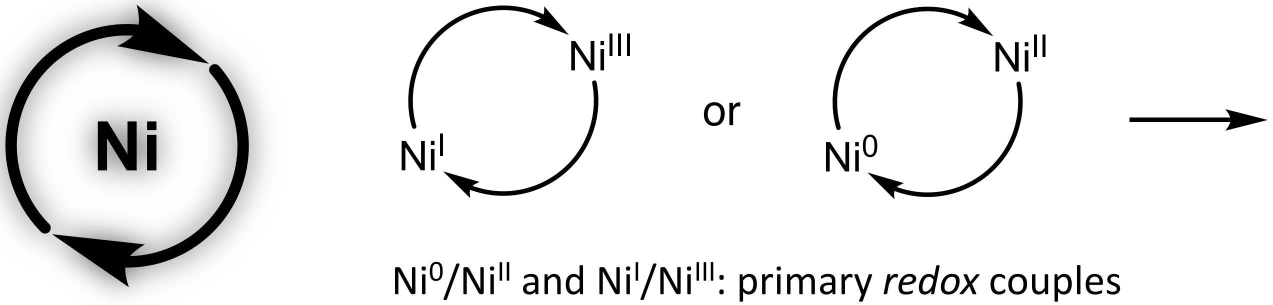
Isolable Nickel (IV) Complexes in Organic Reactions

MR Mar 11th 2023

Yumeng Liao, D1

Background Ni(IV) compounds in Nickel Chemistry

Nickel Intermediate



various cross couplings and bond activation

Ni^{0}/Ni^{II} and Ni^{I}/Ni^{III}: primary *redox* couples

Ni(0~III):

Countless examples in organometallic and synthetic chemistry

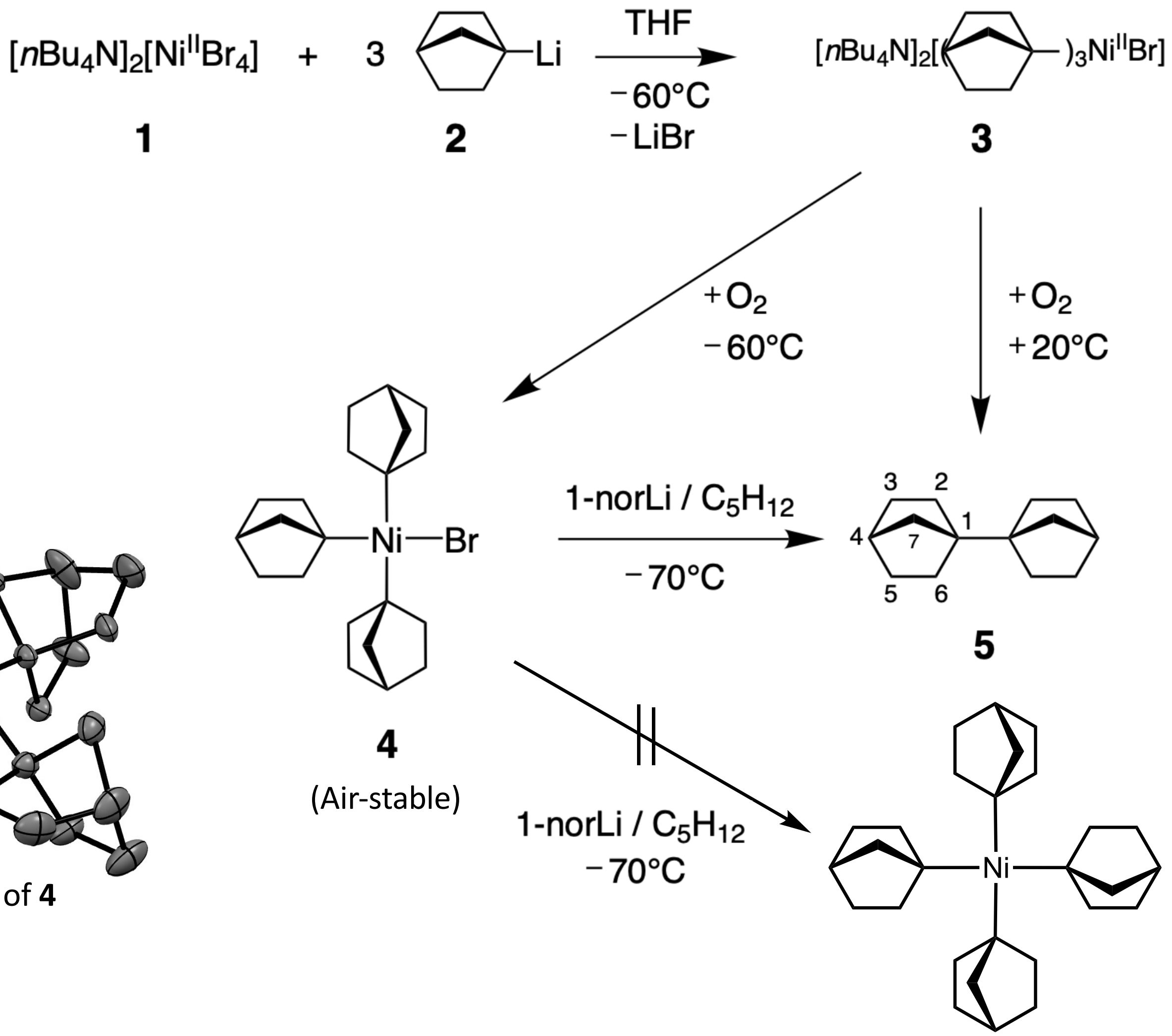
Ni(IV):

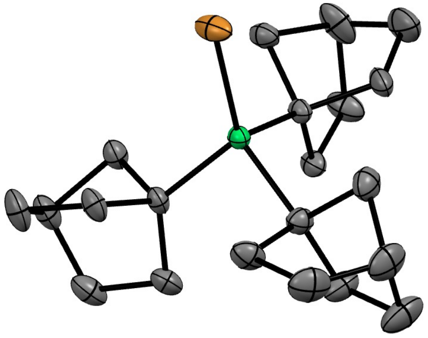
Very few examples of isolable complexes

“low stability and rapid reductive elimination to release product)”

Introduction Ni(IV) in C–C Bond Formation

1) Bromotris(1-norbornyl)Ni(IV) (Dimitrov 2003)



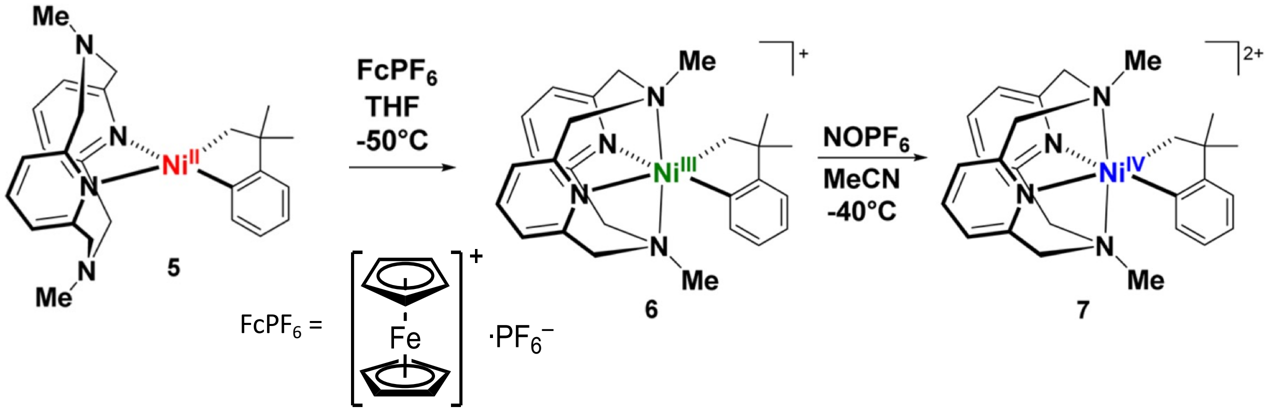

ORTEP of **4**

Dimitrov V. *et al* *ACIE* **2003**, *42*, 2641.

Introduction | Ni(IV) in C–C Bond Formation

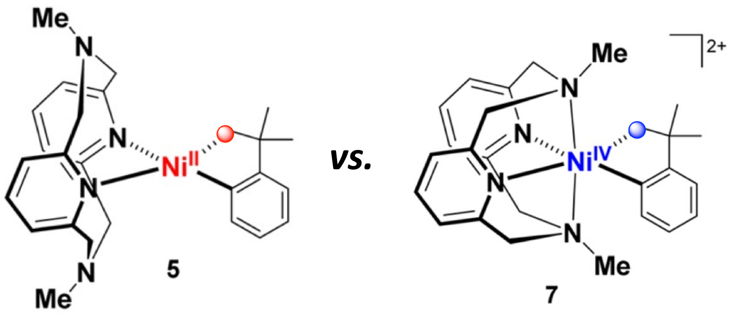
2) [(MeN$_4$)Ni(CH$_2$CMe$_2$-*o*-C$_6$H$_4$)(MeCN)]$^{2+}$ (Mirica 2016)

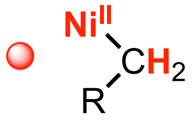
[Synthesis of Ni(IV) complex **7**$^{2+}$]



Isolated as orange-red complex
Spectroscopic studies succeeded
scXRD measurement failed

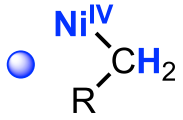
[Spectroscopic study on Ni(IV) center]





1.24 (s, 2H)

More oxidazed Ni center caused a significant downfield shift



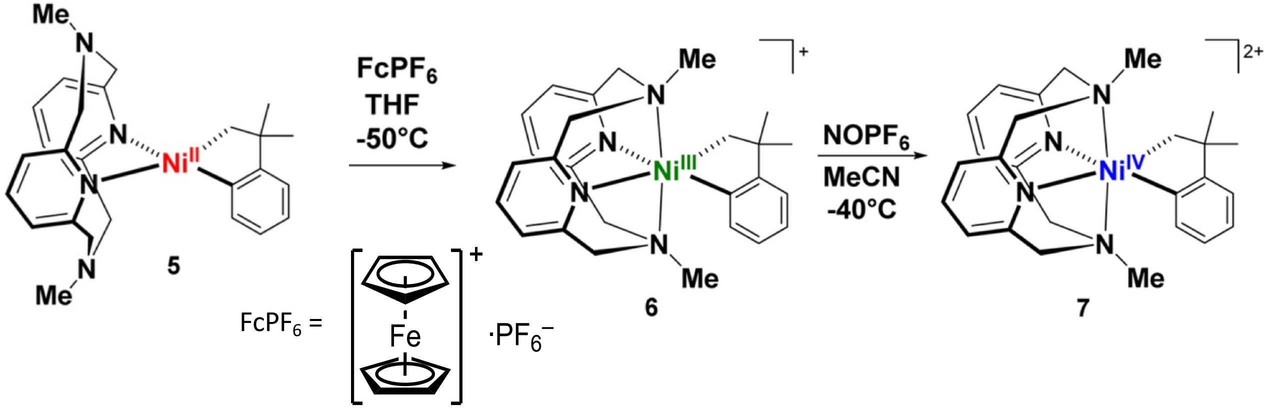
5.33 (s, 2H)

Mirica L. M. *et al JACS* **2016**, *138*, 12928.

Introduction Ni(IV) in C−C Bond Formation

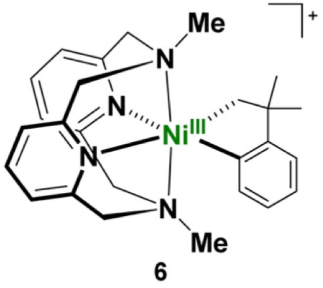
2) [(MeN$_4$)Ni(CH$_2$CMe$_2$-*o*-C$_6$H$_4$)(MeCN)]$^{2+}$ (Mirica 2016)

[Synthesis of Ni(IV) complex **7**$^{2+}$]



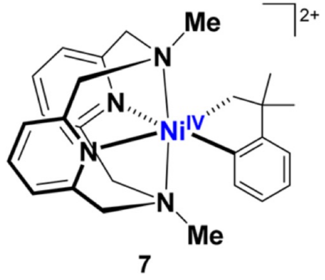
Isolated as orange-red complex
Spectroscopic studies succeeded
scXRD measurement failed

[X-ray photoelectron spectroscopy (XPS) study on **6** and **7**]

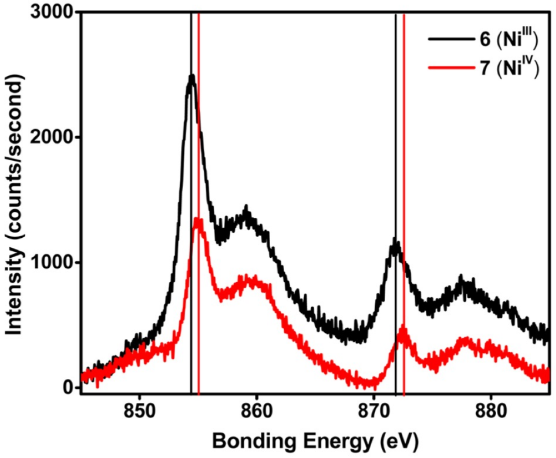


6

vs.



