

Ni/Photoredox-Catalyzed C(sp³)–C(sp³) Coupling between Aziridines and Acetals as Alcohol-Derived Alkyl Radical Precursors

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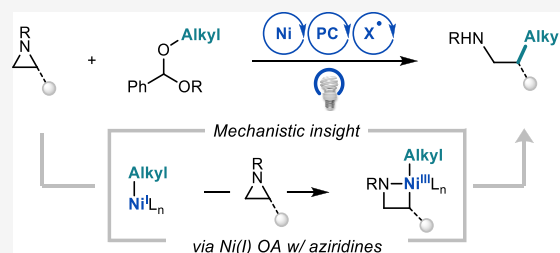


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ABSTRACT: Aziridines are readily available C(sp³) precursors that afford valuable β -functionalized amines upon ring opening. In this article, we report a Ni/photoredox methodology for C(sp³)–C(sp³) cross-coupling between aziridines and methyl/1°/2° aliphatic alcohols activated as benzaldehyde dialkyl acetals. Orthogonal activation modes of each alkyl coupling partner facilitate cross-selectivity in the C(sp³)–C(sp³) bond-forming reaction: the benzaldehyde dialkyl acetal is activated via hydrogen atom abstraction and β -scission via a bromine radical (generated in situ from single-electron oxidation of bromide), whereas the aziridine is activated at the Ni center via reduction. We demonstrate that an Ni(II) azametallacycle, conventionally proposed in aziridine cross-coupling, is not an intermediate in the productive cross-coupling. Rather, stoichiometric organometallic and linear free energy relationship studies indicate that aziridine activation proceeds via Ni(I) oxidative addition, a previously unexplored elementary step.



INTRODUCTION

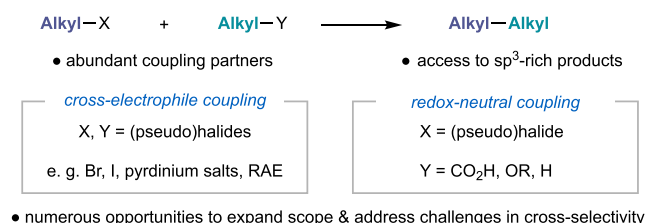
Selective cross-coupling of two different carbon electrophiles, commonly known as cross-electrophile coupling, has emerged as an enabling strategy for C–C bond formation.¹ These processes often operate on readily available and stable organic (pseudo)halides under mild conditions. Extensive progress has been made in developing C(sp³)–C(sp²) cross-electrophile coupling reactions, with Ni catalysis offering a particularly general platform.² Mechanistic studies on select Ni-catalyzed reactions have revealed that distinct, hybridization-dependent activation mechanisms give rise to the cross-selectivity with C(sp²) and C(sp³) electrophiles.^{3,4} In contrast, methods for selective coupling of two C(sp³) electrophiles remain underdeveloped, owing to the more subtle differences in reactivity between the two reaction partners (Figure 1A).⁵ Nevertheless, recently, there has been important progress made in this area using Ni⁶ or Cu catalysis⁷ with chemical reductants and electrochemical methods.⁸ These approaches typically rely on substrate stoichiometry, differences in (pseudo)halide identities, or differences in substitution at the carbon center to achieve selectivity. Alternatively, redox-neutral metallaphotoredox catalysis⁹ can provide a platform for the development of chemoselective C(sp³)–C(sp³) cross-coupling in part by relying on orthogonal redox-dependent activation mechanisms of the two alkyl coupling partners. This approach offers the opportunity to use non-traditional reaction partners beyond alkyl (pseudo)halides, while retaining many of the positive attributes of cross-electrophile coupling. For example, researchers have recently found success coupling two C(sp³) fragments arising from carboxylic acids, activated alcohols, alkyl halides, and C–H bonds.¹⁰ These examples highlight how

the identification of strategies that engage distinct classes of C(sp³) coupling partners in C(sp³)–C(sp³) bond formation can be of broad value from a synthetic and mechanistic perspective.

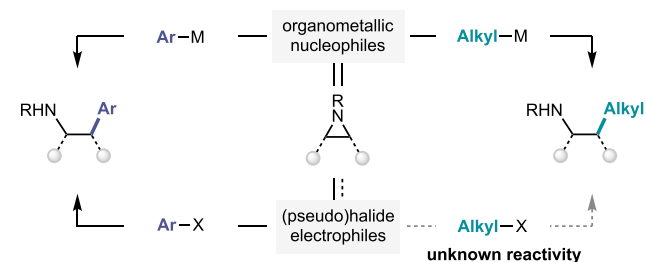
Aziridines have been employed successfully as C(sp³) electrophiles in a number of cross-coupling reactions. Work from our lab¹¹ and those of Michael,¹² Jamison,¹³ Takeda/Minakata,¹⁴ May,¹⁵ and Xiao¹⁶ have demonstrated that coupling reactions with aziridines can afford access to substituted ethylamines, important nitrogen-containing motifs in medicinal chemistry (Figure 1B).¹⁷ Organometallic nucleophiles such as organozinc halides or organoboron reagents have been employed as coupling partners to form both C(sp³)–C(sp²) and C(sp³)–C(sp³) bonds (Figure 1B, top). Recently, our lab demonstrated that aziridines can also participate in cross-electrophile coupling reactions with aryl iodides, using either a stoichiometric inorganic reductant¹⁸ or a photo-assisted reductive coupling strategy.¹⁹ Like other C(sp³)–C(sp²) cross-electrophile coupling reactions, these methods take advantage of the difference in hybridization of each coupling partner to impart selectivity (Figure 1A, bottom).²⁰ Unfortunately, direct extension of the methods for cross-selective C(sp³)–C(sp³) coupling with unactivated

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A. Prior art: C(sp³)-C(sp³) cross-electrophile & redox-neutral metallaphotoredox coupling



B. Prior art: Cross-coupling reactions with aziridines



C. This work: Ni/photoredox C(sp³)-C(sp³) coupling with aziridines

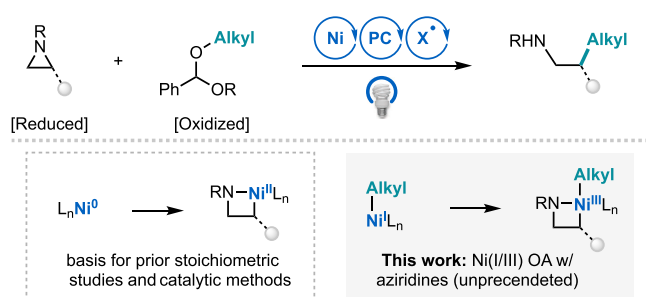


Figure 1. Cross-electrophile and redox-neutral metallaphotoredox coupling with C(sp³) precursors.

alkyl halides was not possible as both precursors undergo indiscriminate reduction at the Ni center. To address this challenge, we questioned whether we could design a selective redox-neutral C(sp³)-C(sp³) cross coupling with aziridines by using an alternative C(sp³) partner where the activation mode is decoupled from that of aziridine oxidative addition.

