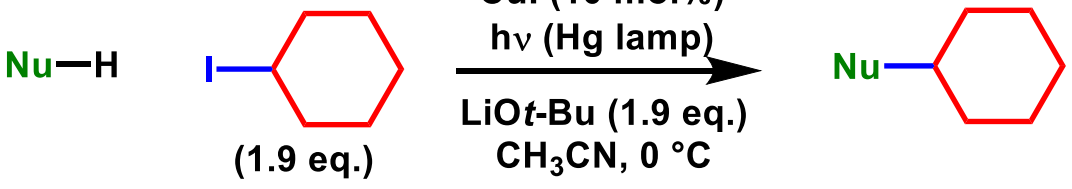
Difficulty of coupling with aliphataic amine

- Excitation of Cu(I) complex

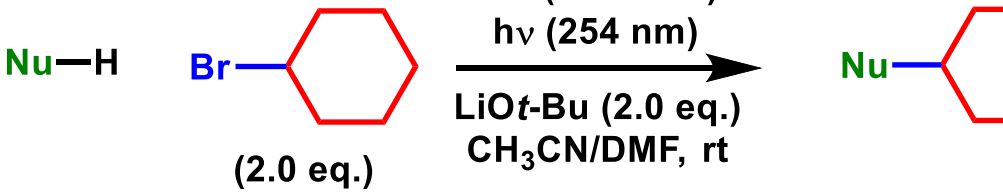


MLCT

Cu d orbital to arene π*



Nu-H	yield (%)
carbazole	76%
Ph NH$_2$	<1%

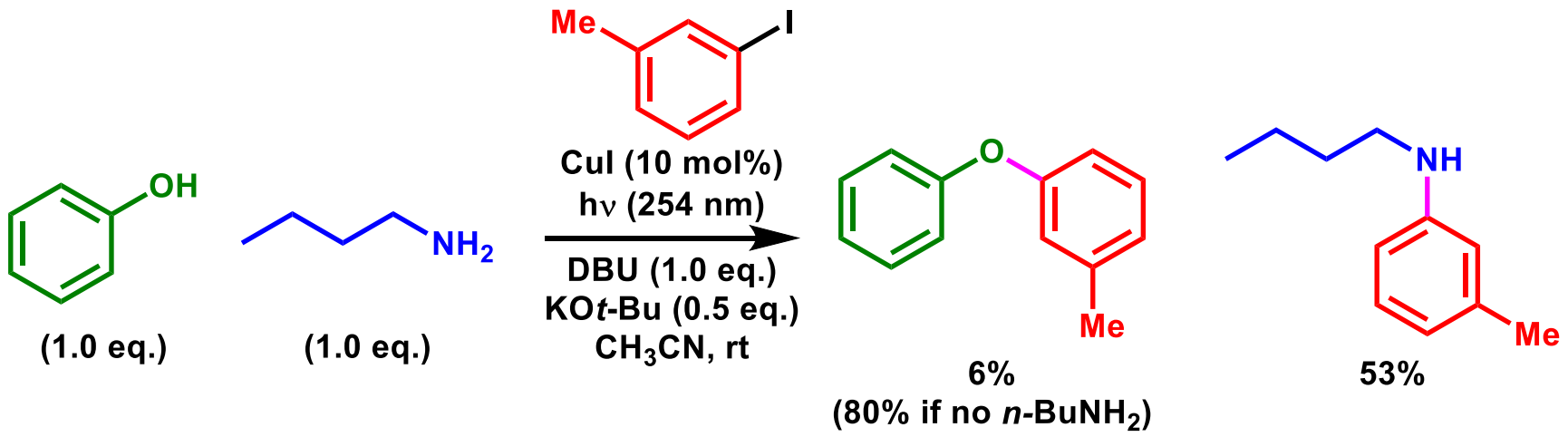