7



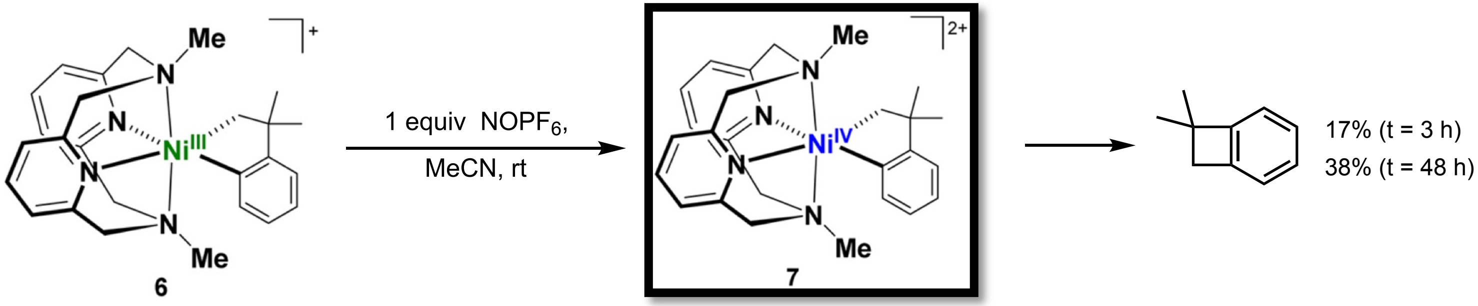
An increased binding energy indicated a more oxidized Ni center

Mirica L. M. *et al JACS* **2016**, *138*, 12928.

Introduction Ni(IV) in C−C Bond Formation

2) $[(MeN_4)Ni(CH_2CMe_2\text{-}o\text{-}C_6H_4)(MeCN)]^{2+}$ (Mirica 2016)

[Reactivity on reductive elimination for $C(sp^2)-C(sp^3)$ Bond Formation]



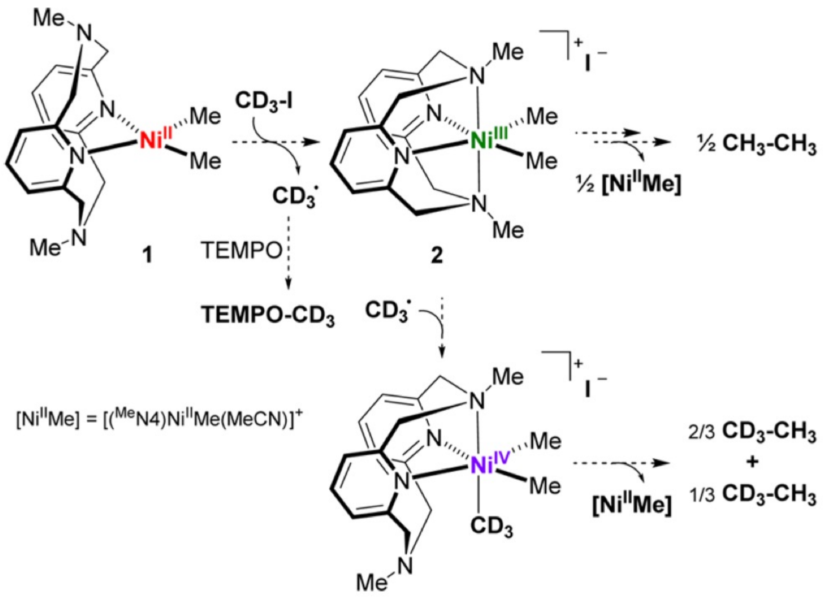
*In-situ generation of **7***

[Reactivity on reductive elimination for $C(sp^3)-C(sp^3)$ Bond Formation]

$$({}^{Me}N4)Ni^{II}Me_2 \xrightarrow[\text{24 hrs, RT; MeCN}]{\text{1 eq } CD_3I} \underset{67\%}{CH_3\text{-}CH_3} + \underset{20\%}{CH_3\text{-}CD_3}$$

$$({}^{Me}N4)Ni^{II}Me_2 \xrightarrow[\text{24 hrs, RT; MeCN}]{\text{1 eq } CD_3I\text{; 2 eq TEMPO}} \underset{70\%}{CH_3\text{-}CH_3} + \underset{85\%}{TEMPO\text{-}CD_3}$$

TEMPO-trapped product obtained

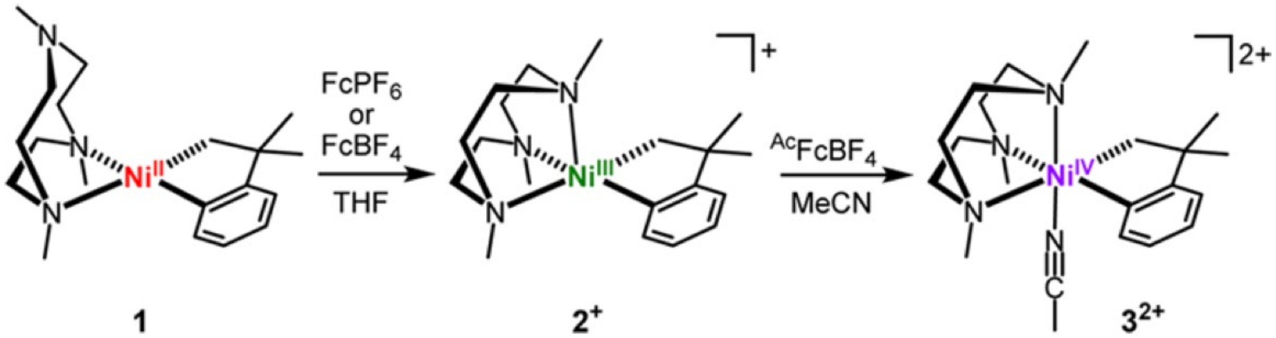


Mirica L. M. *et al JACS* **2016**, *138*, 12928.

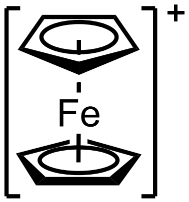
Introduction Ni(IV) in C–C Bond Formation

3) [(Me$_3$tacn)Ni(CH$_2$CMe$_2$-*o*-C$_6$H$_4$)(MeCN)]$^{2+}$ (Mirica 2017)

[Synthesis of Ni(IV) complex **3**$^{2+}$]

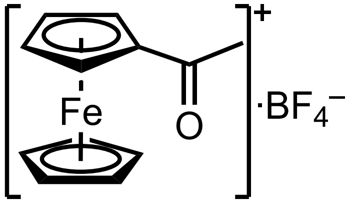


FcPF$_6$ or FcBF$_4$ =



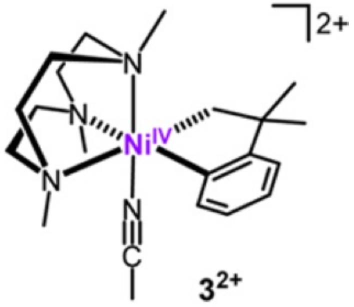
·BF$_4^-$or·PF$_6^-$

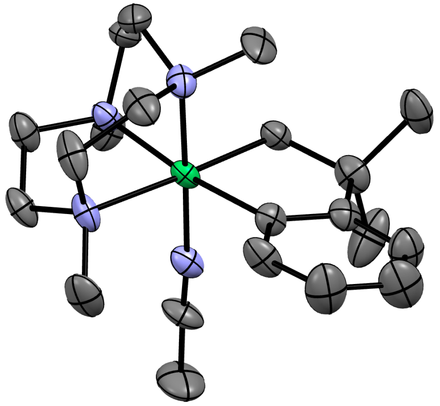
^{Ac}FcBF4 =



·BF$_4^-$

[ORTEP of Ni(IV) complex **3**$^{2+}$ (counteranion omitted)]





Mirica L. M. *et al JACS* **2017**, *139*, 35.

Ni(IV) in C−C Bond Formation

3) [(Me$_3$tacn)Ni(CH$_2$CMe$_2$-*o*-C$_6$H$_4$)(MeCN)]$^{2+}$ (Mirica 2017)

[Reactivity of Ni(IV) complex **3**$^{2+}$]

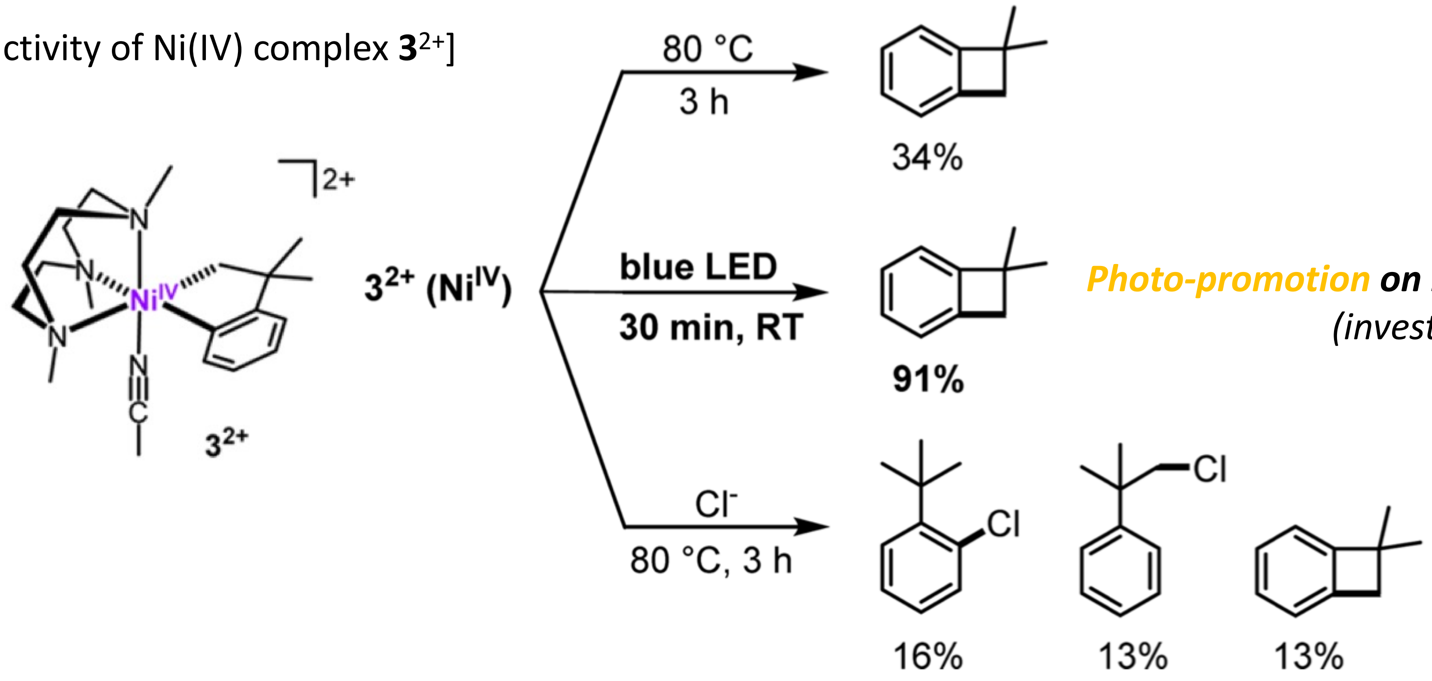


Photo-promotion on reactivity!