Herein, we report progress toward this goal in the development of a redox-neutral Ni/photoredox-catalyzed alkylation of aziridines to generate 2°-Me, 2°-1°, 2°-2° alkyl bonds (Figure 1C). The method facilitates the synthesis of a range of β -substituted sulfonamides that were previously inaccessible by traditional cross-coupling methods with aziridines. Benzaldehyde dialkyl acetals serve as the second C(sp³) coupling partner in the method, functioning to activate unactivated alcohols toward homolytic C(sp³)-O cleavage in an oxidative process²¹ that is orthogonal to aziridine activation via reduction. Differentiation of the activation modes affords an opportunity to independently tune the rate of reaction of the two partners to achieve cross-selectivity using easy to manipulate variables like light intensity. Mechanistic studies suggest that aziridine activation does not occur via Ni(0) oxidative addition, but rather via Ni(I), an elementary step that has no prior stoichiometric or catalytic precedent.^{20b,e,22}

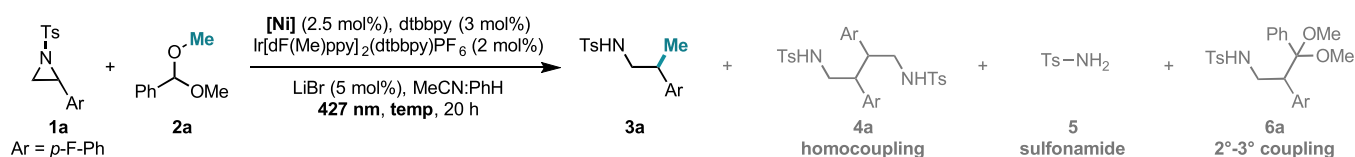
RESULTS AND DISCUSSION

Reaction Optimization. We began reaction optimization using 2-(4-fluorophenyl)-1-(*p*-tolylsulfonyl)aziridine (**1a**) and benzaldehyde dimethyl acetal (**2a**) as a methyl radical precursor. On the basis of prior studies, including our own recent work,²¹ we explored the use of halide salts as precursors to halogen radicals for HAT. We were pleased to find that using 2.5 mol % Ni(cod)₂, 5 mol % NH₄Br ($E_{1/2}[\text{Br}^-/\text{Br}^\cdot] = +0.80$ V vs SCE in DCE), and 2 mol % Ir[dF(Me)-ppy]₂(dtbbpy)PF₆ ($E_{1/2}[\text{Ir}^{\text{II}}/\text{Ir}^{\text{III}*}] = +0.97$ V vs SCE in MeCN)^{2g,23} with a 427 nm Kessil lamp at 25 °C, the desired cross-coupled product **3a** was formed in 22% yield (Table 1, entry 1). Because hydrolysis of the acetal **2a** was also observed under these conditions, we next evaluated non-protic bromide salts, including LiBr, which led to the formation of **3a** in 32% yield (Table 1, entry 2). In both these reactions, numerous undesired side products also accompanied product formation, including the dimerized aziridine (**4a**), sulfonamide **5**,²⁴ and the direct product of cross-coupling with the 3° carbon of the acetal (**6a**). Since **4a** and **5** both presumably arise from unproductive consumption of an azanickellacycle intermediate, we hypothesized that increasing the rate of methyl radical formation from **2a** might lead to better selectivity for the cross-coupled product **3a**.²⁵ Consistent with this hypothesis, we found that simply adding another lamp and increasing the lamp intensity, variables that should differentially impact the HAT cycle, afforded **3a** in 70% yield (Table 1, entry 3–4). Increasing the acetal equivalents from 1.8 to 2.4 also afforded a modest improvement in the yield of **3a** (Table 1, entry 5).

Although the conditions in entry 5 afforded a high yield of the desired product, we sought to test the robustness of the reaction under a more simplified light setup. Interestingly, while only one lamp with fan cooling afforded 34% yield of **3a**, simply removing the fans to increase the reaction temperature gave a significant increase in the yield of **3a** to 72% (Table 1, entries 6, 7), potentially because higher temperatures facilitate β -scission and increase the concentration of Me radical in solution. Finally, evaluation of a Ni precatalyst identity showed that NiBr₂·glyme gave a 10% increase in yield over Ni(cod)₂ (Table 1, entry 8).

With these optimized reaction conditions, we were pleased to find that **3a** can be obtained in useful yield even with reduced equivalents of the acetal (Table 1, entries 9 and 10). Moreover, although NiBr₂·glyme can serve as the sole source of bromide for HAT, control reactions omitting LiBr led to diminished reactivity, consistent with previous observations that the counter cation of the additive may facilitate stabilization of the anionic sulfonamide and product release (Table 1, entry 11).^{20c} Because NiBr₂·glyme is the optimal Ni source and is air- and moisture stable, the reaction can be set up and run on the benchtop, as opposed to the glovebox, and delivers **3a** with only a small decrease in yield (Table 1, entry 12).