Nu-H	yield (%)
CyCONH$_2$	90%
Ph NH$_2$	<1%

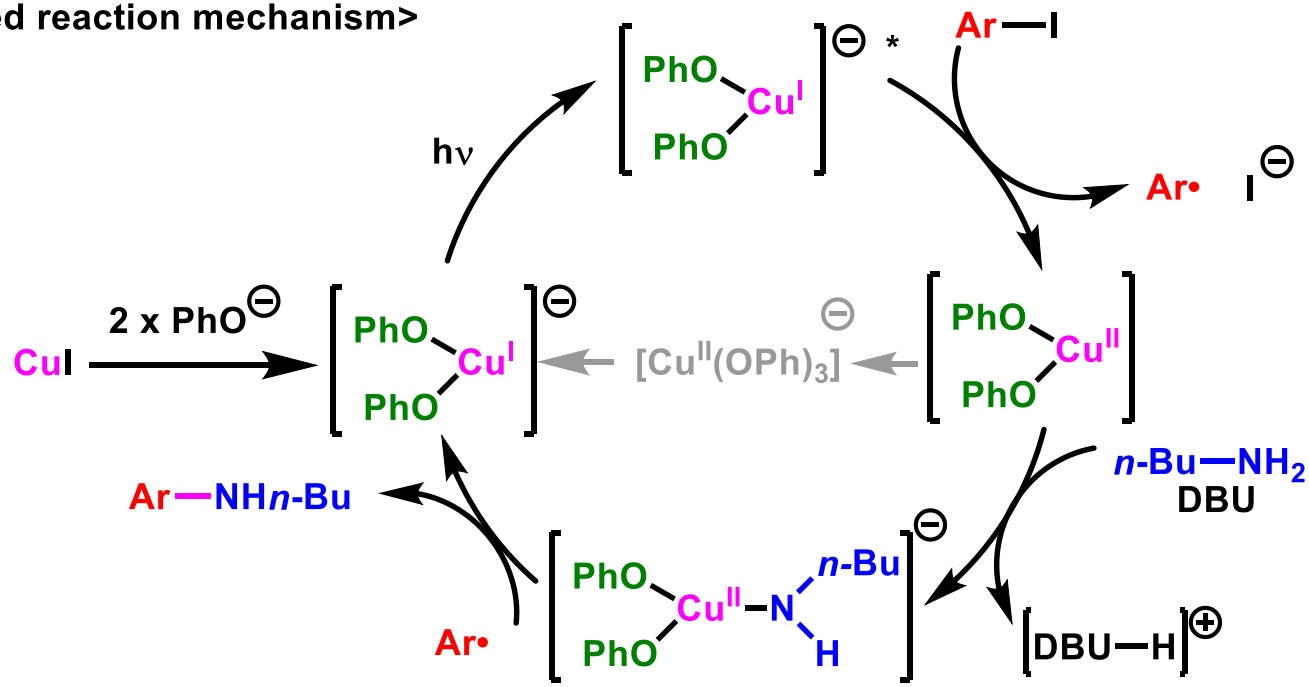
Lotino, K. J. and Peters, J. C. *Chem. Commun*. **2010**, *46*, 3690.

Matier, C. D.; Schwaben, J.; Peters, J. C.; Fu, G. C. *J. Am. Chem. Soc*. **2017**, *139*, 17707.

