Chapter 5

Ni-Catalyzed Halogenation of Alkenyl Triflates[‡]

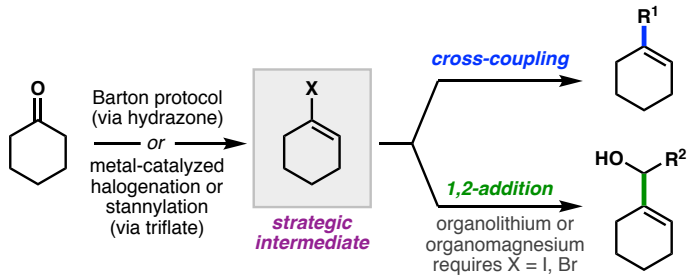
5.1 INTRODUCTION

Alkenyl halides are versatile functional groups that can be used in various carbon–carbon and carbon–heteroatom bond-forming reactions. For example, alkenyl halides are commonly used in transition metal-catalyzed cross-coupling reactions,[1,2] or are converted via metal-halogen exchange to nucleophiles for 1,2-additions to carbonyl compounds (Figure 5.1).[3] Furthermore, the alkenyl halide moiety also appears in some natural products and bioactive molecules.[4–6] Whereas acyclic alkenyl halides are easily prepared from the corresponding alkyne[7–11] or aldehyde,[12,13] most cyclic alkenyl halides are synthesized from

[‡]The research presented in this chapter was completed in collaboration with Kelsey E. Poremba (graduate student) and Alexander M. Shimozono (graduate student) in the Reisman group. Portions of this chapter are reproduced from a manuscript which was currently under peer review at the time of thesis publication.

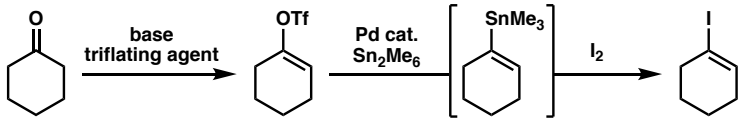
the corresponding ketone. The most direct method for alkenyl halide synthesis is the Barton reaction (and variations thereof),[14–20] which proceeds through an intermediate hydrazone. These reactions are notoriously capricious: the formation of the requisite hydrazone can be challenging on sterically encumbered substrates and the halogenation step often produces mixtures of alkenyl halide isomers or dihalide side products.[13]

Figure 5.1 *Strategies to access alkenyl halides and their utility in organic synthesis.*



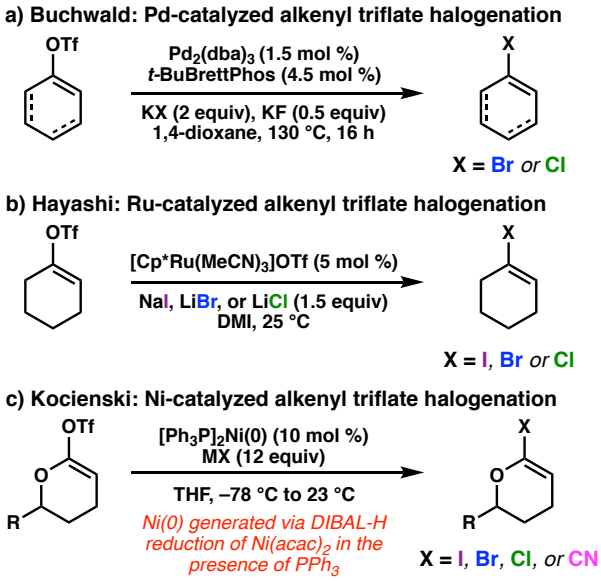
As a result, alkenyl triflates, which can be prepared directly from cyclic ketones under either kinetic or thermodynamic control, have emerged as attractive "pseudohalides" for transition metal-catalyzed cross-coupling processes. Unfortunately, alkenyl triflates cannot be directly converted to the corresponding alkenyllithium or alkenylmagnesium species commonly employed in 1,2-addition reactions. In cases where the Barton procedure to prepare the alkenyl halide is poor yielding, a multistep alternative is frequently employed: 1) conversion of the ketone to alkenyl triflate, 2) conversion of the triflate to the alkenyl stannane, and 3) conversion of the stannane to the alkenyl halide (Scheme 5.1).[21] This process uses stoichiometric quantities of hexamethylditin, which is a volatile, toxic substance. The ability to develop direct, mild methods to convert alkenyl triflates to alkenyl halides that proceed without the need for organostannane reagents (Sn_2Me_6) would improve and streamline the preparation of valuable alkenyl halide intermediates.