Substrate Scope. Methylation of C(sp³) carbons is a powerful strategy in medicinal chemistry that can lead to an increase in potency, higher selectivity among bioreceptors, alteration in solubility, and enhanced protection against enzyme metabolism.²⁶ Accordingly, amines and sulfonamides bearing β -methyl groups are a highly sought structural motif in pharmaceuticals.²⁷ Nevertheless, methylation of aziridines has only been accomplished with highly nucleophilic organometallic reagents, such as Grignard reagents, organocuprates,

Table 1. Optimization of Aziridine Alkylation with Benzaldehyde Dialkyl Acetals^a

entry	acetal equiv	[Ni]	light intensity/no. of lamps	temp (°C)	yield (%)			
					3a (rsm)	4a	5	6a
1	1.8	Ni(COD) ₂	25%/1	25 ^{b,c}	22 (59)	3	12	7
2	1.8	Ni(COD) ₂	25%/1	25 ^c	32 (20)	2	10	7
3	1.8	Ni(COD) ₂	25%/2	28 ^c	68	4	10	6
4	1.8	Ni(COD) ₂	50%/2	31 ^c	70	4	5	6
5	2.4	Ni(COD) ₂	50%/2	31 ^c	79	4	7	5
6	2.4	Ni(COD) ₂	50%/1	26 ^c	34	3	22	5
7	2.4	Ni(COD) ₂	50%/1	38 ^d	72	5	7	5
8	2.4	NiBr ₂ ·glyme	50%/1	38 ^d	82	6	5	4
9	1.1	NiBr ₂ ·glyme	50%/1	38 ^d	58	10	8	7
10	1.8	NiBr ₂ ·glyme	50%/1	38 ^d	68	8	10	7
11	2.4	NiBr ₂ ·glyme	50%/1	38 ^d	47	11	12	3
12	2.4	NiBr ₂ ·glyme	50%/1	38 ^{d,e}	65	7	14	5

^aReactions performed on 0.1 mmol scale, with 1-fluoronaphthalene as the external standard (¹⁹F NMR yield for **3a**, **4a**, **6a**, ¹H NMR yield for **5**). Entries 1–2 were performed at 0.04 M, and entries 3–12 were performed at 0.057 M. For reactions with 25% intensity, vials were placed 1.5 cm away from the Kessil lamp, and for 50% intensity, vials were placed 3 cm away. Entries without (rsm) showed full conversion of the aziridine. ^bNH₄Br was used instead of LiBr. ^cThree fans were used to cool the reaction. ^dNo fans were used to cool the reaction. ^eReaction was set up on the benchtop under an inert atmosphere. Reaction with either no light, no photocatalyst, no nickel, or no nickel/ligand all gave 0% yield of the desired product.

and AlMe₃, and often results in poor regioselectivity.²⁸ Moreover, there have been no reports of successful Ni- or Pd-catalyzed cross-coupling of aziridines with methyl nucleophiles.^{11–14} Therefore, with the optimized reaction conditions in hand, we investigated the scope of the reaction with various aziridines using benzaldehyde dimethyl acetal as a methylating reagent.

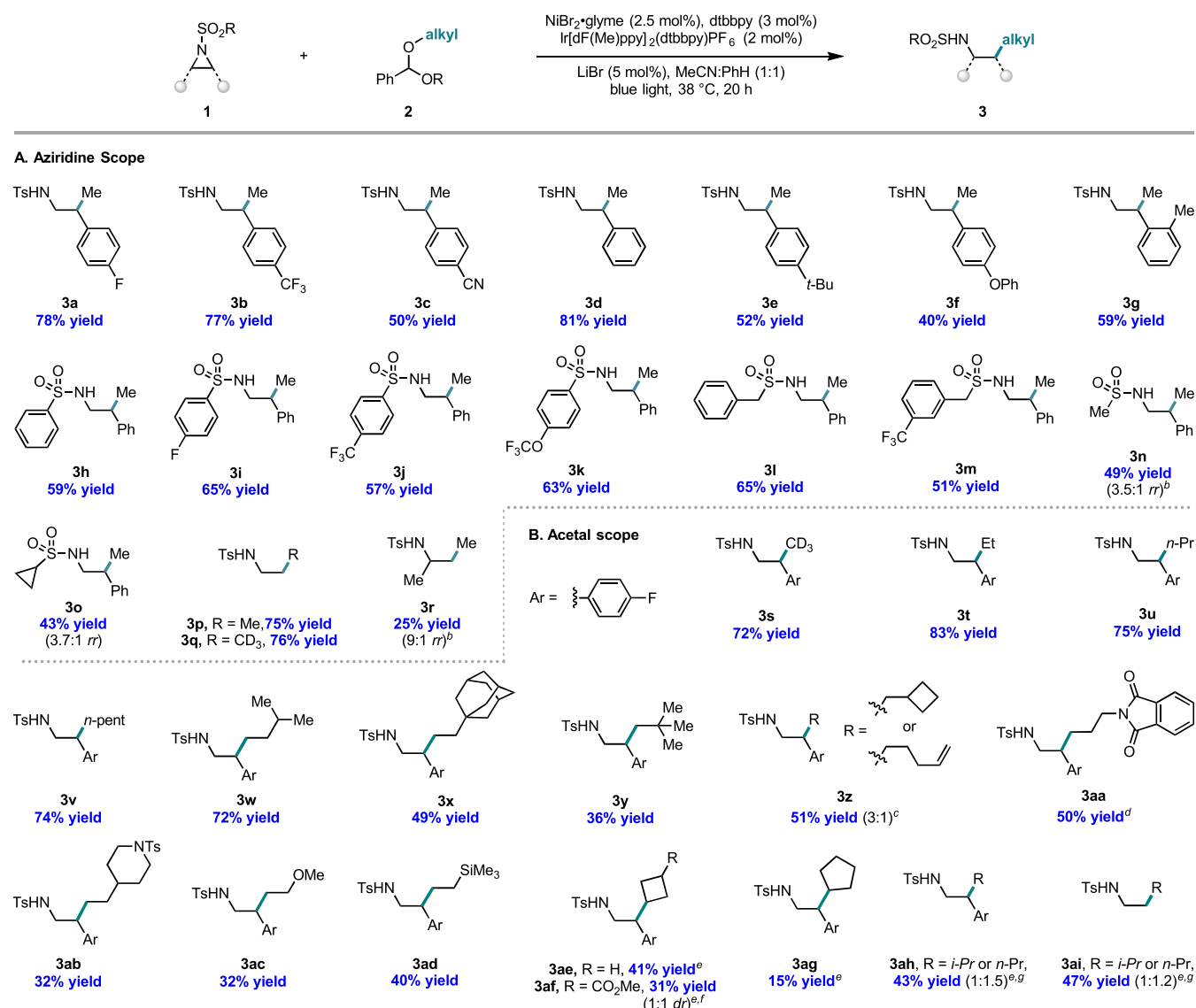
We were excited to find that a broad range of styrenyl aziridines were compatible with this Ni/photoredox methylation reaction (Table 2). Substrates bearing electron-deficient groups such as *p*-CF₃ (**3b**) or *p*-CN (**3c**) gave the β -methylated sulfonamide products in 77 and 50% yield, respectively. An unsubstituted styrenyl aziridine (**3d**) as well as those bearing electron-donating groups such as *p*-*t*-Bu (**3e**) or *p*-OPh (**3f**) also afforded the methylated products in good yield. The reaction showed minimal sensitivity to steric hindrance on the arene, with **3g** formed in 59% yield.