(investigation is undergoing…)

[exclusion of radical pathway]

Ni Complex	Additive	Illumination Time	1,1-dimethylbenzocyclobutene
3^{2+}	none	30 min	**91%**
3^{2+}	TEMPO	30 min	84%

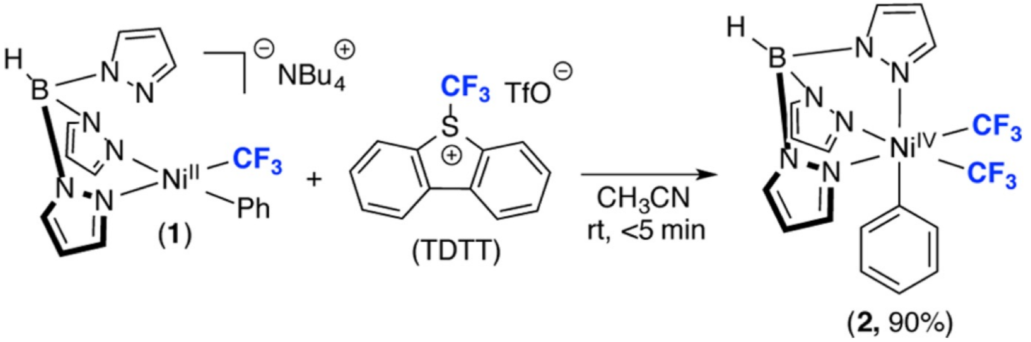
No significant change

Mirica L. M. *et al JACS* **2017**, *139*, 35.

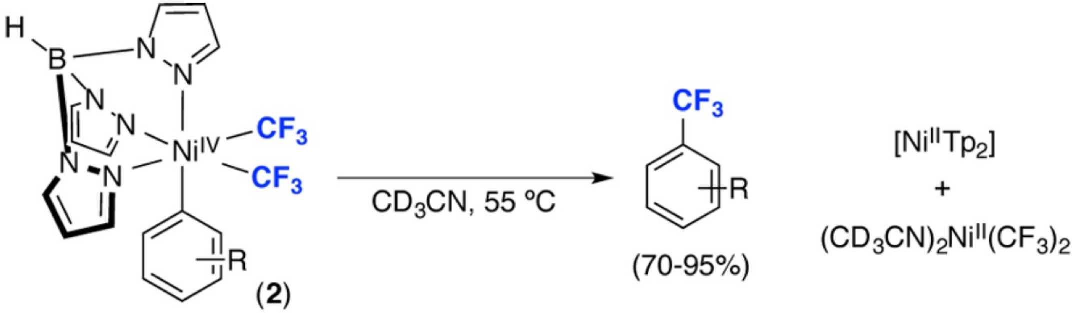
Introduction Ni(IV) in C–CF_3 Coupling

1) Stoichiometric C(sp^2)–CF_3 Coupling (Sanford 2015)

[Synthesis of Ni (IV) complex **2**]



[Reductive elimination of **2** to accomplish C(sp^2)–CF_3 bond formation]

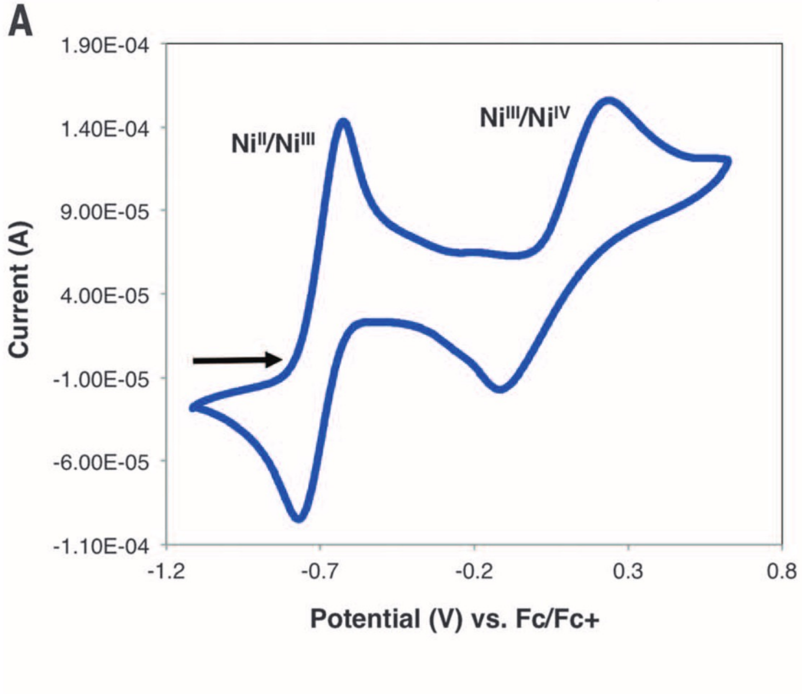


Sanford M. *et al JACS* **2015**, *137*, 8034.

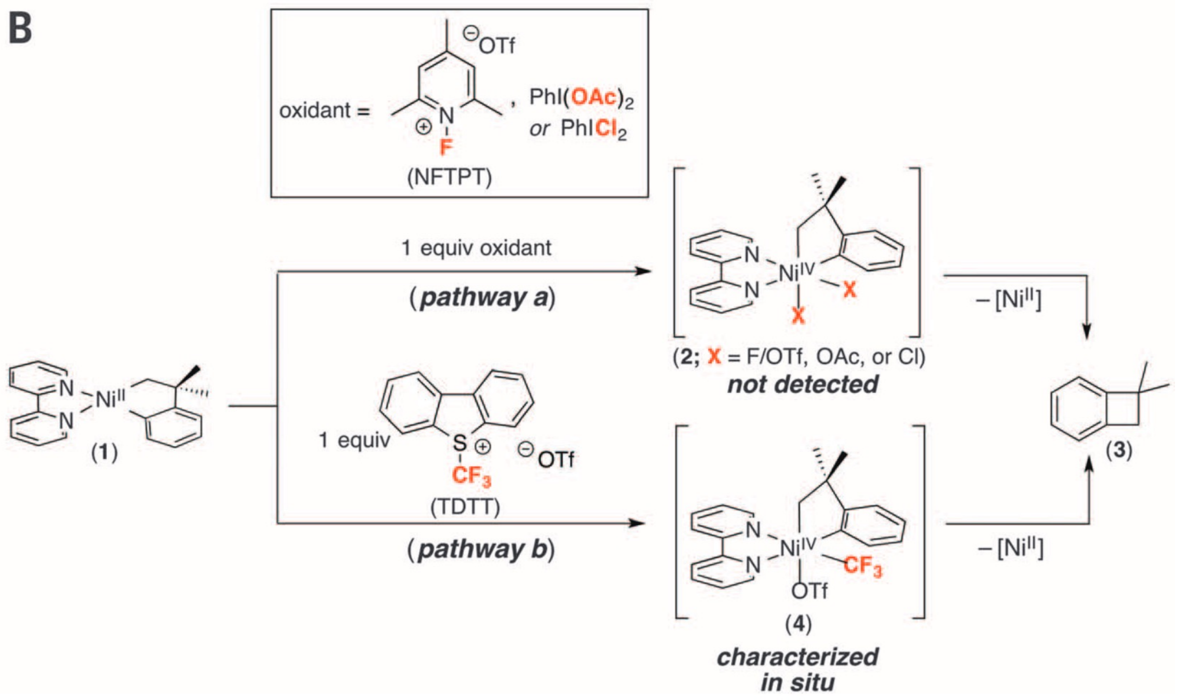
Introduction Ni(IV) in C−Heteroatom Coupling

1) Stoichiometric C(sp^2)–Heteroatom Coupling (Sanford 2015)

[Initial trial on Ni(II) complex **1**]



*CV measurement indicated a possible access to Ni(IV) from Ni(II) complex **2***



*pathway a: **Int-2** is highly reactive/not detectable*

*pathway b: **Int-4** was characterized in-situ*

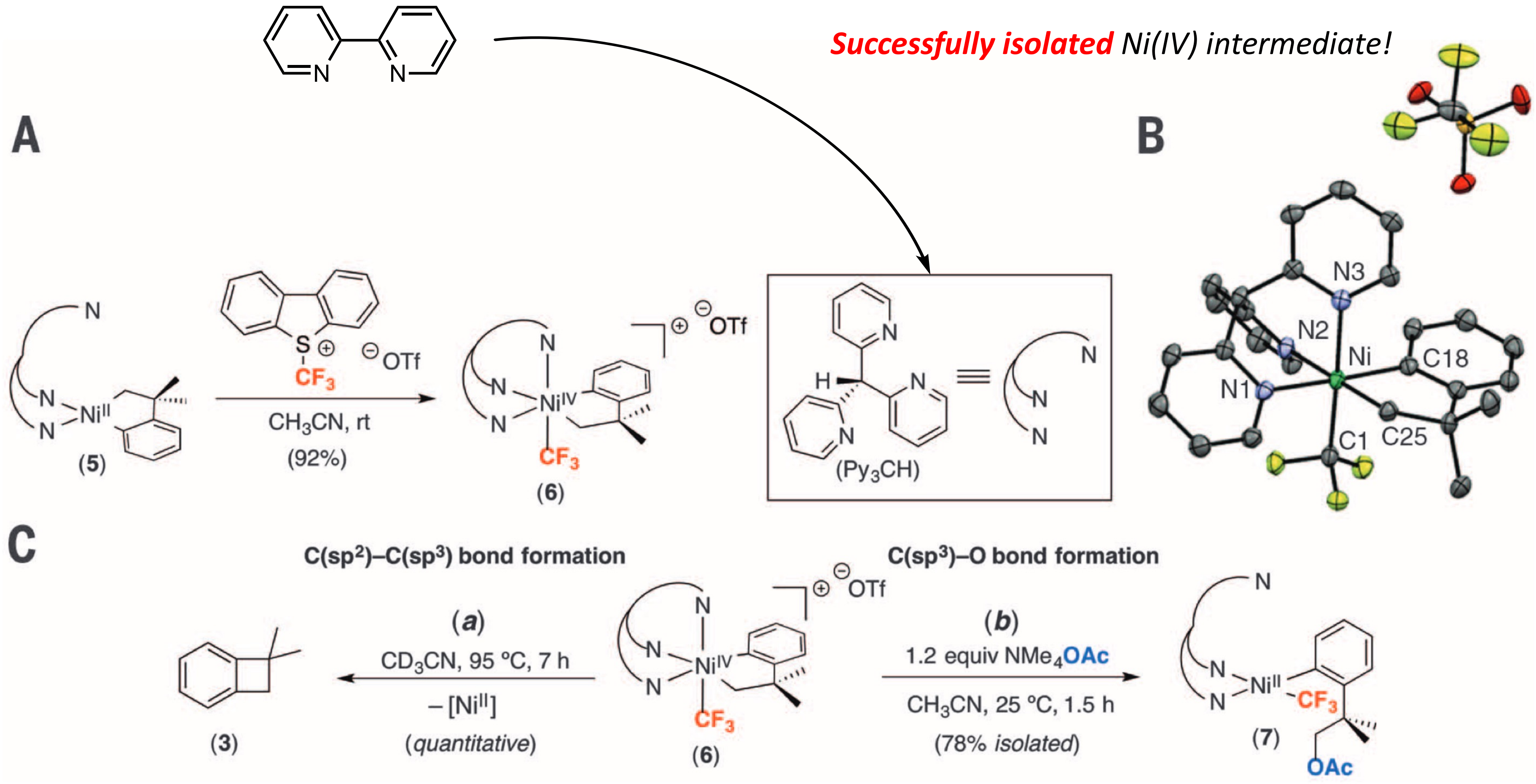
(CF3 ligand-stablization?)

Sanford M. *et al. Science* **2015**, *6227*, 1219.

Introduction Ni(IV) in C–Heteroatom Coupling

1) Stoichiometric C(sp^2)–Heteroatom Coupling (Sanford 2015)

[Replacement into a tridentate ligand for stabliation]



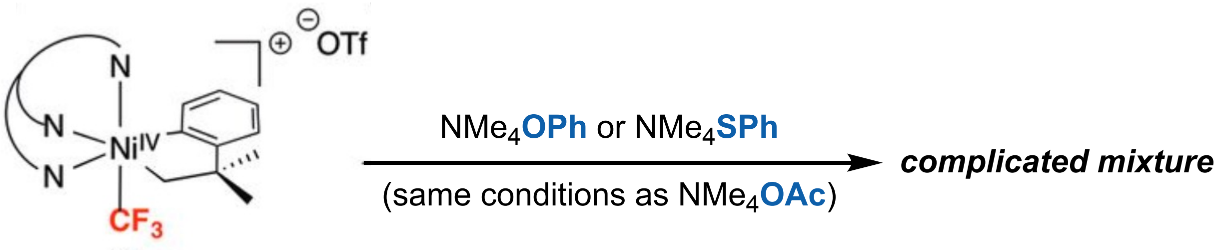
Successfully isolated *Ni(IV) intermediate!*

Sanford M. *et al. Science* **2015**, *6227*, 1219.