Previous study about O-arylation of phenol

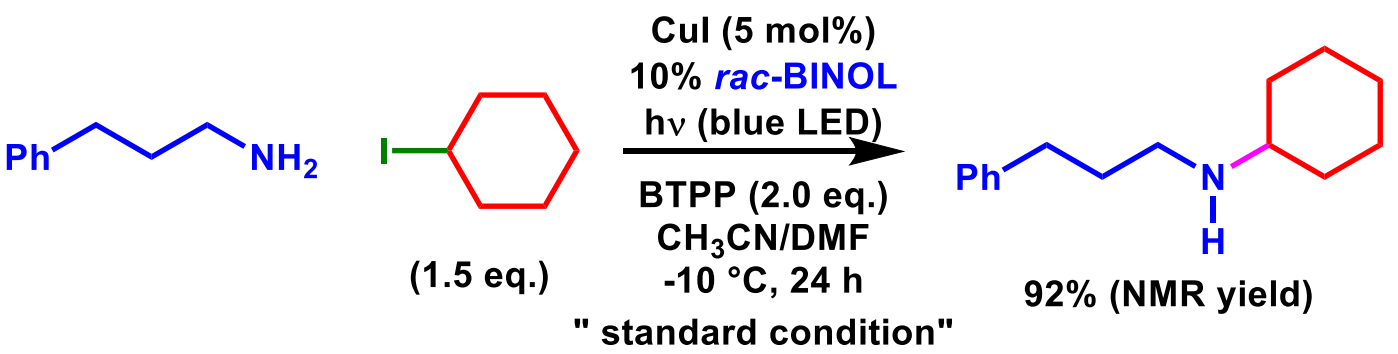


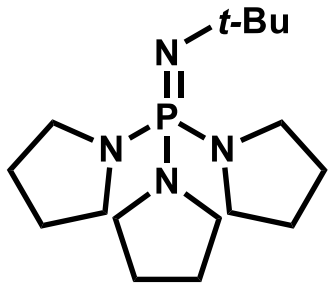
<Proposed reaction mechanism>



Matier, C. D.; Schwaben, J.; Peters, J. C.; Fu, G. C. *J. Am. Chem. Soc.* **2017**, *139*, 17707.
Tan, Y.; Munoz-Molina, J. M.; Fu, G. C.; Peters, J. C. *Chem. Sci.* **2014**, *5*, 2831.

Coupling reaction with aliphatic amine



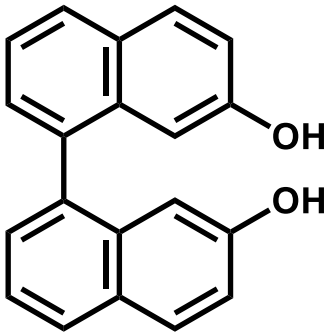


BTPP

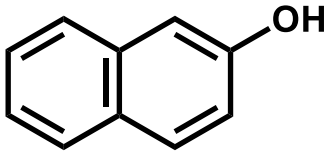
(pK_{aH+} = 28.4 in MeCN)

Table 3: Effect of reaction parameters

entry	Change from standard conditions	NMR yield (%)
1	no CuI or no *rac*-BINOL or no hν or no BTPP	<1
2	$Cu(OTf)_2$ instead of CuI	82
3	*rac*-BINOL dimethyl ether instead of *rac*-BINOL	<1
4	2-naphthol instead of *rac*-BINOL	14
5	LiO*t*-Bu instead of BTPP	14
6	CyBr or CyCl or CyOTs	<1