As sulfonamides have been frequently employed in medicinal chemistry, we also investigated aziridines with sulfonyl substituents other than a tosyl group. Aryl (**3h–3k**), benzyl (**3l**, **3m**), and alkyl sulfonamides,²⁹ such as methanesulfonamide (**3n**)^{29c} and cyclopropanesulfonamide (**3o**),^{29d,e} were tolerated in the reaction, although the alkyl sulfonamides were formed as mixtures of regioisomers with methylation favoring the benzylic position. Finally, an unsubstituted aziridine was also converted to the deuteromethyl- and methylated products **3p** and **3q** in 75 and 76% yield, respectively. A current limitation of the methodology is that aliphatic aziridines give poor conversion to the product, even with prolonged reaction times (**3r**). While styrenyl aziridines undergo preferential cleavage at the substituted site governed by the weak benzylic C–N bond strength, aliphatic aziridine **1r** undergoes methylation to give the linear product **3r** in 9:1 selectivity, likely due to a change in mechanism

favoring addition of Ni to the least sterically encumbered position.^{11b,22}

We next explored the scope of the acetal partner using 2-(4-fluorophenyl)-1-(*p*-tolylsulfonyl)aziridine (**1a**). Traditionally, β -aryl β -alkyl-substituted ethylamines have been accessed via hydride ring opening of 1,2-disubstituted aziridines;³⁰ hydroaminomethylation of styrenes with anilines;³¹ or reduction of β -aryl β -alkyl nitriles,³² nitro alkanes (or alkenes),³³ and enamides.³⁴ However, these methods require prior installation of the β -substituent, whereas the Ni/photoredox aziridine alkylation would enable introduction of the β -alkyl group late in a synthetic sequence. In so doing, this method could be more amenable to SAR studies³⁵ and the preparation of a common motif in medicinal agents such as venlafaxine (antidepressant)³⁶ and baclofen (muscle relaxants).³⁷ Indeed, we found that deuteromethyl (**3s**) as well as other unactivated linear alkyl groups such as ethyl (**3t**), *n*-propyl (**3u**), *n*-pentyl (**3v**), isoamyl (**3w**), and adamantly ethyl (**3x**) all afforded the desired products in 49–83% yield. Moreover, β -substituted alkyl coupling partners such as neopentyl (**3y**) were effective in the reaction. As another example, a methylene cyclobutyl group could be transferred in 51% yield (**3z**), wherein both the direct cross-coupling (**3z1**) and the radical ring-opened terminal alkene (**3z2**) were observed in a 3:1 ratio. Alkyl groups bearing nitrogen-derived functional groups previously reported to be incompatible with Negishi couplings of aziridines^{11a} were tolerated, such as phthalimide **3aa** and piperidine **3ab**. Ether (**3ac**)- and silyl (**3ad**)-containing alkyl coupling partners also afforded the cross-coupled products in synthetically useful yields.

We were also excited to observe reactivity between 2° alkyl coupling partners and aziridines, given that cross-coupling of 2° alkyl groups with aziridines is not feasible under reported Negishi conditions.^{11,13} Moreover, 2°–2° C–C bond formation presents a particular challenge in cross-electrophile

Table 2. Reaction Substrate Scope with Aziridines and Benzaldehyde Dialkyl Acetals^a

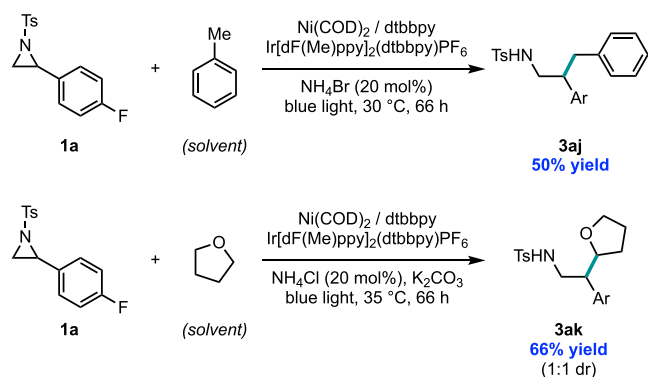
^aReactions performed on 0.2 mmol scale. 0.48 mmol of the acetal coupling partner was used. ^b48 h instead of 20 h. ^cRatio of ring-closed to ring-opened isomers. ^dPerformed on a 0.1 mmol scale using a 1 mol % photocatalyst and 1.1 equivalent of acetal at 25 °C. ^e5,5'-difluoro-2,2'-bipyridine was used instead dtbbpy. ^f1:1 *dr* at the benzylic stereogenic center of the *trans* cyclobutane. ^gdiisopropyl benzaldehyde acetal was used as the coupling partner.

strategies, with only a few examples reported to date.^{6d,e} When testing the reactivity between 2° alkyl coupling partners and aziridines, we found that application of 5,5'-difluoro-2,2'-bipyridine rather than dtbbpy as ligand enabled higher conversion to the desired product (see Supporting Information III-E for details). Both cyclic and acyclic secondary alkyl groups underwent coupling. The reaction was most efficient with cyclobutane derivatives (**3ae** and **3af**). A decrease in yield was observed as the ring size was expanded to cyclopentyl (3ag). Interestingly, use of isopropyl acetal as the 2° coupling partner afforded a cross-coupled product with a 1:1.5 ratio of branched and linear propyl groups (**3ah**). Isomerization was also observed when using an unsubstituted aziridine as a coupling partner (**3ai**), indicating that isomerization is not restricted to only congested 2°–2° C–C bond formation (*vide infra*).

Interestingly, in cases where the alkyl scaffolds are commonly employed as laboratory solvents, we found that direct C(sp³)–H alkylation can take place. For example, rather than employing benzyl alcohol or tetrahydrofuranol, we found that it is possible to directly employ toluene and THF as alkylating reagents to afford **3aj** and **3ak** in 50 and 66% yields, respectively (Scheme 1), with slight variation on the reaction conditions.