Introduction Ni(IV) in C−Heteroatom Coupling

1) Stoichiometric C(sp^2)–Heteroatom Coupling (Sanford 2015)

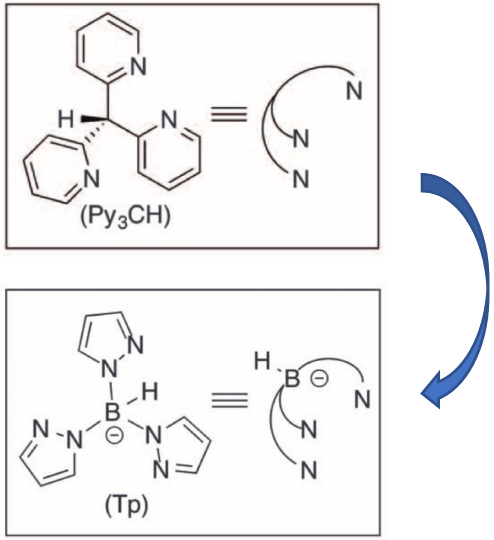
[Trial to other nucleophiles containing O and S atoms]

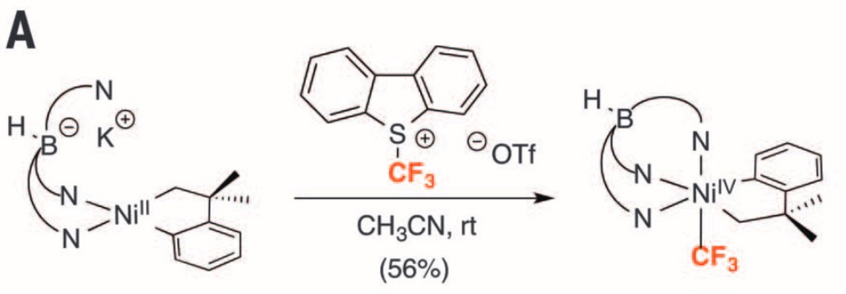


(6)

“+1 charge” on complex 6 causes it too electrophilic

[Replacement into Tp ligand] (Tp = trispyrazolylborate)





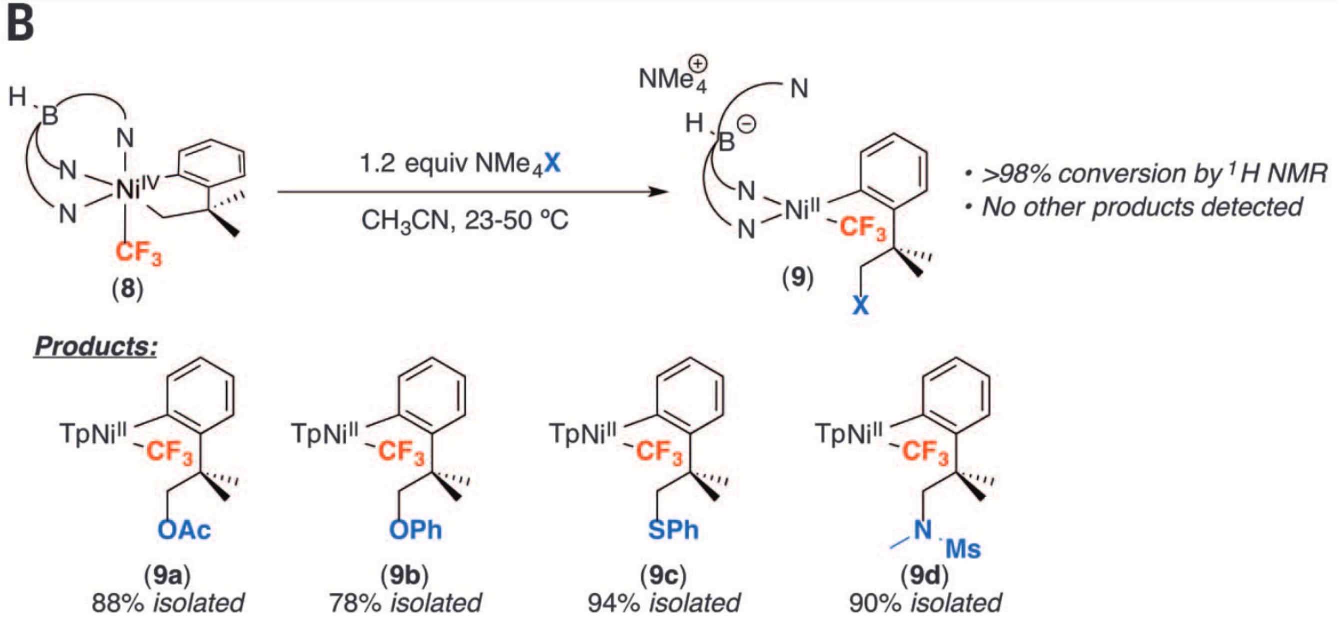
(8)

Successful preparation of Ni(IV) intermediate 8

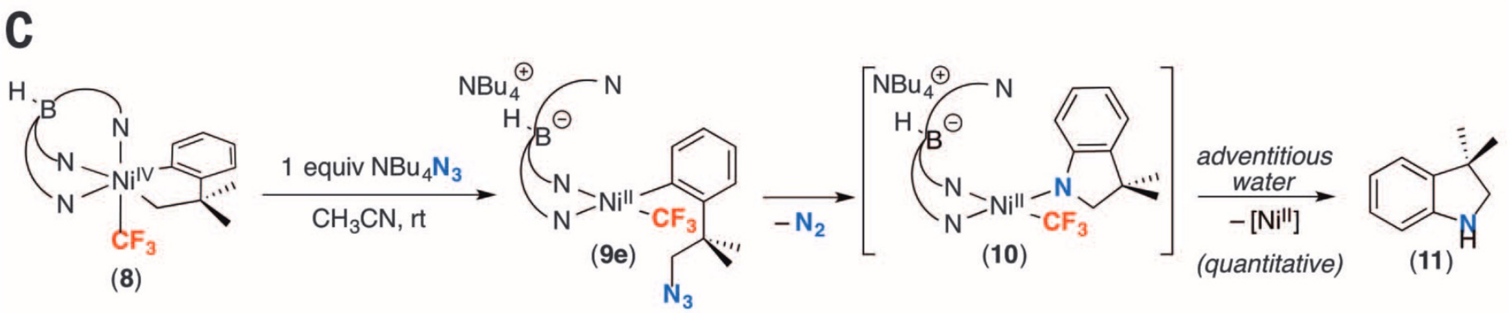
Sanford M. *et al. Science* **2015**, *6227*, 1219.

Introduction Ni(IV) in C−Heteroatom Coupling

[C−O, C−S, and C−N bond formation]



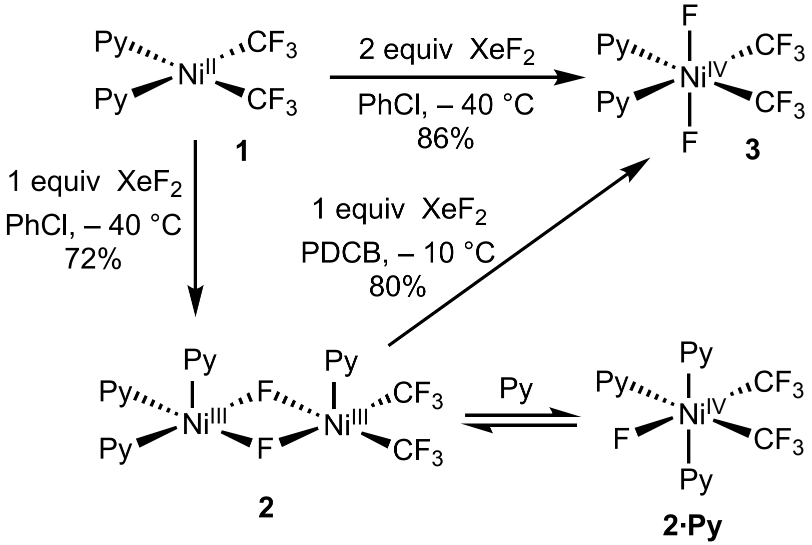
[Reaction with azide nucleophile]

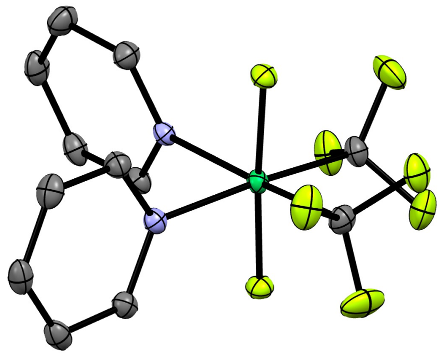


Sanford M. *et al.* *Science* **2015**, *6227*, 1219.

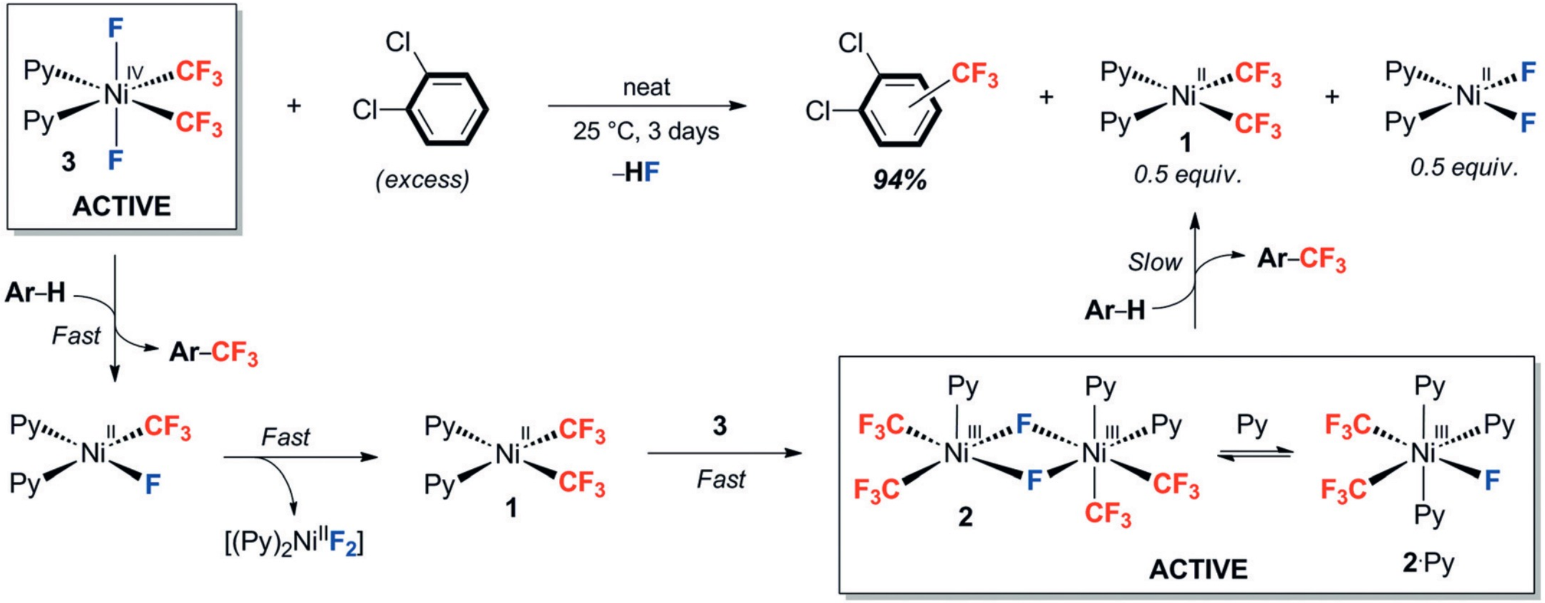
Introduction Ni(IV) in C–H Trifluoromethylation

1) Stoichiometric C–H trifluoromethylation (Mézailles & Nebra 2017)





ORTEP of **3**

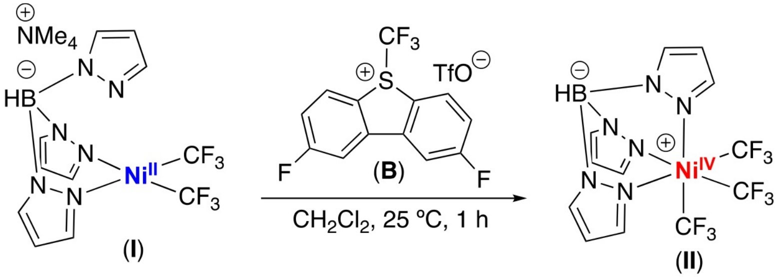


Mézailles N.; Nebra N. *et al* *ACIE* **2017**, *56*, 12898.