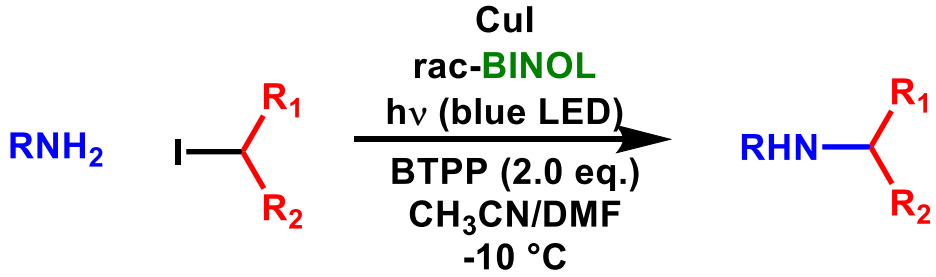
BINOL

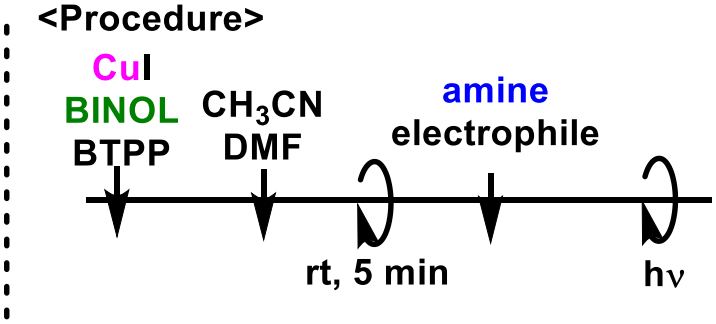


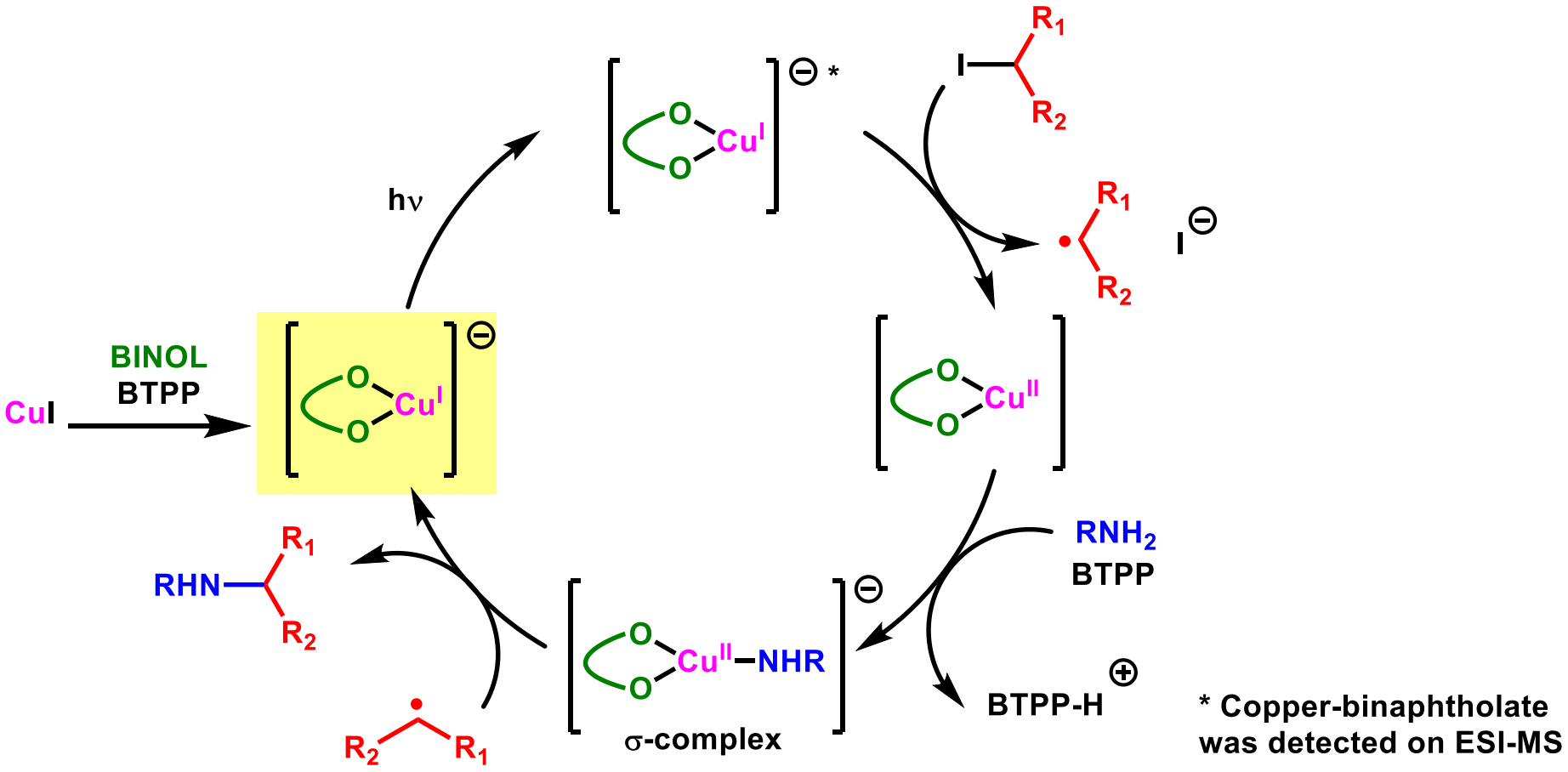
2-naphthol

Matier, C. D.; Schwaben, J.; Peters, J. C.; Fu, G. C. *J. Am. Chem. Soc.* **2017**, *139*, 17707.