Scheme 5.1 *Preparation of alkenyl halides through organostannane intermediates.*



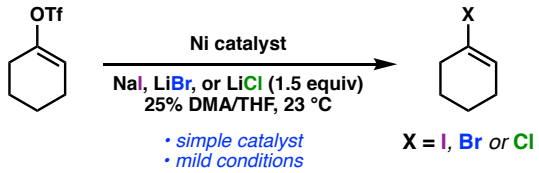
Towards this end, Buchwald and coworkers reported a Pd-catalyzed reaction to convert alkenyl triflates to alkenyl bromides and chlorides;[22,23] however, there are no examples of alkenyl iodide formation, and the reaction requires an expensive ligand, temperatures greater than 100 °C, or additives such as fluoride salts or *i*-Bu_3Al (Scheme 5.2a). These additives limit the functional group compatibility of the reaction, particularly with common groups such as silyl ethers. More recently, Hayashi and coworkers reported a Ru-catalyzed method to convert alkenyl triflates to iodides, bromides, or chlorides that proceeds at ambient temperature (Scheme 5.2b); however, the requisite ruthenium catalyst is not commercially available and only three examples of alkenyl iodide formation are reported.[23,24] An example of a Ni-catalyzed bromination of a dihydropyranyl triflate was reported by Kocienski and coworkers (Scheme 5c),[25] which proceeds with an active Ni(0) catalyst generated via DIBAL–H reduction of $Ni(acac)_2$ in the presence of PPh_3. While the authors note that the corresponding iodide, bromide, chloride, and nitrile can be obtained, only moderate yields of the bromide and nitrile are reported; no yields for the iodide and chloride are disclosed. In our hands, application of these conditions to a simple cyclic alkenyl triflate derived from menthone provided <10% yield of product (iodide, bromide, and chloride). Given the reported literature conditions, it is well-precedented that a general Ni-catalyzed alkenyl triflate halogenation could be developed; however, mild reaction conditions are required to render the reaction permissive of sensitive functional groups.

Scheme 5.2 *Metal-catalyzed alkenyl triflate halogenations.*



During our investigations of Ni-catalyzed asymmetric reductive coupling reactions of alkenyl bromides, we observed an off-pathway halide exchange process that generated alkenyl chlorides and iodides (see Chapter 4, Figure 4.16–17).[26,27] Whereas Ni-catalyzed aryl[28,29] and alkenyl[29–33] halide exchange processes have been previously reported and extensively investigated, the corresponding reactions of alkenyl triflates have not been developed.[25,34] Having observed promising reactivity with styrenyl triflates in a related cross-coupling reaction (see Chapter 2, Scheme 2.3),[35] we hypothesized that an appropriate Ni catalyst and inexpensive halide salts might enable the direct conversion of alkenyl triflates to alkenyl halides under mild conditions. Herein, we report the development of a simple procedure where commercially available $Ni(cod)_2$ catalyzes the conversion of alkenyl triflates to alkenyl iodides, bromides, and chlorides in good to excellent yields (Scheme 5.3). Mechanistic studies of the reaction are conducted and development of conditions that proceed with Ni(II) and a metal reductant are discussed.