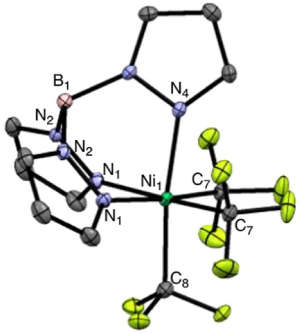
Introduction Ni(IV) in C–H Trifluoromethylation

2) Catalytic C–H trifluoromethylation (Sanford 2019)

[Synthesis of complex **II** (cat.) and optimization of conditions]

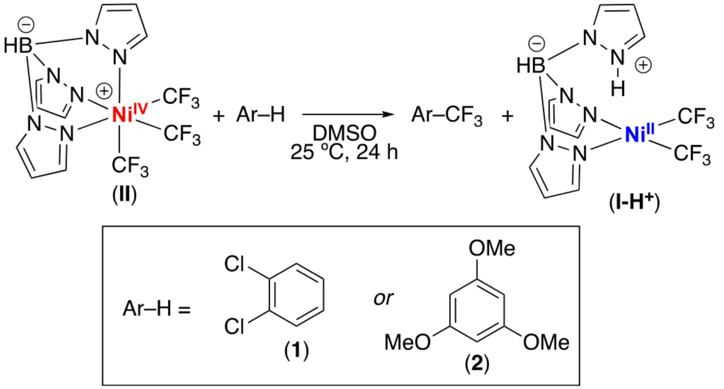


(47% isolated)



ORTEP of **II**

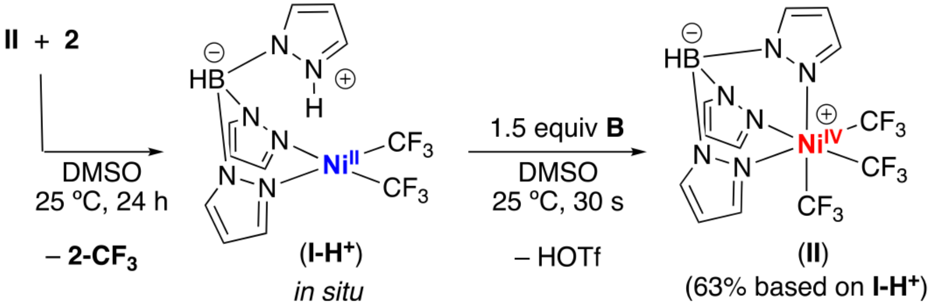
[Feasibility of $Ni^{II}/Ni^{IV}/Ni^{II}$ cycle (regeneration of Ni^{II} species)]



entry	Ar–H	equiv of Ar–H	yield (%)[a]
1	**1**	1 equiv	trace
2	**1**	neat	9[b]
3	**2**	1 equiv	47
4	**2**	5 equiv	72

[a] Yields determined by ^{19}F NMR spectroscopy using trifluorotoluene as an internal standard and are based on **II**. All reactions conducted using 1.0 equiv of **II**. [b] 1:1.2 ratio of **1-CF$_3$** isomers.

Ni^{II}/Ni^{IV} pathway



(63% based on **I-H$^+$**)

Regenerated!

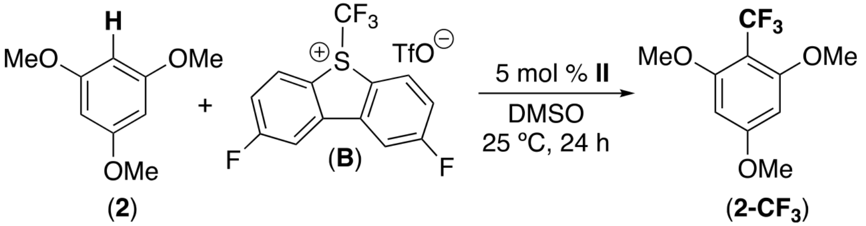
Ni^{IV}/Ni^{II} pathway

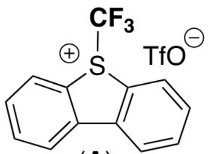
Sanford M. *et al. JACS* **2019**, *141*, 12872.

Introduction Ni(IV) in C–H Trifluoromethylation

2) Catalytic C–H trifluoromethylation (Sanford 2019)

[Optimization of conditions and scope of arenes]

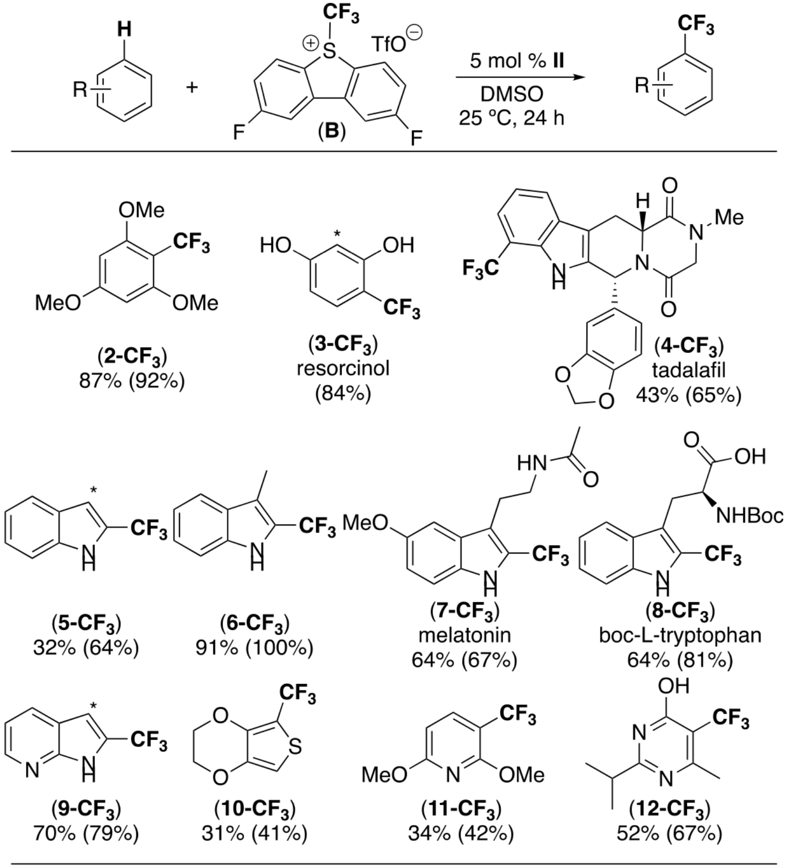




(**A**)

entry	modification	yield (%)[a]
1	dark	37
2	no **II**	0
3	ambient light	35
4	**I** as catalyst	25
5	**A** used as oxidant	25
6	2 equiv substrate	62
7	5 equiv substrate	93

[a] Yields were determined by ^{19}F NMR spectroscopy using trifluorotoluene as an internal standard and are based on **B** as the limiting reagent. Standard conditions: 1.0 equiv of **2**, 1.0 equiv of **B**, 5 mol% **II** in DMSO at room temperature for 24 h.



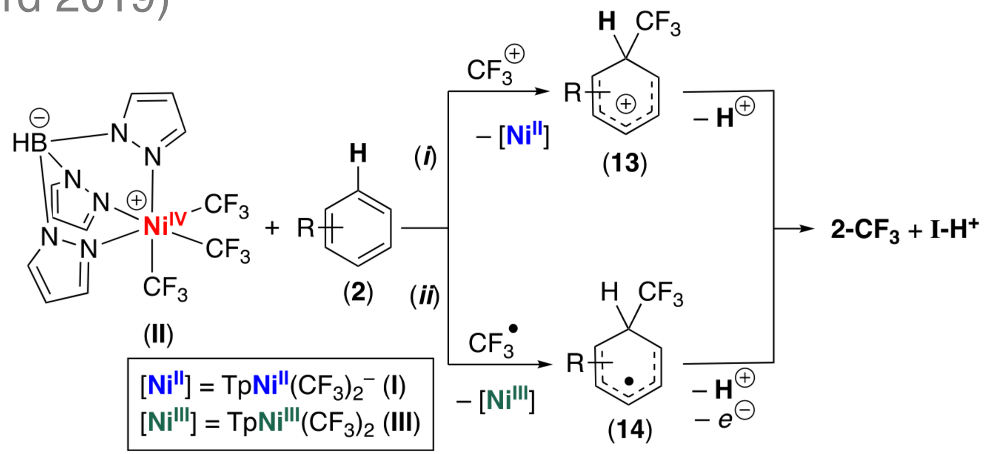
[a] General conditions: 1.0 equiv of **B**, 5.0 equiv of arene, 5 mol% **II** in DMSO for 24 h at 25 °C. ^{19}F NMR yields are in parentheses and were determined using trifluorotoluene as an internal standard. In cases where multiple isomers were formed, NMR yield is given as a combined yield. Asterisk (*) signifies the site of a minor isomer.

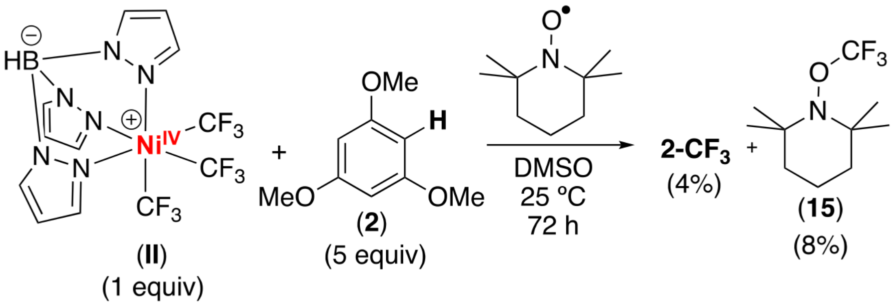
Sanford M. *et al.* *JACS* **2019**, *141*, 12872.

Introduction Ni(IV) in C–H Trifluoromethylation

2) Catalytic C–H trifluoromethylation (Sanford 2019)

[Two plausible mechanism for CF$_3$ transfer]





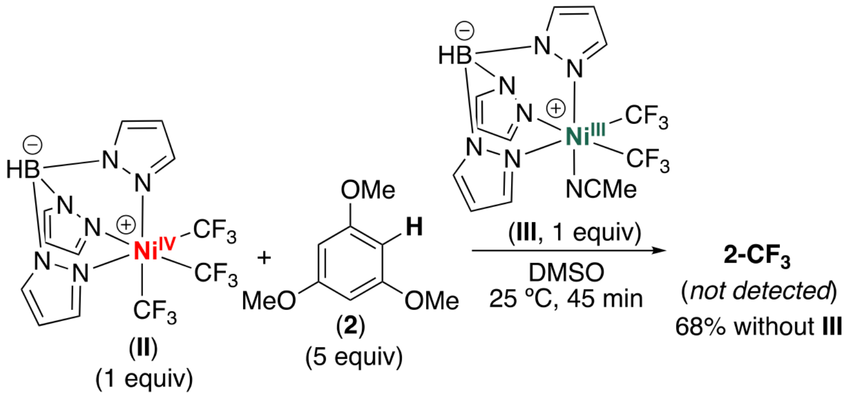
[Radical trapping with TEMPO]

Diminished yield of 2-CF$_3$ *(72% to 4%)*

Trapping product 15 was obtained

[Addition of Ni^{III} diminished the reaction]