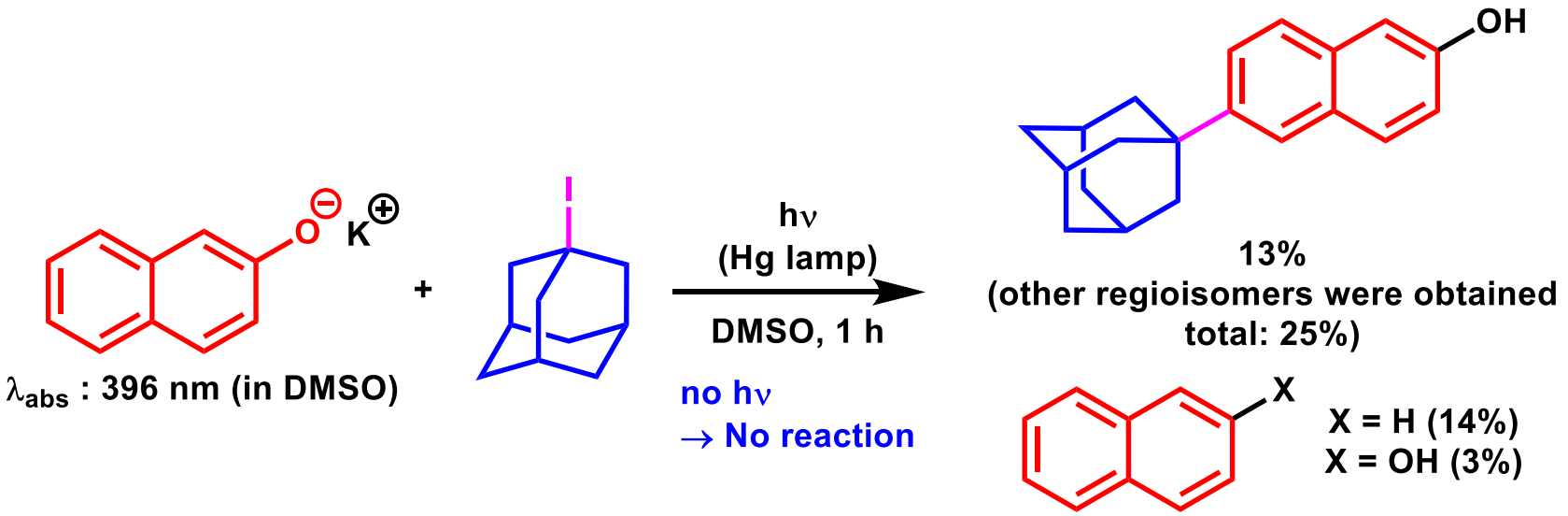
Possible reaction mechanism (1) (my proposal)





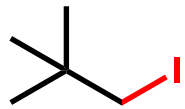
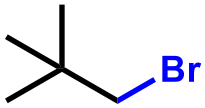


Possibility of BINOL anion as photoreductant



λ_{abs} : 396 nm (in DMSO)

Table 3: Fluorescent quenching of 2-naphthoxide anion

entry	Alkyl halide	E(V) vs SCE	LUMO (eV)**	K_{sv}	k_q ($M^{-1}s^{-1}$)
1		-2.16	0.5279	106.8±1.5	6.0×10^9
2		-2.75	0.896	0.61±0.03	3.4×10^7

* AM1 method was used.