Scheme 5.3 *Mild Ni-catalyzed halogenation of alkenyl triflates.*

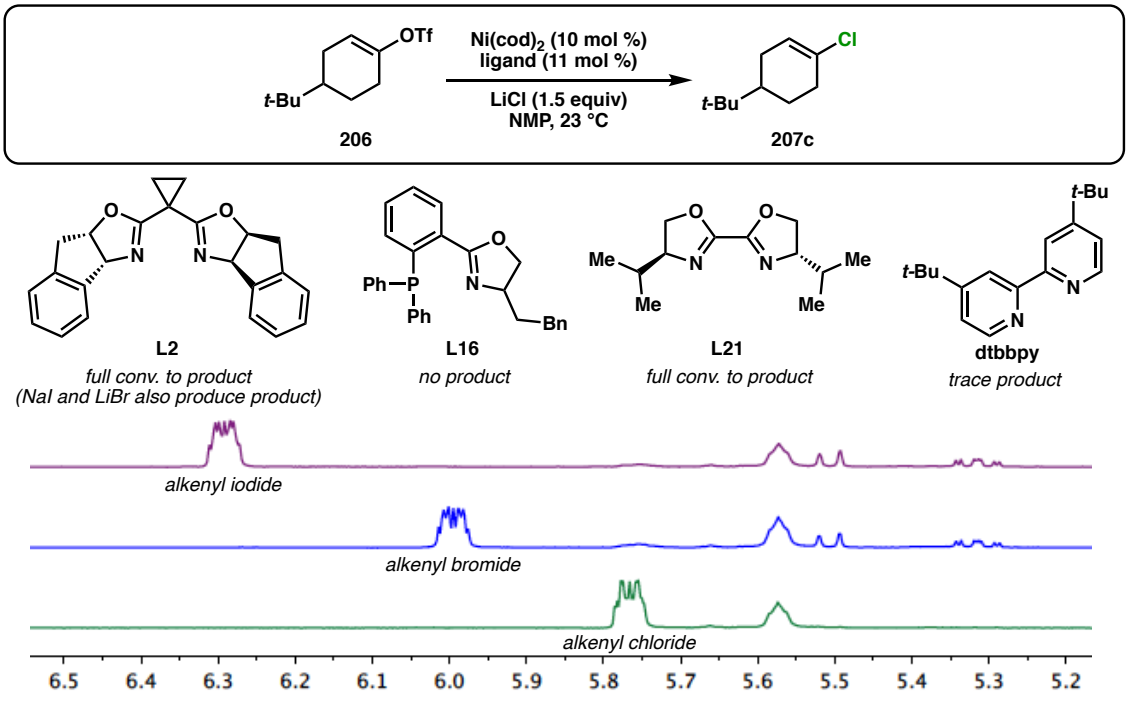


5.2 REACTION OPTIMIZATION

5.2.1 Initial Hit

Given our observation of alkenyl halide exchange during previously developed reductive cross-couplings with alkenyl bromides, we set out to test conditions that could afford alkenyl triflate halogenation in the presence of ligands used for reductive cross-couplings (Figure 5.2). When catalytic $Ni(cod)_2$ and either BOX ligand **L2** or BiOX

Figure 5.2 *Initial observation of Ni(0)-mediated alkenyl triflate halogenation.*

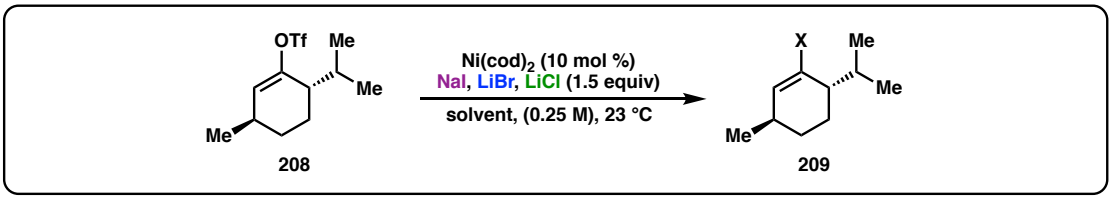


ligand **L21** were used with LiCl in NMP at room temperature (conditions used to mimic Hayashi's Ru-catalyzed reaction), the desired alkenyl chloride was formed with full consumption of starting material. PHOX ligand **L16** and bipyridine ligand dtbbpy failed to provide the desired alkenyl chloride product. When NaI and LiBr were used as the halide source in combination with BOX ligand **L2**, the desired alkenyl bromide and iodide were formed with full consumption of the alkenyl triflate. The β-alkenyl proton relative to the alkenyl halide is observed to shift downfield in the ^{1}H NMR spectrum as the halide increases in size and polarizability. Interestingly, a control experiment showed the alkenyl halide product was formed in the absence of ligand, indicating that added ligand is not required to promote the transformation.

5.2.2 Solvents

We set out to quantify and optimize the desired halogenation reaction with alkenyl triflate **208**, which is prepared in one step from commercially available menthone. Our goal was to identify general conditions that could provide the alkenyl iodide, bromide, or chloride simply by changing the halide salt. A variety of solvents were evaluated in the presence of 10 mol % $Ni(cod)_2$ and 1.5 equiv of halide salt (either NaI, LiBr, or LiCl) (Table 5.1). These initial experiments showed that alkenyl iodide formation proved most sensitive to the solvent: for example, while the bromination and chlorination worked comparably well in DMA, THF, and DMF, the yield of the alkenyl iodide was significantly better in DMA than both THF and DMF (entries 1–3). Due to improved physical properties of the reaction mixture and work-up, mixtures of DMA and THF were evaluated, and a 1:3 mixture of DMA and THF was selected as the optimal solvent system (entries 5–7).