[Ni^{III}] was not the major Ni (III) species formed under reaction conditions



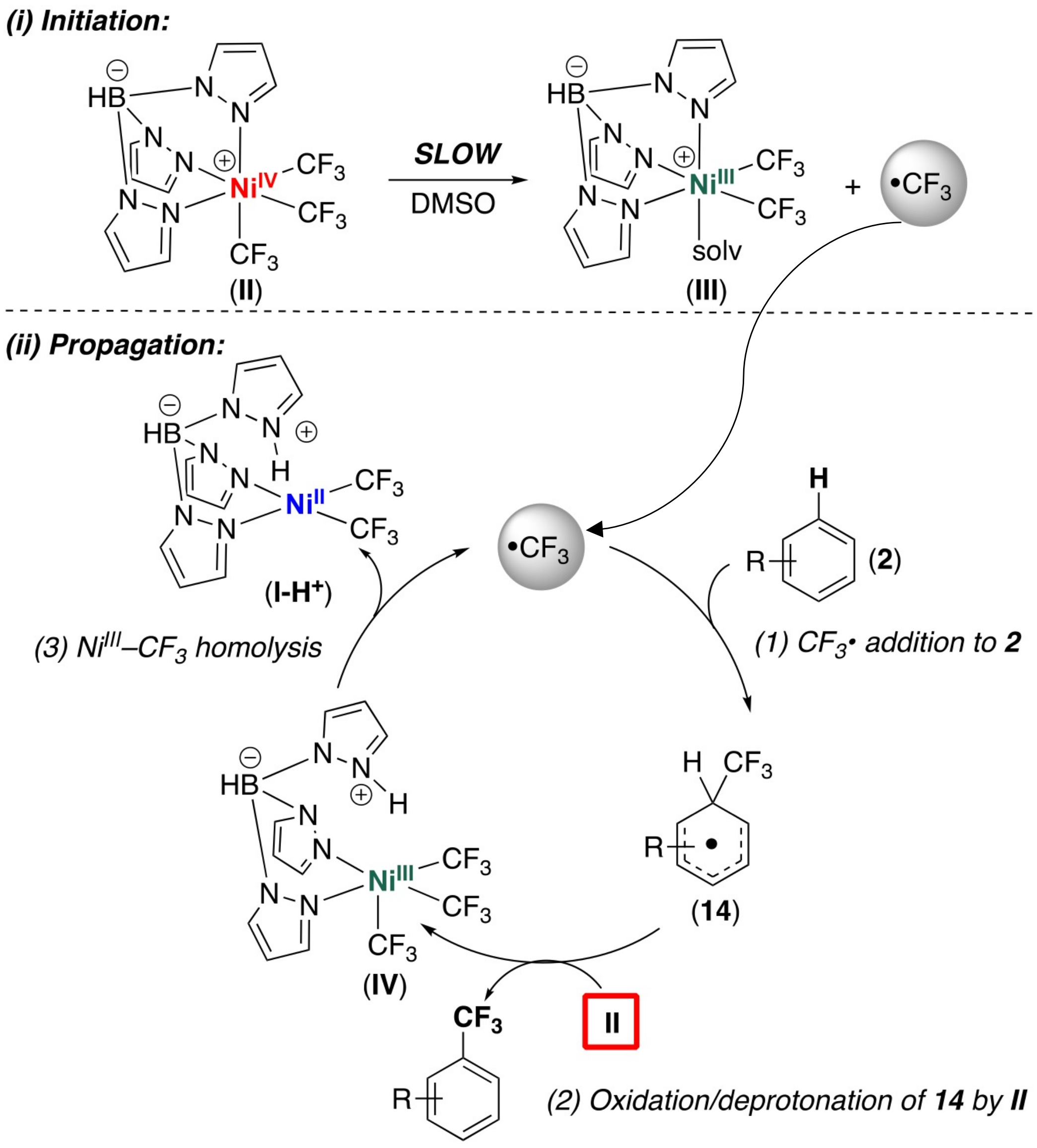
Sanford M. *et al. JACS* **2019**, *141*, 12872.

Introduction Ni(IV) in C–H Trifluoromethylation

2) Catalytic C–H trifluoromethylation (Sanford 2019)

[Proposed initiation of CF_3 radical]

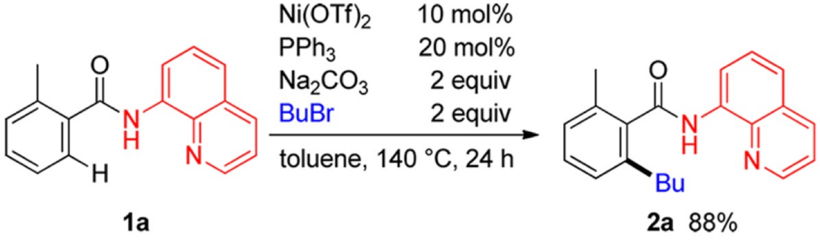
[Proposed mechanism involving Ni(III) species **IV**]

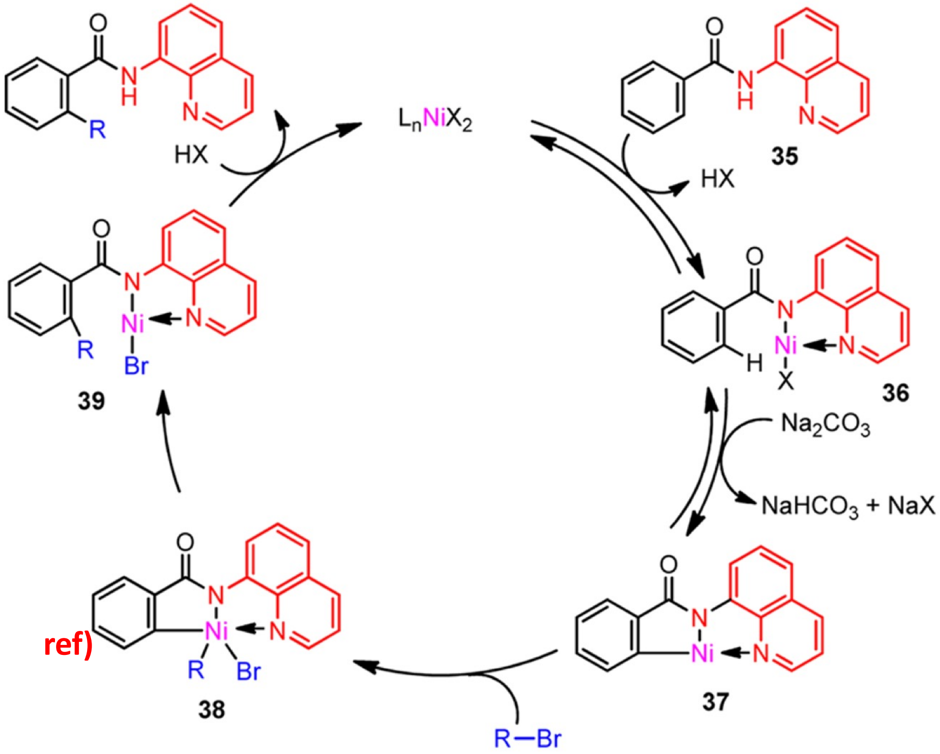


Sanford M. *et al.* *JACS* **2019**, *141*, 12872.

Introduction Ni(IV) in C–H Bond Alkylation

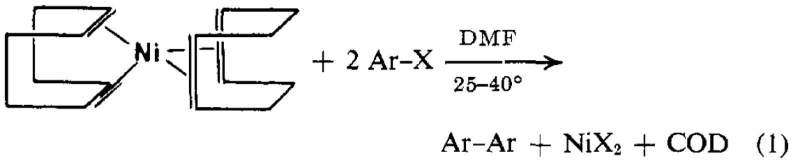
1) Ni(IV) not isolated (Chatani 2013)

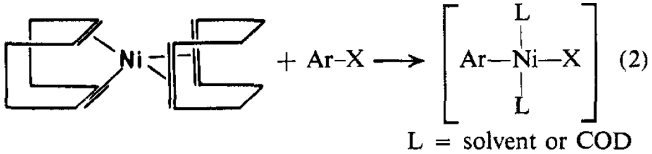


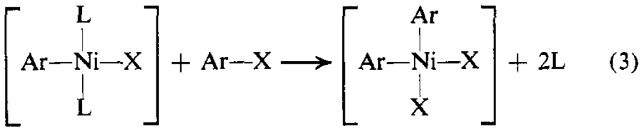


Chatani N. *et al.* *JACS* **2013**, *135*, 5308.

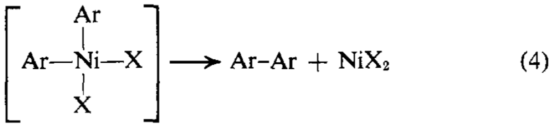
ref) Ni(IV) formation







$$\left[\begin{array}{c} L \\ Ar-Ni-X \\ L \end{array}\right] + Ar-X \longrightarrow \left[\begin{array}{c} Ar \\ Ar-Ni-X \\ X \end{array}\right] + 2L \qquad (3)$$

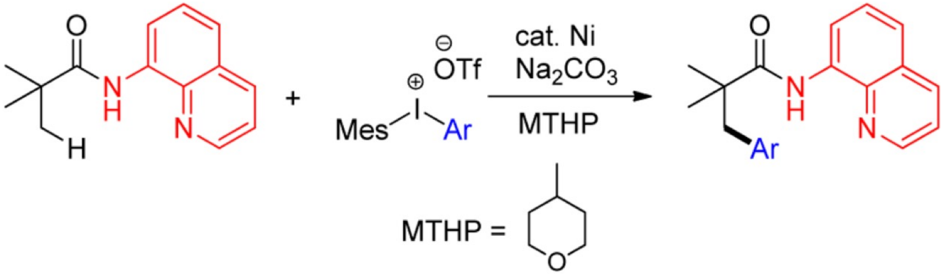


$$\left[\begin{array}{c} Ar \\ Ar-Ni-X \\ X \end{array}\right] \longrightarrow Ar\text{–}Ar + NiX_2 \qquad (4)$$

Semmelhack M. F. *et al.* *JACS* **1971**, *93*, 5908.

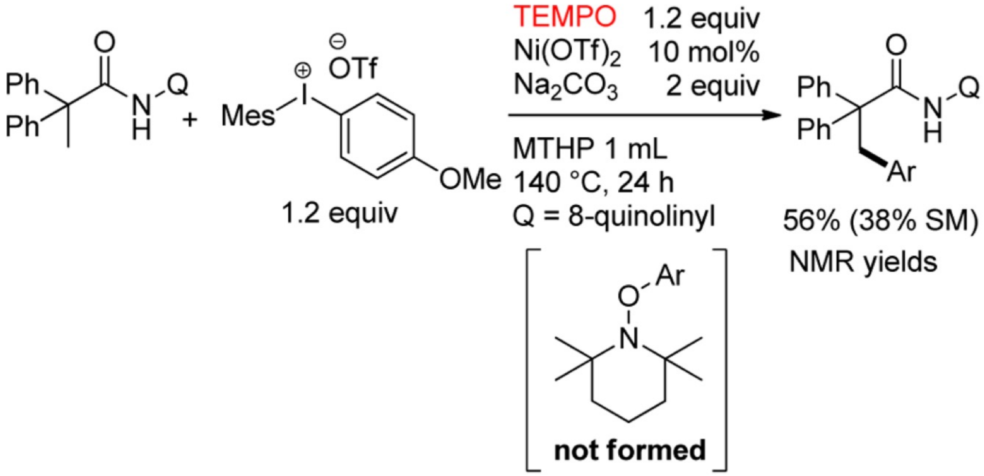
Introduction Ni(IV) in C–H Bond Arylation

1) Ni(IV) not isolated (Chatani 2014)



[Radical trapping with TEMPO]

No effect to the product yield & no radical trapped product obtained

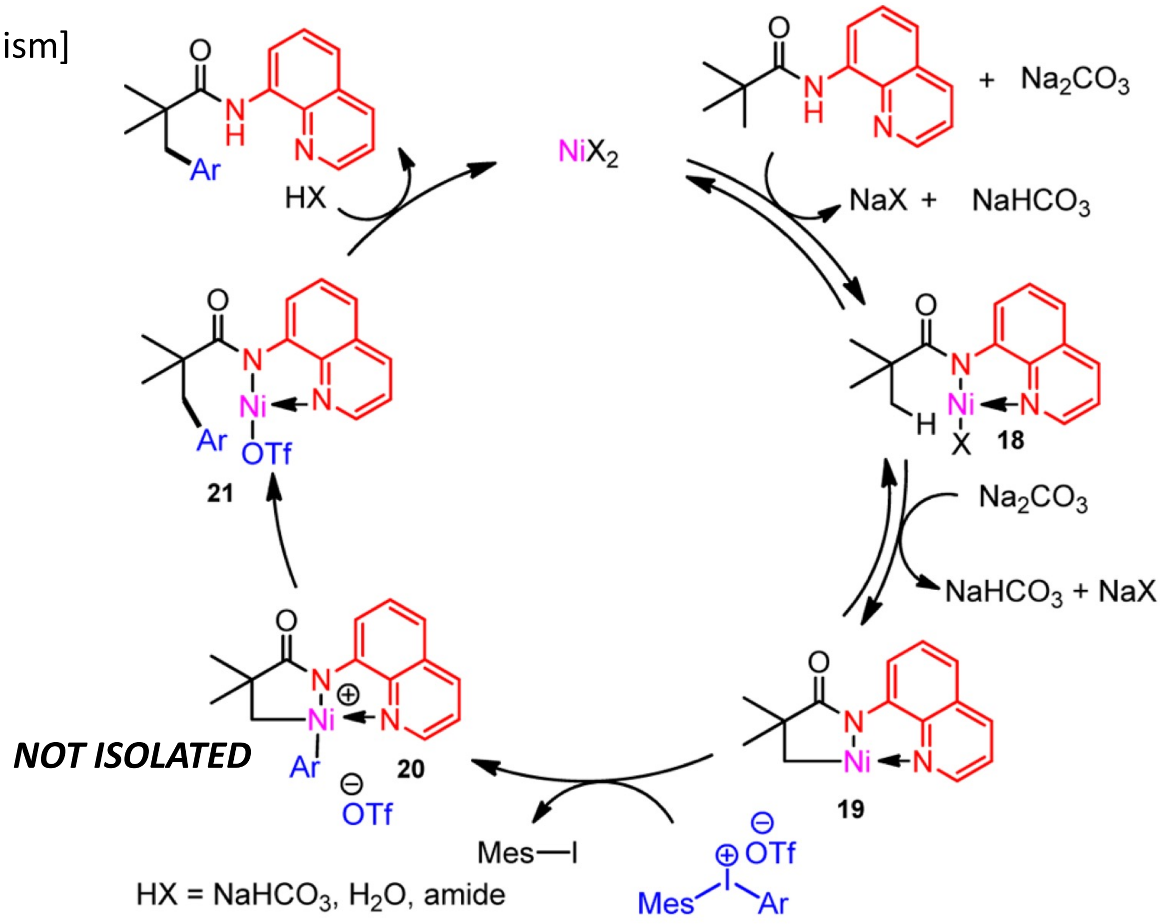


Chatani N. *et al. JOC* **2014**, *79*, 11933.