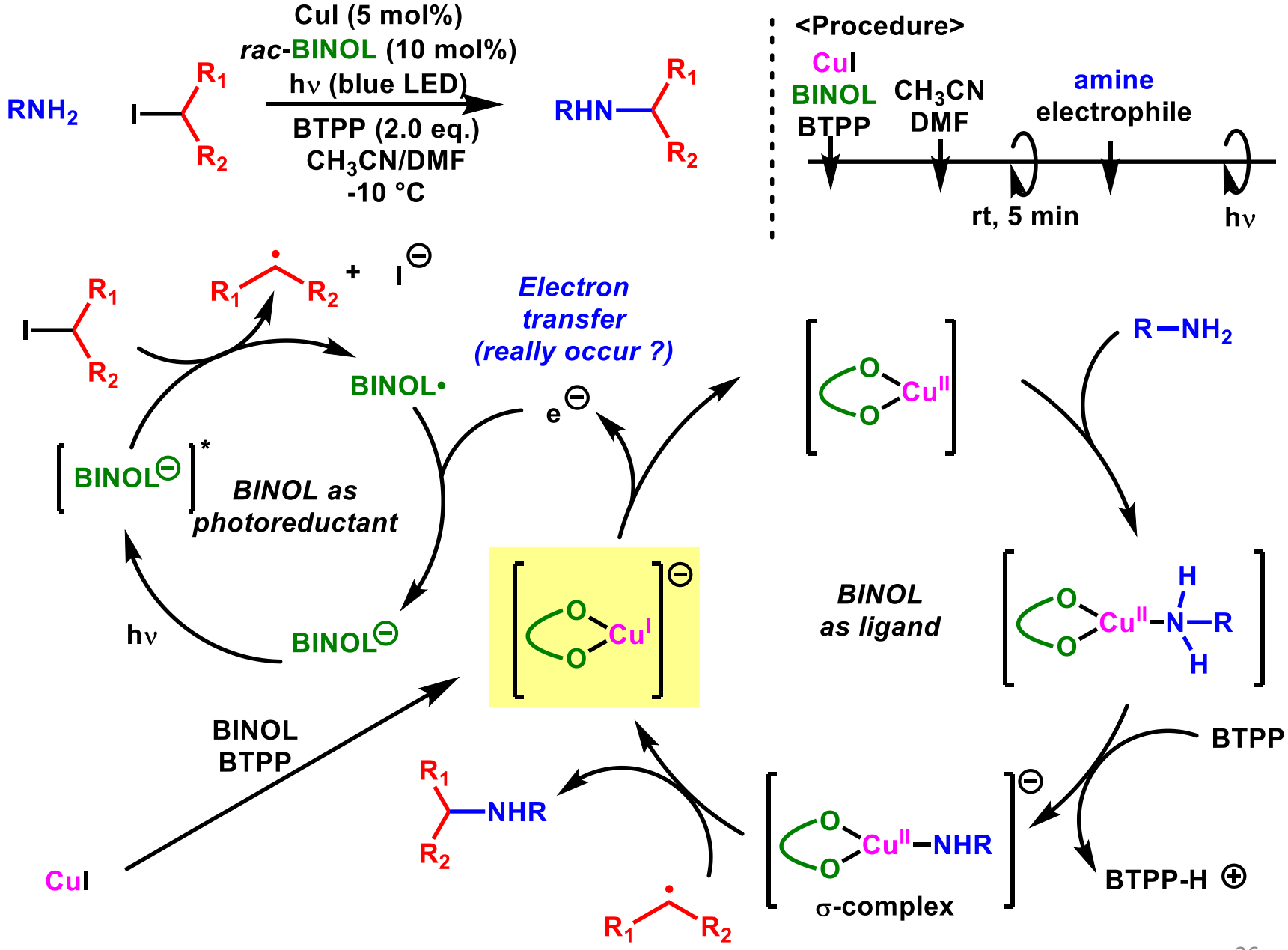
k_q : quenching rate const.