Possible Mechanistic Pathways. Oxidative addition of aziridines to Ni(0) has been established in stoichiometric studies,²² with the resulting Ni(II) azametallacycle proposed as a common catalytic intermediate in cross-coupling reactions with aziridines.^{11–13,16,20b,e} Therefore, at the outset of our reaction design, we initially hypothesized that oxidative addition of Ni(0) **I** to generate a Ni(II) azametallacycle **II** would be operative; subsequent capture of the alkyl radical to generate Ni(III) **III** followed by reductive elimination would

Scheme 1. Alkylation of Aziridine via Direct Incorporation of C(sp³)–H Substrates^a

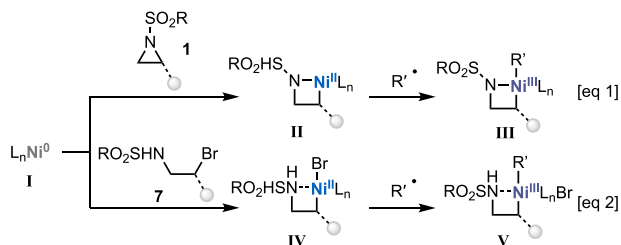


^aReactions were performed on 0.2 mmol scale, with two Kessil lamps and a fan for cooling.

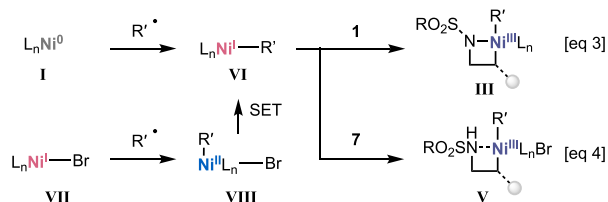
furnish the desired product (Scheme 2, eq 1). Alternatively, Ni(II) complex IV could instead arise via oxidative addition of

Scheme 2. Possible Mechanistic Pathways for Accessing Ni(III) to Enable Product Formation

A. OA of aziridines via Ni(0)–Ni(II) pathway



B. OA of aziridines Ni(I)–Ni(III) pathway



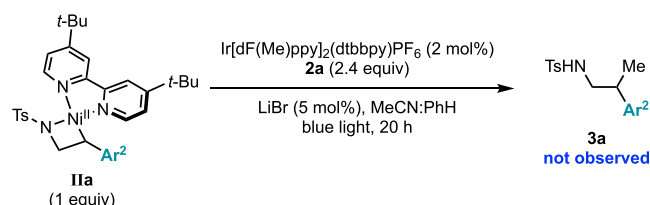
Ni(0) to benzylbromide 7 generated in situ, given the catalytic presence of bromide in solution (Scheme 2, eq 2).^{19,20e}

Nevertheless, the generation of linear/branched isomers using acyclic secondary alkyl reaction partners appeared inconsistent with these pathways (Table 2, 3ah, 3ai). In particular, β -hydride elimination and reinsertion should be more favorable at a low-valent Ni(I) VI center as opposed to the Ni(III) intermediate III in eqs 1 and 2 since isomerization necessitates a vacant coordination site and an intermediate with a relatively long lifetime.³⁸ Interestingly, the intermediacy of a Ni(I) alkyl VI would imply that aziridine activation takes place by Ni(I)–Ni(III) oxidative addition, an elementary step that does not have precedent in stoichiometric studies for aziridines (Scheme 2, eq 3), or an analogous Ni(I)–Ni(III) pathway could also be proposed with benzyl bromide 7 (Scheme 2, eq 4). The Ni(I) alkyl VI intermediate could either be accessed via radical addition to the Ni(0) I, or via radical addition to Ni(I)Br VII to first generate Ni(II)(alkyl)(Br) VIII, followed by SET.

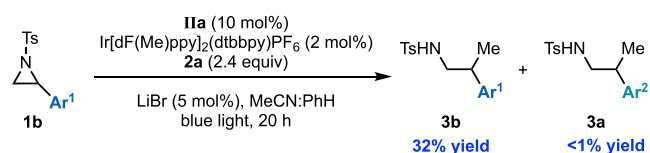
Mechanistic Investigations. To interrogate the mechanism of aziridine activation, we first sought to synthesize the Ni(II) II oxidative adduct and test its intermediacy in the coupling reaction (Scheme 2, eq 1). Complex IIa was independently synthesized by reacting Ni(cod)₂ with 1a in the presence of dtbbpy (Scheme 3A). The stoichiometric

Scheme 3. Crossover Experiment and Stoichiometric Studies with Azametallacycle IIa^a

A. Stoichiometric reactivity of azametallacycle IIa



B. Crossover experiment



^a1-Fluoronaphthalene was used as the external standard for ¹⁹F NMR yield.

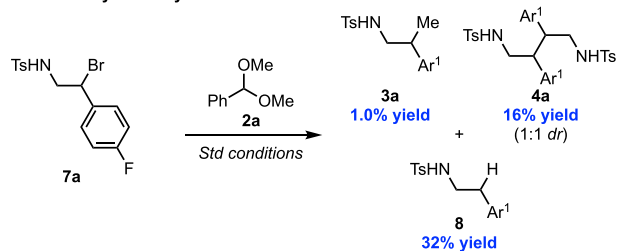
reaction of IIa under the standard reaction conditions did not result in the formation of products. Instead, IIa underwent conversion (30%) to a mixture of aziridine dimer 4a, sulfonamide 5, and reduced aziridine (see Supporting Information V-A for details). To determine if IIa accesses a catalytically relevant intermediate and if the attached aziridine in the Ni complex can be directly converted to the desired methylated product, a crossover experiment was designed using *p*-CF₃ styrenyl aziridine 1b as a substrate in the presence of 10 mol % azametallacycle IIa as the sole nickel catalyst source (Scheme 3B). However, less than 1% of the product originating from IIa (3a) was obtained, whereas the product from 1b was formed in 32% yield. These results provide evidence against the pathway shown in Scheme 2, eq 1. Furthermore, when a time-course experiment was performed, IIa was never spectroscopically observed (see Supporting Information V-A for details).

Next, we investigated the intermediacy of benzylbromide 7, pertinent to Scheme 2, eq 2 or eq 4, which could be generated by the 7.5% of bromide (2.5% from NiBr₂·glyme and 5% from LiBr) in the reaction mixture. When benzyl bromide 7a was subjected to the reaction, only 1% of the product was generated. Instead, the majority of bromide 7a was converted to dimer 4a and reduced aziridine 8 (Scheme 4A).