Introduction Ni(IV) in C−H Bond Arylation

1) Ni(IV) intermediate not isolated (Chatani 2014)

[Proposed mechanism]

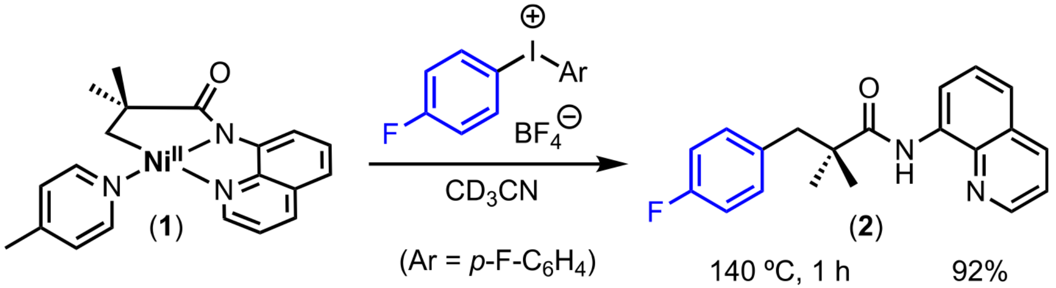


Chatani N. *et al.* *JOC* **2014**, *79*, 11933.

Ni(IV) in C−H Bond Arylation

2) Ni(IV) intermediate **successfully isolated** (Sanford 2022)

[Sanford's initial conditions]

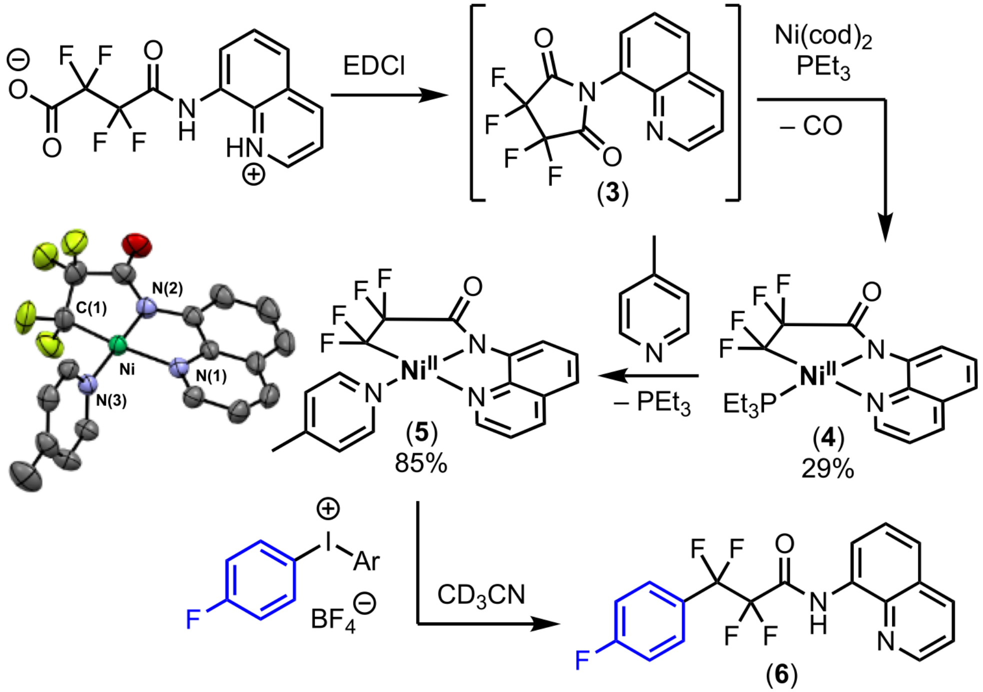


140 °C, 1 h	92%
25 °C, 5 min	>95%

Reaction proceeds too fast even at low temperature

Failed to trap reaction intermediate

[Modified ligand for slower reaction]



140 °C, 3 h	69%
25 °C, 7 days	no rxn

Perfluorated alkyl chain could stabilize high oxidation state Ni intermediate *(hypothesis)*

Sanford M. *et al. JACS* **2022**, *144*, 21030.

Introduction Ni(IV) in C–H Bond Arylation

2) Ni(IV) intermediate **successfully isolated** (Sanford 2022)

[Comparison on reactivity of **1** and **5** by CV]

1 vs. 5

Large possitive shift:

consistent with the slower reaction with Ar_2IBF_4 oxidant

1 vs. 5 + [Me_4N]PA

Large negative shift:

addition of [Me_4N]PA to replace 4-picoline ligand of ***5*** *into a anionic Ni complex.*

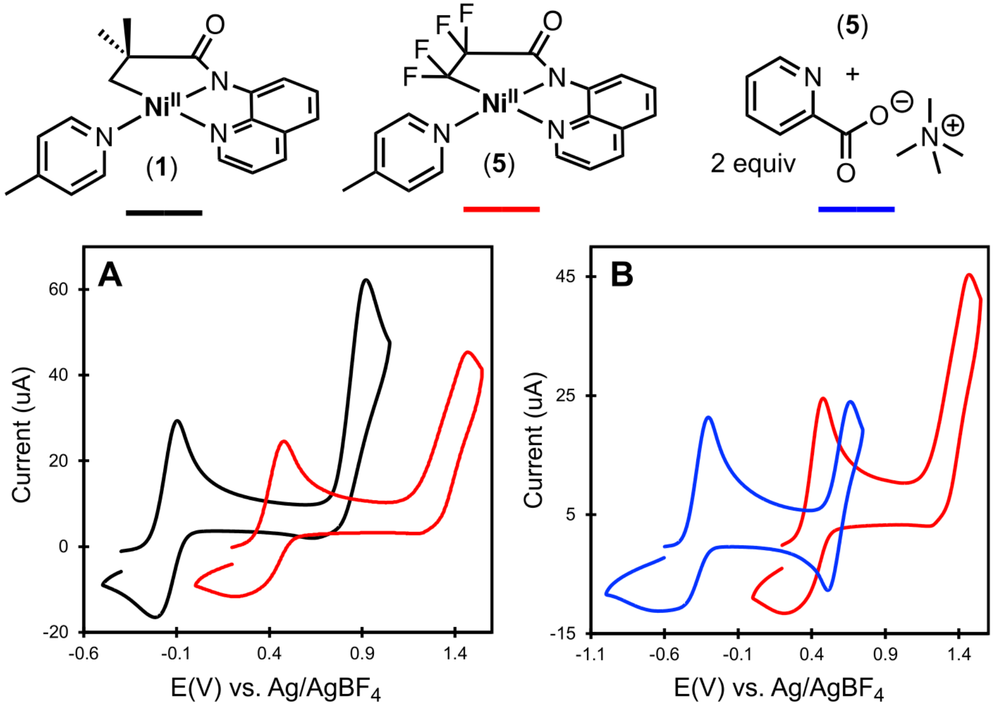


Figure 2. (A) Overlaid CVs of **1** (*black*) and **5** (*red*). (B) Overlaid CVs of **5** (*red*) and **5** + 2 equiv of tetramethylammonium picolinate (*blue*). Conditions: 0.01 mM solution of [Ni^{II}] in 0.1 M NBu_4PF_6 in CH_3CN; scan rate of 100 mV/s.

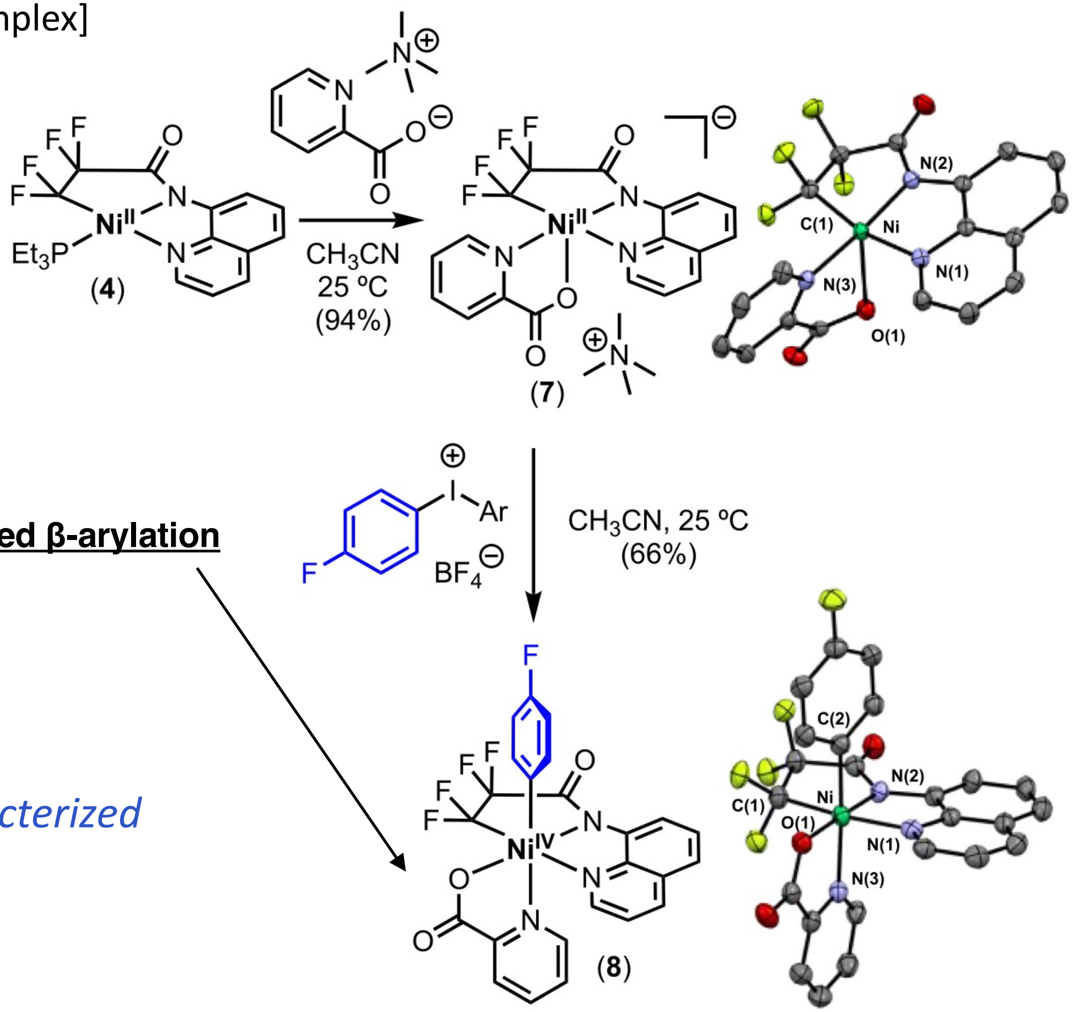
Complex 5 + [Me_4N]PA emerged as nice candidates!

Sanford M. *et al. JACS* **2022**, *144*, 21030.