Table 5.1. *Evaluation of solvents.*

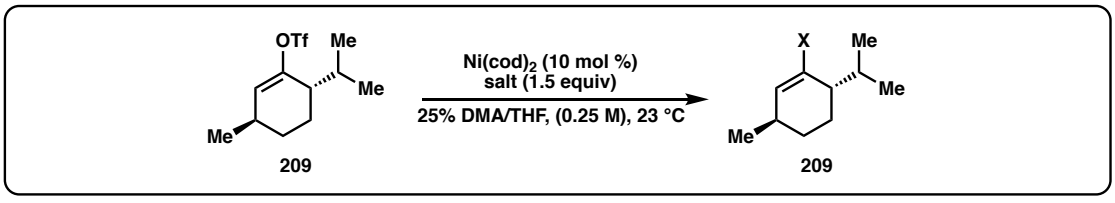


		Iodination		Bromination		Chlorination	
Entry	Solvent	Yield (%)	Triflate (%)	Yield (%)	Triflate (%)	Yield (%)	Triflate (%)
1	DMA	72	0	75	0	70	0
2	THF	35	43	75	0	61	5
3	DMF	34	47	74	0	70	3
4	MeCN	4	85	52	36	7	81
5	10% DMA/THF	68	30	68	0	77	0
6	25% DMA/THF	74	3	74	0	74	0
7	40% DMA/THF	68	0	71	0	64	0

5.2.3 Halide Source

We then investigated a variety of salts used as the halide source (Table 5.2). While K^+ salts provided poor results for all halides (entry 3), Na^+ salts only provided poor yields for bromination and chlorination (entry 1). The iodination with NaI proceeded in good yield. In contrast to K^+ and Na^+, both Li^+ salts and tetrabutylammonium salts worked well for all halides providing the alkenyl halide products in comparable yields (entries 2 and 4).

Table 5.2. *Evaluation of halide salts.*

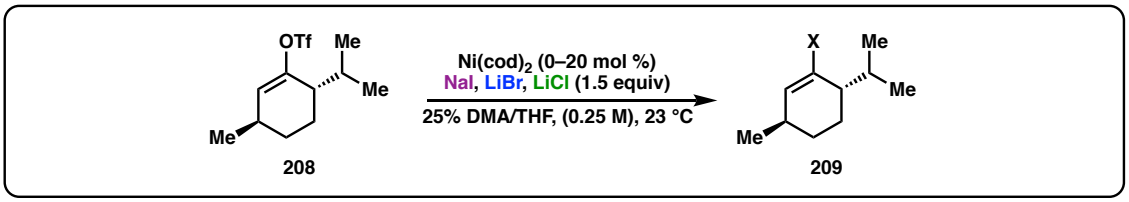


		Iodination		Bromination		Chlorination	
Entry	Salt	Yield (%)	Triflate (%)	Yield (%)	Triflate (%)	Yield (%)	Triflate (%)
1	NaX	74	3	58	6	10	69
2	LiX	70	0	74	0	74	0
3	KX	36	43	8	61	13	75
4	TBAX	71	5	84	0	80	10

5.2.4 Catalyst Loading

The catalyst loading of $Ni(cod)_2$ was evaluated and shown to provide the alkenyl iodide **209a** with the highest yield at 10 mol % Ni, whereas alkenyl bromide **209b** and alkenyl chloride **209c** were formed with the highest yield at 5 mol % Ni. Typically, higher Ni loadings resulted in decreased yield due to the increased formation of alkene homodimer. Overall, 10 mol % $Ni(cod)_2$ was selected for further optimization and used to evaluate the substrate scope because it proved most robust over a broad range of substrates. However, for highly reactive substrates, lower catalyst loadings can be beneficial to reduce formation of homodimer.

Table 5.3. *Evaluation of catalyst loading.*



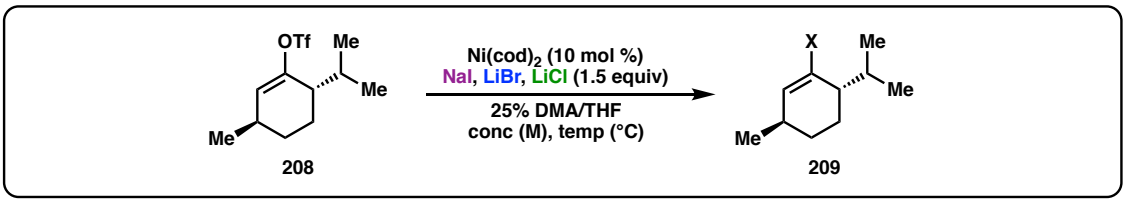
		Iodination		Bromination		Chlorination	
Entry	Ni (mol %)	Yield (%)	Triflate (%)	Yield (%)	Triflate (%)	Yield (%)	Triflate (%)
1	0	0	82	0	96	0	94
2	5	68	4	83	0	77	0
3	10	74	3	74	0	74	0
4	20	70	0	55	0	67	0