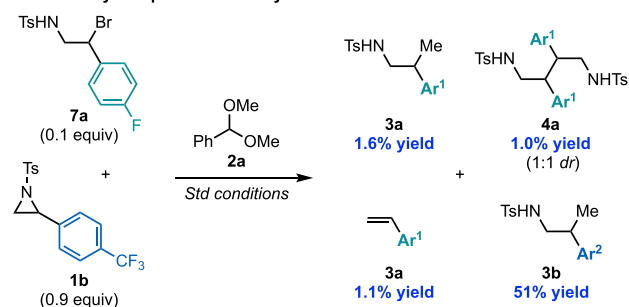
When 7a was used in catalytic quantities in the presence of aziridine 1b, as a way to simulate the catalytic formation of 7a under the standard condition, 1.6% of the product originating from 7a was observed, whereas the product derived from 1b was formed in 51% yield (Scheme 4B). Based on these observations, we propose that any in situ generated 7 most likely leads to off-cycle byproducts, presumably via oxidative addition of the benzyl bromide or halogen abstraction to generate the benzylic radical, followed by free-radical

Scheme 4. Reactivity of Benzyl Bromide 7a^a

A. Reactivity of benzylbromide



B. Reactivity comparison of benzyl bromide and aziridine



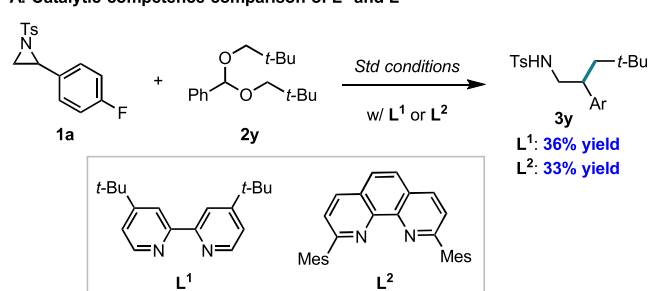
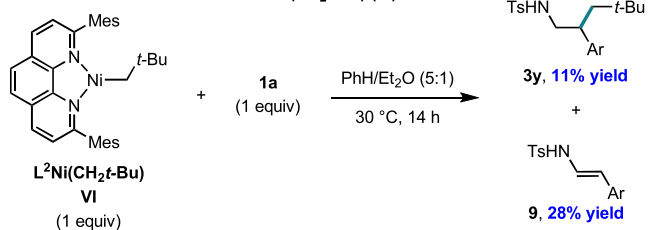
^a(A) Reaction performed 0.1 mmol scale using a stoichiometric amount of benzylbromide 7a vs (B) catalytic amount of benzylbromide 7a (0.01 mmol) and aziridine (0.09 mmol). Ar¹ = *p*-F-benzene Ar² = *p*-CF₃-benzene. Yields are based on 0.1 mmol 1-fluoronaphthalene as the external standard by ¹⁹F NMR.

recombination, a common off-cycle pathway in aryl benzyla-tion with benzylic halides.³⁹

Oxidative Addition of Aziridines via the Ni(I)–N(III) Pathway. Taken together, these data are most consistent with a pathway wherein Ni(I) undergoes oxidative addition to the aziridine (Scheme 2, eq 3). Since this step has not been previously observed, we sought direct experimental evidence for the stoichiometric oxidative addition of Ni(I) to aziridine 1a. Unfortunately, an isolable dtbbpyNi(I)(alkyl) complex has not previously been prepared. However, in their investigation of the reactivity of CO₂ at Ni(I), the Martin group reported the synthesis of a (mesityl-phenanthroline)Ni(I)(CH₂*t*-Bu) VI (Scheme 5).⁴⁰ Therefore, we sought to test this Ni(I) alkyl complex for oxidative addition reactivity with 1a. Prior to exploring stoichiometric studies with VI, we established that mesityl-substituted phenanthroline (L²) gives a yield similar to dtbbpy (L¹) in the catalytic reaction. Indeed, mesityl-substituted phenanthroline afforded 33% yield of 3y, in close agreement with the 36% yield of 3y seen with dtbbpy (Scheme 5A).

Having confirmed the catalytic competence of L², we turned our attention to the stoichiometric reaction (Scheme 5B). VI was generated in situ by adding a solution of neopentyl MgBr to L²Ni(I)Br,⁴⁰ with the resulting complex then subjected to aziridine 1a. This led to a full consumption of the aziridine, affording 11% of the cross-coupled product 3y and 28% of enamide 9, which could result from oxidative addition at the Ni(I) center, followed by elimination.⁴¹ It is possible that enamide 9 serves as a source for sulfonamide formation 5, which is observed under the catalytic conditions with L¹ and L². Taken together, these data support the catalytic relevance of a Ni(I) species for aziridine activation.

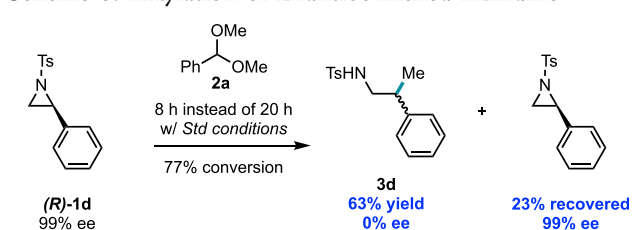
Having established the catalytic relevance of Ni(I), we sought to gain further insight into the mechanism of oxidative

Scheme 5. Stoichiometric Studies with the Ni(I) Complex^aA. Catalytic competence comparison of L¹ and L²B. Stoichiometric studies with L²Ni(CH₂*t*-Bu) (VI)

^a(A) Control experiments with L¹ (4,4'-di-*tert*-butylbipyridine) and L² (2,9-dimesityl-1,10-phenanthroline); (B) reactivity of the L₂Ni-(CH₂*t*-Bu) complex VI with aziridine 1a.

addition at Ni(I) by subjecting enantioenriched aziridine (*R*)-1d (99% ee) to the standard reaction conditions (Scheme 6).

Scheme 6. Alkylation of Enantioenriched Aziridine



^aReaction was performed on 0.2 mmol scale. Isolated yields are reported.