Introduction Ni(IV) in C–H Bond Arylation

2) Ni(IV) intermediate **successfully isolated** (Sanford 2022)

[**5** + [Me$_4$N]PN] enables forming stable Ni(IV) complex]



First isolated Ni(IV) intermediate in Ni-catalyzed β-arylation

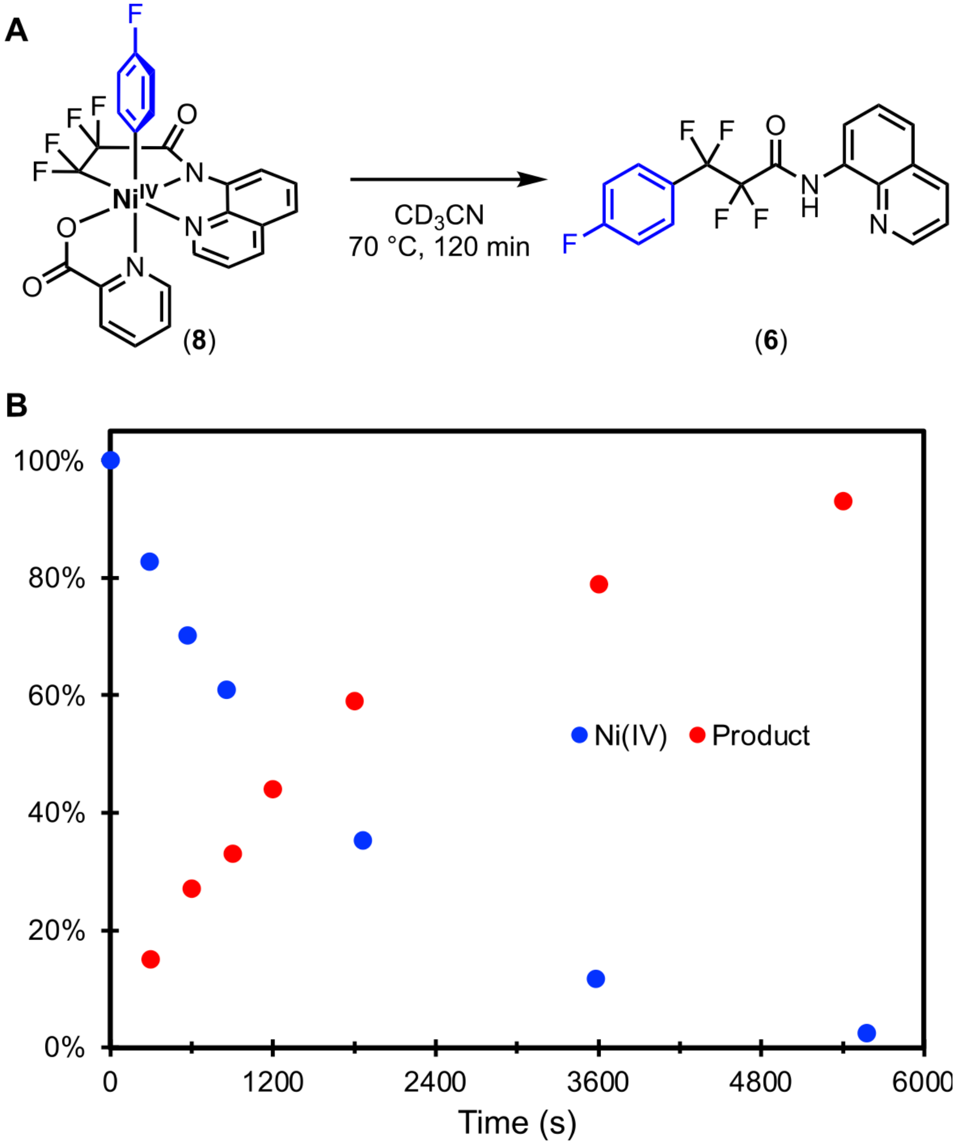
Chatani	***Sanford***
Proposed only	*Isolated/characterized*

Sanford M. *et al. JACS* **2022**, *144*, 21030.

Introduction Ni(IV) in C–H Bond Arylation

2) Ni(IV) intermediate successfully isolated (Sanford 2022)

[C(sp²)–C(sp³) bond forming reductive elimination from Ni(IV) complex **8**]

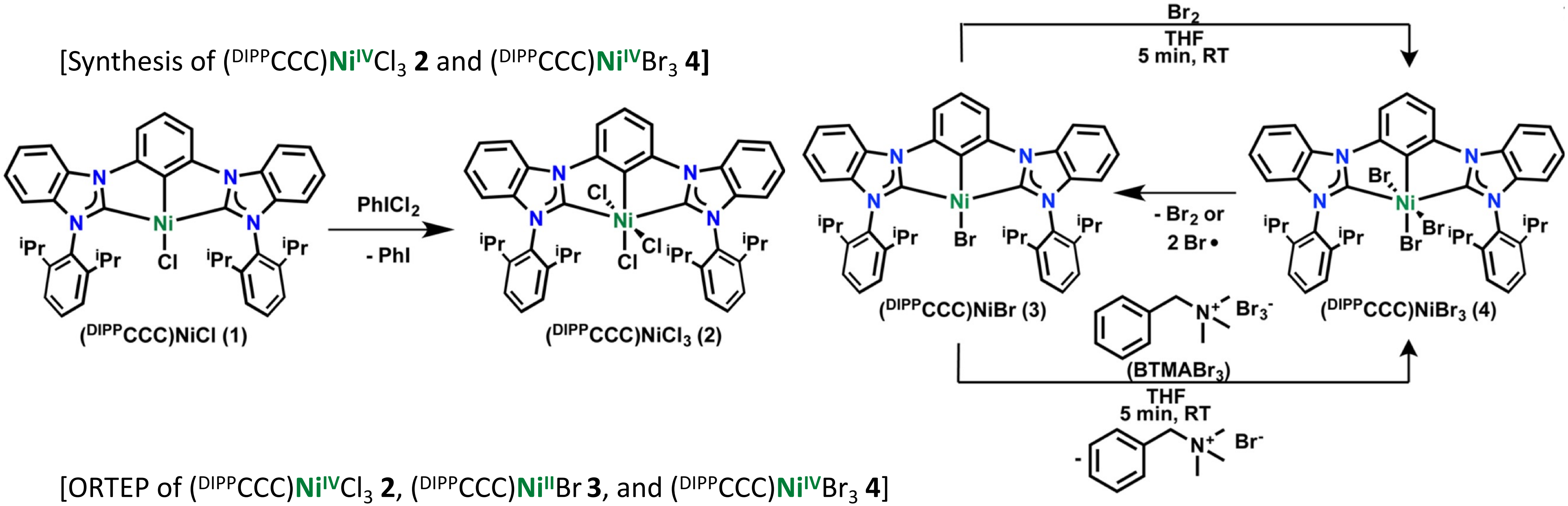


Sanford M. *et al. JACS* **2022**, *144*, 21030.

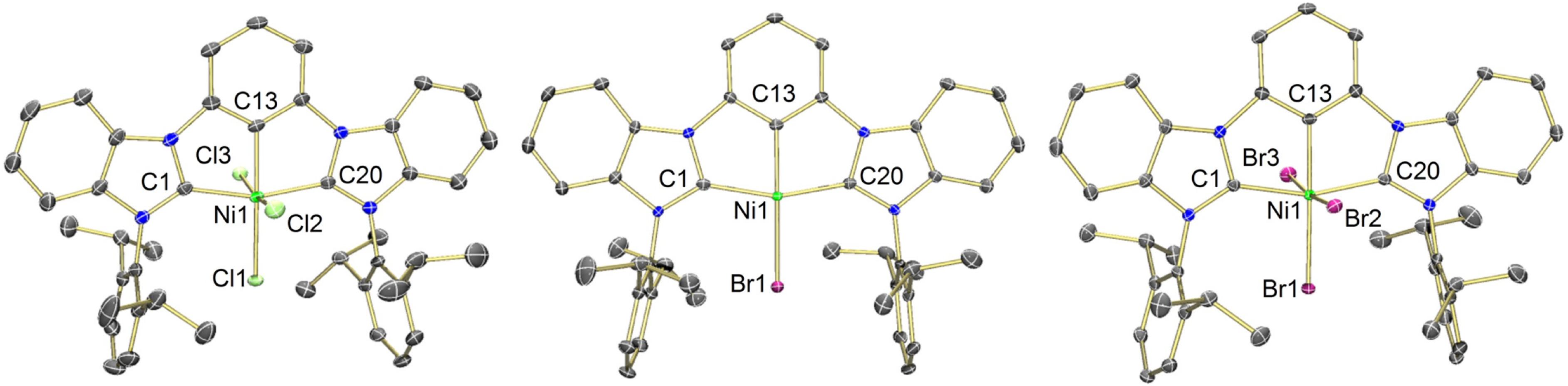
Introduction Ni(IV) in Bromination

1) Isolated Ni(IV) for bromination (Fout 2016)

[Synthesis of (^{DIPP}CCC)**Ni**^{IV}Cl_3 **2** and (^{DIPP}CCC)**Ni**^{IV}Br_3 **4]**



[ORTEP of (^{DIPP}CCC)**Ni**^{IV}Cl_3 **2**, (^{DIPP}CCC)**Ni**^{II}Br **3**, and (^{DIPP}CCC)**Ni**^{IV}Br_3 **4**]

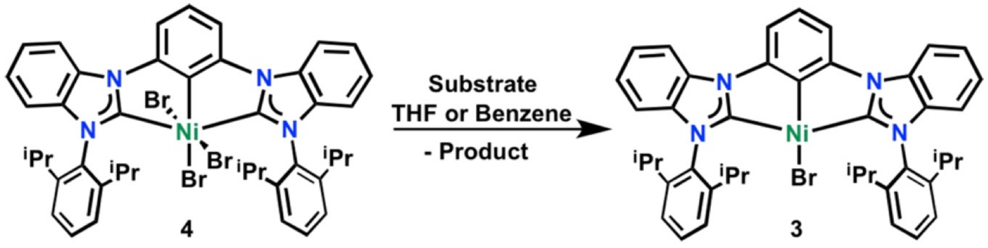


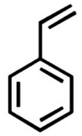
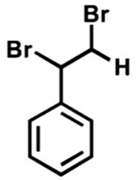
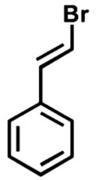
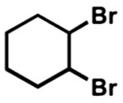
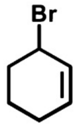
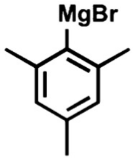
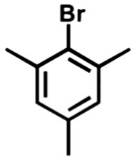
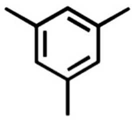
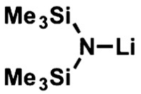
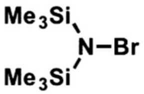
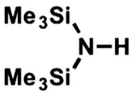
Fout A. R. *et al.* *JACS* **2016**, *138*, 4290.

Introduction Ni(IV) in Bromination

1) Isolated Ni(IV) for bromination (Fout 2016)

[Reactivity of (^{DIPP}CCC)**Ni^{IV}**Br$_3$ **4** for bromination]



Substrate	Products* (Yield)		% Conversion to 3
 100 eq.^{a}	 87%	 not observed	87%
 100 eq.^{a}	 71%	 not observed	> 99%
 1 eq.^{b}	 50%	 33%	> 99%
 $(Me_3Si)_2N{-}Li$ 1 eq.^{b}	 $(Me_3Si)_2N{-}Br$ 50%	 $(Me_3Si)_2N{-}H$ 50%	> 99%

* Product formation was determined by GC-MS and ^{1}H NMR spectroscopy.
^{a} Reaction in THF. ^{b} Reaction in benzene.

Fout A. R. *et al. JACS* **2016**, *138*, 4290.

Summary

Isolable Ni(IV) Complexes

Very rare in the chemistry of nickel

Not like Ni(0), Ni(I), Ni(II), and Ni(III), **Ni(IV)** are very rare in nature, especially for their detection, isolation and characterization.

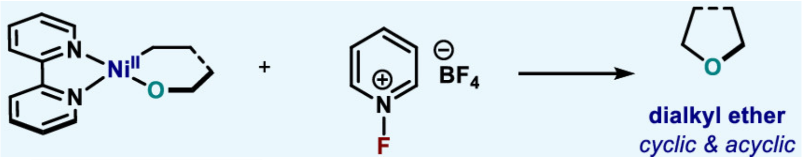
Rational ligand design enables stable Ni(IV) complex

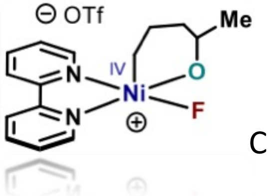
Chemists either introduce fluorinated group to the ligand or replace it to a tri-/tetradentate ligand, to stabilize the high-valent nickel center.

My perspective

There are still some Ni(IV) intermediates remaining hypotheses (not isolated). *ex) Ni(IV) in ether formation*

But ligand re-design might stabilize them (I'm confident).





Proposed NI(IV) intermediate

Cornella J. *et al. JACS* **2020**, *142*, 19540.

For more info. ……

Recommend review article: Pal A. K. *et al. Coord. Chem. Rev.* **2022**, *474*, 214849

Both **proposed** and **isolated** Ni(IV) in inorganic and organometallic chemistry…all you can enjoy