5.2.5 Concentration and Temperature

The concentration and temperature of the reaction were evaluated to determine if alternate conditions could increase the yield of product (Table 5.4). When the halogenation reaction was conducted at 0 °C (entry 1), the yield was suppressed compared to room temperature (entry 3). Increasing the temperature to 60 °C only provided slight

improvement of yield (entry 5). The concentration was also investigated, and the desired alkenyl halide products were formed in comparable yields across a range of conditions (0.1–0.4 M).

Table 5.4. *Evaluation of temperature and solvents.*

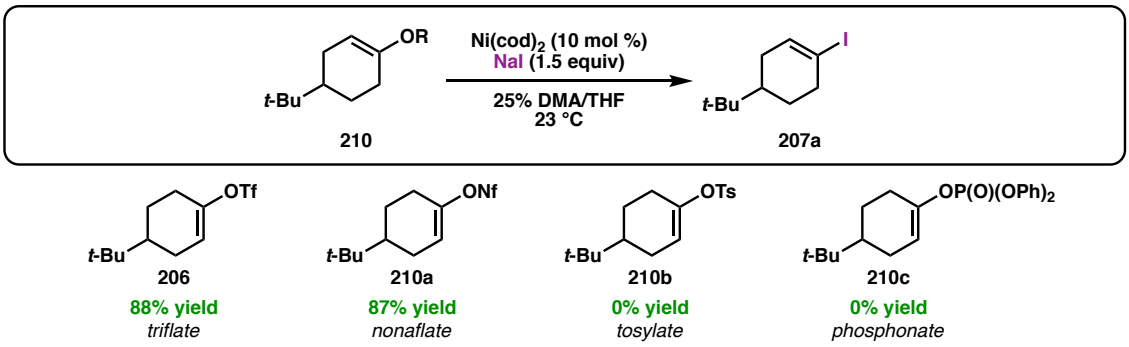


			Iodination		Bromination		Chlorination	
Entry	Temp (°C)	Conc (M)	Yield (%)	Triflate (%)	Yield (%)	Triflate (%)	Yield (%)	Triflate (%)
1	0	0.2	12	74	61	26	61	0
2	23	0.1	67	0	71	0	63	0
3	23	0.2	74	3	74	0	74	0
4	23	0.4	62	30	82	0	72	0
5	60	0.2	77	10	80	0	72	0

5.2.6 Other Alkenyl Electrophiles

Other alkenyl electrophiles were evaluated given that Hayashi and coworkers successfully employed alkenyl nonaflates, tosylates, and phosphonates in their Ru-catalyzed alkenyl triflate halogenation halogenation.[23] When $Ni(cod)_2$ was used as the catalyst, indeed both the alkenyl triflate **206** and alkenyl nonaflate **210a** were competent substrates to form desired alkenyl iodide **207a** (Figure 5.3). However, alkenyl tosylate **210b** and alkenyl phosphonate **210c** did not react under the optimized conditions. Although this diminishes the scope of the Ni-catalyzed transformation, it enables a divergent approach where substrates containing both an alkenyl triflate and alkenyl tosylate moiety could potentially be differentiated using a Ni-catalyzed approach in contrast to the Ru-catalyzed method.