$$k_q = \frac{K_{sv}}{\tau_0}$$

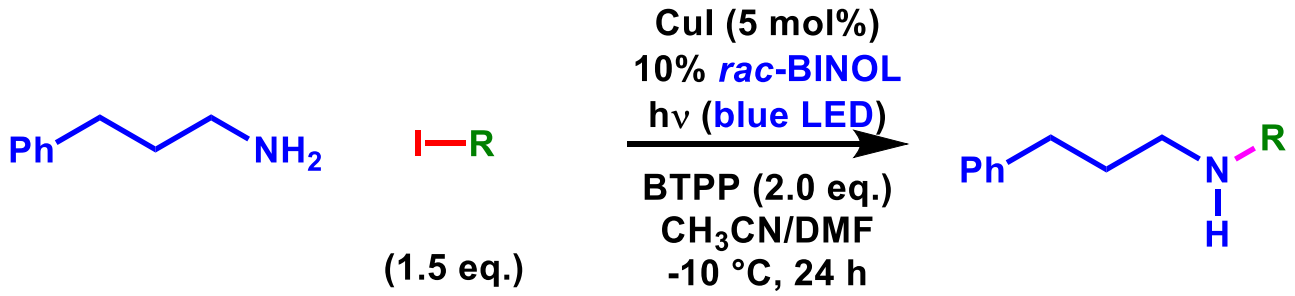
τ_0: lifetime of excited singlet of 2-naphthoxide anion (without alkyl halide)

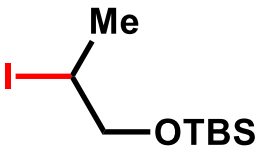
1) Arguëllo, J. E. and Penenory, A. B. *J. Org. Chem*. **2003**, *68*, 2362. 2) Legros, B.; Vandereecken, P.; Soumillion, J. Ph. *J. Phys. Chem*. **1991**, *95*, 4752. Soumillion, J. Ph.; Vandereecken, P.; Van Der Auweraer, M.; De Schryver, F. C.; Schanck, A. *J. Am. Chem. Soc*. **1989**, *111*, 2217.

Possible reaction mechanism (2) (my proposal)

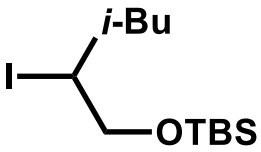


Substrate scope of electrophile

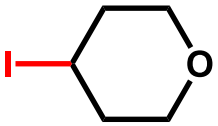




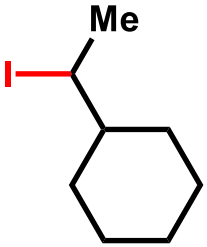
74%



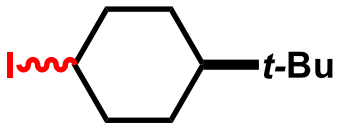
34%



82%



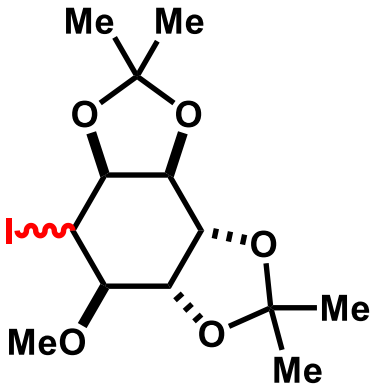
41%



cis/trans = 5 : 1

54%

(trans/cis > 20/1)

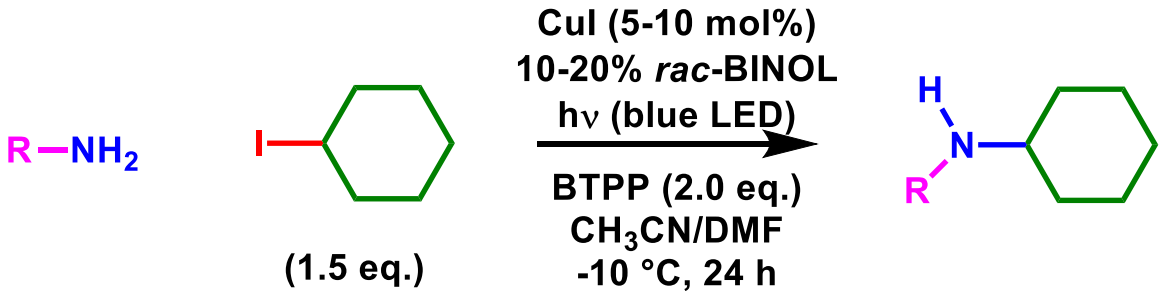


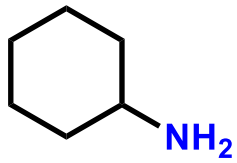
β/α > 20/1

61%

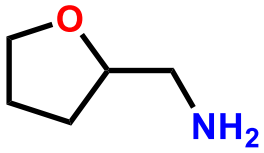
(α/β > 20/1)