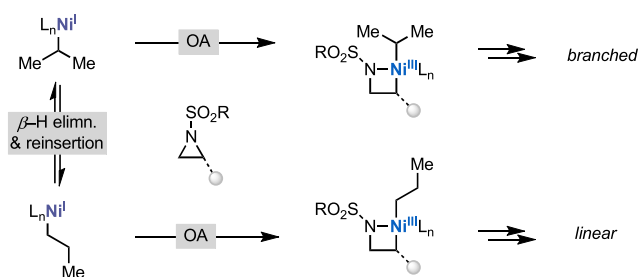
We found that the product 3d is obtained in 0% ee, while the aziridine was recovered in 99% ee at an early time point (8 h instead of 20 h). This is consistent with either (a) an irreversible and stereoablative oxidative addition via single electron-transfer^{11a} or (b) a stereospecific oxidative addition followed by racemization at Ni(III) [Scheme 2, eq 1].⁴²

Hammett Analysis. To understand the mechanism of aziridine activation via Ni(I), we evaluated the impact of aziridine substitution (Hammett analysis) on the relative rate of methylation and on the branched/linear ratio of product arising from alkylation with *i*-Pr acetal 2ah. If isomerization of the Ni(*i*-Pr) occurs prior to oxidative addition, aziridines that undergo faster oxidative addition to Ni(I) should afford higher branched/linear ratios of the product according to the proposed mechanism (Scheme 7A).⁴³ Moreover, the ρ value measuring the impact of aziridine substitution on the b/l isomer ratio with *i*-Pr acetal 2ah should be the same as the ρ value measuring the impact of aziridine substitution on rate of methylation (k_X/k_H) in this mechanistic scenario.

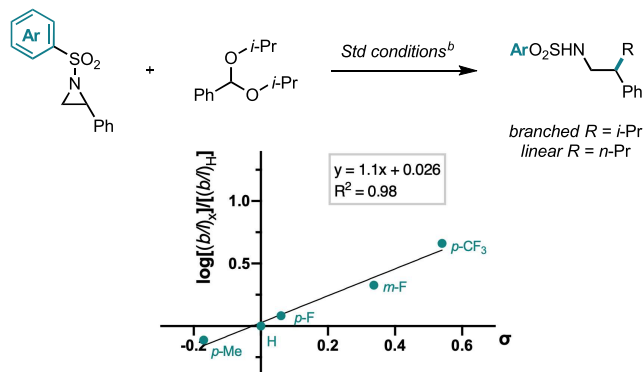
Two sites of the aziridine were independently evaluated: the benzene sulfonamide (Scheme 7B) and the benzylic arene

Scheme 7. Hammett Plot Analysis^a

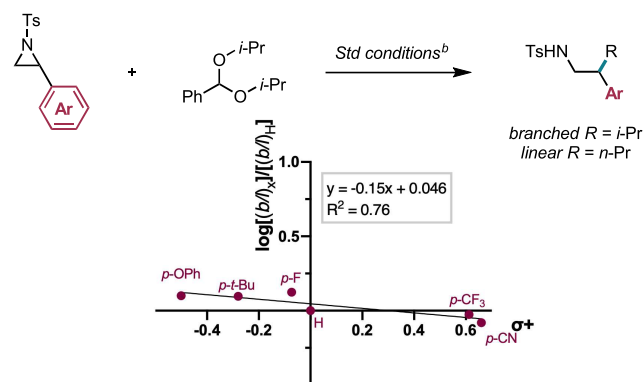
A. Isomerization of branched to linear alkyl at Ni(II) center



B. Hammett plot varying the electronics on the sulfonamide arene



C. Hammett plot varying the electronics on the styrenyl arene



^a(A) Isomerization of branched to linear alkyl species at Ni center.

(B) Hammett plot of branched vs linear product against varying substituents on aryls on sulfonamide and (C) styrenyl arene.

^bReaction was performed on 0.2 mmol scale using under standard conditions.

(Scheme 7C). When the substituents on the benzene sulfonamide were varied, we observed a high linear correlation between the $\log[(b/l)_k]/[(b/l)_H]$ [$(b/l)_k$ = branched/linear ratio of various arene substituents, $(b/l)_H$ = branched/linear ratio of Ph] with a positive ρ value ($R^2 = 0.98$, $\rho = 1.1$) (Scheme 7B). The positive, but relatively low magnitude, slope indicates that electron-withdrawing groups on the sulfonamide facilitate faster oxidative addition. Notably, a similar ρ value was obtained for the Hammett analysis measuring relative initial rates of methylation ($R^2 = 0.87$, $\rho = 1.0$) using these same substituted aziridines, providing support for the proposed mechanism wherein the b/l ratio is influenced by relative oxidative addition rates (see Supporting Information V-E).⁴⁴ When the electronics of the benzylic aryl group were modified

and plotted against Hammett–Brown constants σ^+ ,⁴⁵ or with Jiang's spin-delocalization substituent constants σ_{JJ}^\bullet (indicative of a radical stabilization effect),⁴⁶ a slightly negative but near 0 value slope was observed with $\log[(b/l)_k]/[(b/l)_H]$ (for σ^+ , $R^2 = 0.76$, $\rho = -0.15$; for σ_{JJ}^\bullet , $R^2 = 0.87$, $\rho = -0.15$) (Scheme 7C). This indicates that the identity of the benzylic arene has negligible impact on oxidative addition rates.

The distinct ρ values obtained when varying the arene on the sulfonamide versus the arene on the benzylic site, combined with the results on the stereochemical course of the coupling reaction, are most consistent with a single electron transfer oxidative addition, where Ni(I) reduces the aziridine to generate a Ni(II)-sulfonamide complex and a benzylic radical, which is followed by fast recombination of the tethered benzylic radical to afford Ni(III). The observed LFERs are inconsistent with a concerted oxidative addition, which would be expected to have positive ρ values of similar magnitude for both experiments⁴⁷ or an oxidative addition via an S_N2 -type process, which has been shown to result in a negative ρ value of larger magnitude ($\rho < -1$) in prior examples of Ni-catalyzed coupling reactions with styrenyl aziridines.⁴⁸