Substrate scope of aliphatic amine

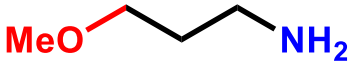




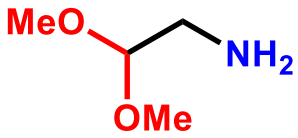
71%



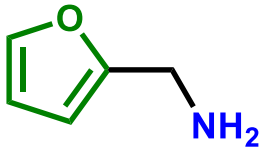
60%



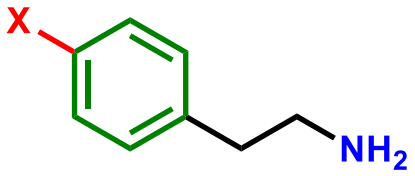
84%*



75%*



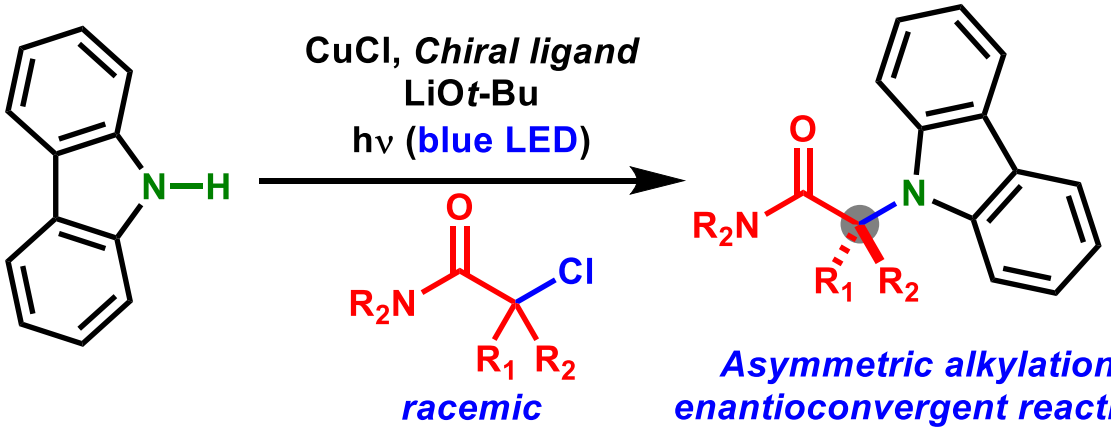
54%



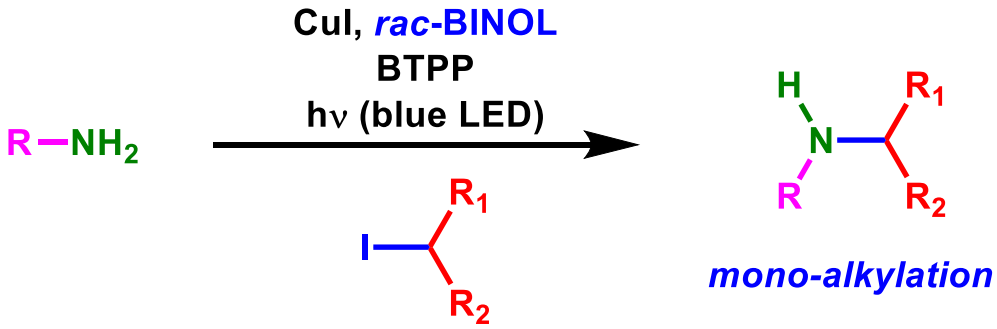
X = Cl, 64%
X = Br, 52%

* Isolated as trifluoroacetamide derivatives

Summary



1. Tuning of photoreductant
2. π system including amine



1. Anionic Cu^{I} precatalyst
2. Bidendate and bulky BINOL ligand