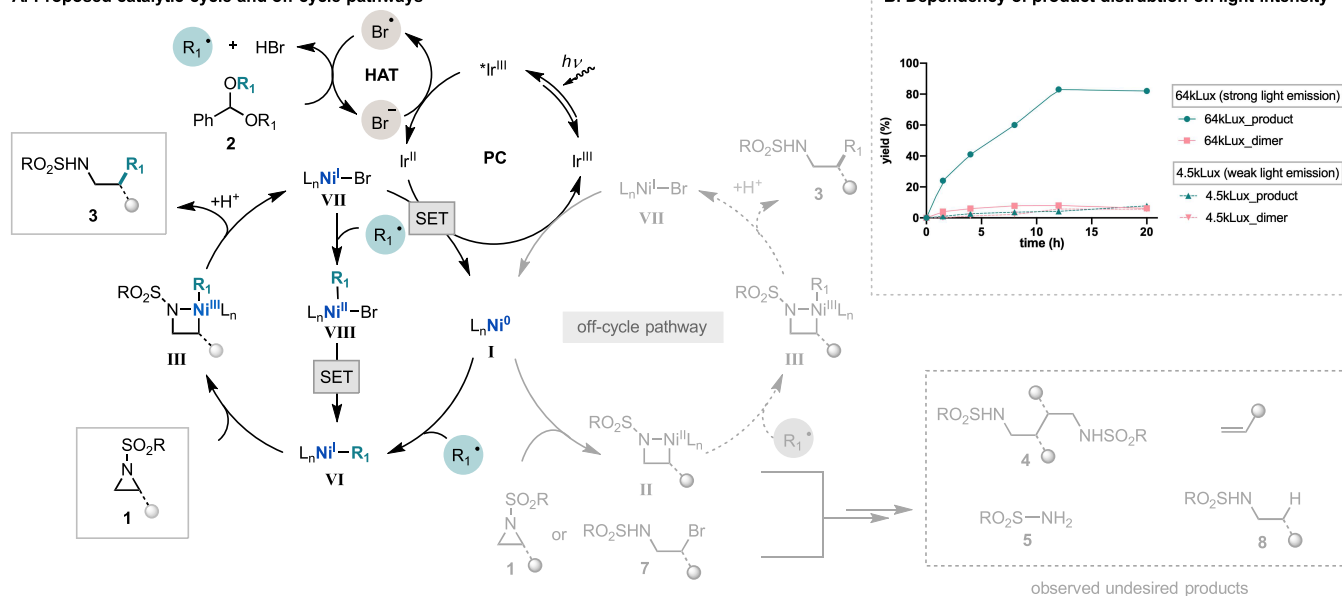
It is worth pointing out that the observed ρ values are also inconsistent with the participation of benzyl bromide 7a as a productive intermediate in the catalytic cycle (Scheme 2, eq 2 or 4). Steeper slopes ($\rho > |5|$) are found in Hammett studies for Ni(I) oxidative addition to substituted benzyl bromides.⁴⁹ Furthermore, the Hammett analysis precludes the possibility of β -H elimination and reinsertion occurring at Ni(III), which has been proposed in prior studies,⁵⁰ as more electron-deficient arenes on the benzylic site would also be expected to lead to faster reductive elimination and reduced isomerization (i.e., both ρ values > 0).

Proposed Catalytic Cycle. On the basis of our mechanistic investigations, we propose the following catalytic cycle (Scheme 8A, black). Upon irradiation with blue light, the excited Ir photocatalyst oxidizes bromide anions. The resulting bromine radical can abstract the 3° benzylic C–H of the benzaldehyde dialkyl acetal, followed by β -scission to generate the alkyl radical and ester byproduct.^{21b} Concurrently, the NiBr₂glyme precatalyst can be reduced to Ni(0) I by Ir(II) to enter the Ni catalytic cycle, which can capture the alkyl radical generated from the β -scission event to afford Ni(I)(alkyl) VI. Alternatively, a NiBr₂glyme precatalyst can be reduced to generate Ni(I)Br, which in turn could intercept the alkyl radical to first generate Ni(II)(Br)(alkyl) followed by SET to generate the same Ni(I)(alkyl) VI intermediate.^{51,52} Based on our stoichiometric, catalytic and spectroscopic observations, we propose that Ni(I)(alkyl) VI undergoes oxidative addition to the aziridine by a single electron transfer mechanism. Reductive elimination from the resulting Ni(III) III complex then affords the cross-coupled product with regeneration of Ni(I) VII. Finally, VII would be reduced by the Ir(II) species to turn over the catalytic reaction.⁵³

We also identified off-cycle pathways that lead to undesired byproducts (Scheme 8A, gray). For instance, if aliphatic radical generation by HAT/ β -scission or trapping by Ni is slow, Ni(0) I oxidative addition to the aziridine would afford Ni(II) azametallacycle II and resulting degradation products. Moreover, any generation of benzylbromide 7 could lead to undesired dimer 4 and reduced aziridine 8. Sulfonamide 5 and styrene formation may arise from inefficient cross-coupling, on the grounds of observing enamide 9 formation

Scheme 8. Proposed Mechanistic Pathway and Off-Cycle Pathways

A. Proposed catalytic cycle and off-cycle pathways



^aStrong light emission: 50% light intensity where the vials were placed 3 cm away from the Kessil lamp, maintained at 38 °C. Weak light emission: 25% light intensity where the vials were placed 20 cm away from the Kessil lamp while heating in an oil bath at 38 °C.

using Ni(I) oxidative addition in the stoichiometric studies. This proposed competition of light-mediated cross-reactivity with off-cycle speciation pathways is further supported by comparing the relative product and dimer formation with varying light intensity (Scheme 8B, see Supporting Information V-F for details). For example, when performing a time-course study comparing the ratio of product **3a** to dimer **4a** at high versus low light intensity (64 kLux, vs 4.5 kLux), the lower light intensity conditions result in the formation of nearly 1:1 ratio of the desired product to the dimer. Suppression of off-cycle speciation is therefore partially dependent on having sufficient light penetration to favor the productive catalytic pathway.

■ CONCLUSIONS

In conclusion, we have developed a $\text{C}(\text{sp}^3)\text{--C}(\text{sp}^3)$ cross-coupling methodology between aziridines and benzaldehyde dialkyl acetals as latent alkyl radical sources. The transformation employs a diverse set of styrenyl aziridines with varying substitution on the sulfonamide. Moreover, methyl and 1° and 2° unactivated aliphatic coupling partners can be installed efficiently. The orthogonal activation of each coupling component and ligation at distinct Ni oxidation states imparts cross-selectivity between two $\text{C}(\text{sp}^3)$ precursors. Specifically, mechanistic studies support a pathway for activation of aziridines via $\text{Ni(I)}\text{--Ni(III)}$ oxidative addition, distinct from the commonly proposed oxidative addition of aziridines to Ni(0) . These mechanistic studies shed light on the nature of the activation modes for unconventional $\text{C}(\text{sp}^3)$ precursors, which we anticipate can lead to the expansion of $\text{C}(\text{sp}^3)\text{--C}(\text{sp}^3)$ cross-coupling methodologies in future studies.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/jacs.2c09294>.

Experimental procedures, detailed optimization tables, characterization of newly synthesized compounds, and spectroscopic data ([PDF](#))

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Notes

The authors declare no competing financial interest.

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