Figure 5.3 *Evaluation of alkenyl electrophiles.*

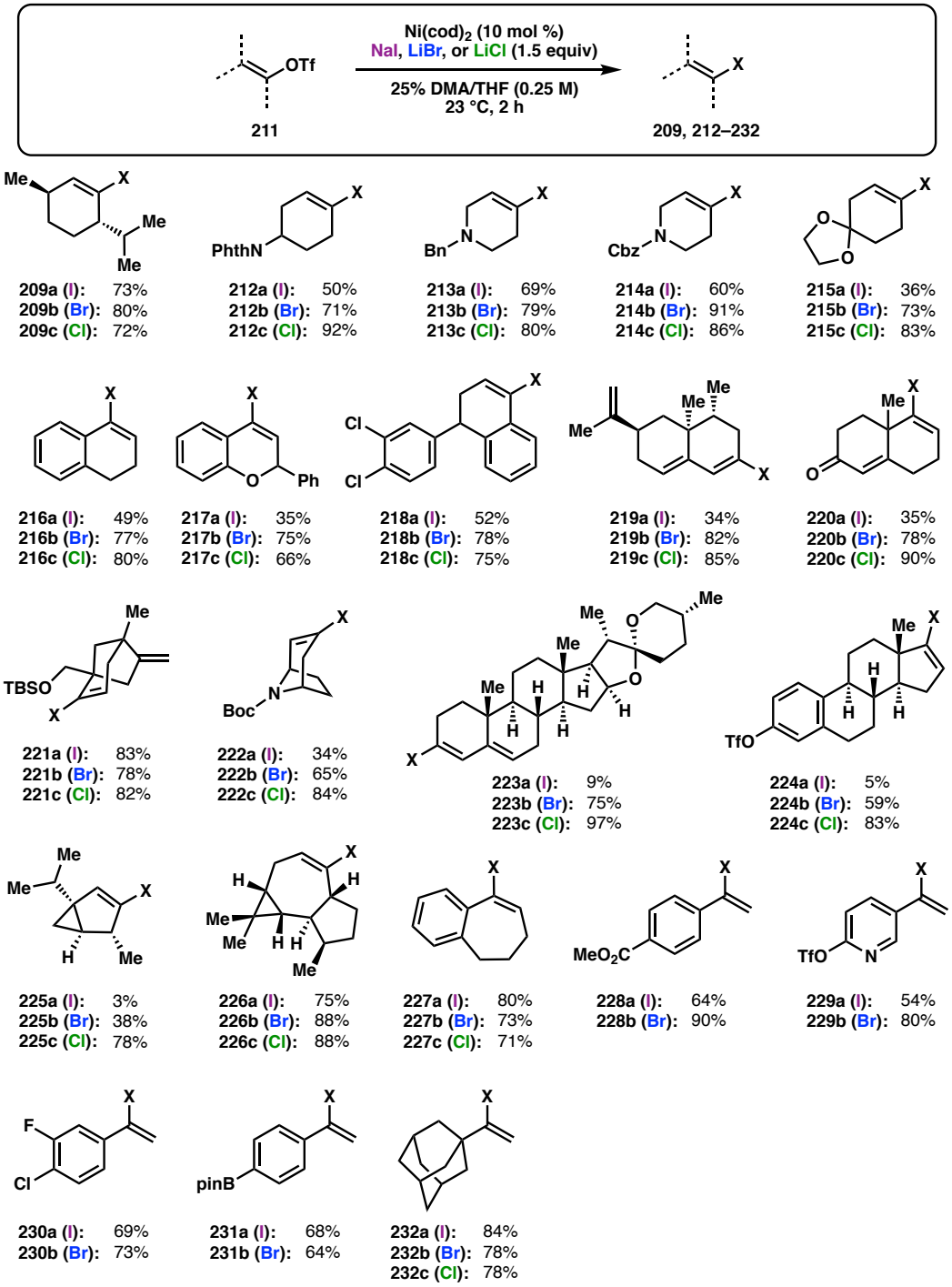


5.3 SUBSTRATE SCOPE

Having identified optimal reaction conditions with the $Ni(cod)_2$ catalyst, the substrate scope of the transformation was investigated (Figure 5.4). The halide exchange was found to be compatible with a variety of common functional groups, including amines (**213**), carbamates (**214**, **222**), pyridines (**229**), alkenes (**219**, **221**), esters (**228**), ketals (**215**, **223**), and enones (**220**). Dienyl bromides and chlorides could also be prepared in good yields; the yields of the corresponding iodides were typically lower (**219, 223**). Chemoselective halogenation of the alkenyl triflate was observed in preference to aryl triflates (**224**, **229**), aryl chlorides (**218**, **230**), and aryl boronates (**231**); however, competitive halide exchange was observed in the presence of aryl bromides and iodides. To demonstrate synthetic utility and scalability, the iodination of **208** was conducted on gram scale to afford 1.1 g of alkenyl iodide **209a** in 71% yield.

Although the Ni-catalyzed halogenation exhibits good functional group tolerance, the iodination, bromination, and chlorination did not perform equally well on all substrates. With the exception of the 1-arylvinyl triflates, the formation of the alkenyl chlorides

Figure 5.4 *Evaluation of substrate scope.*



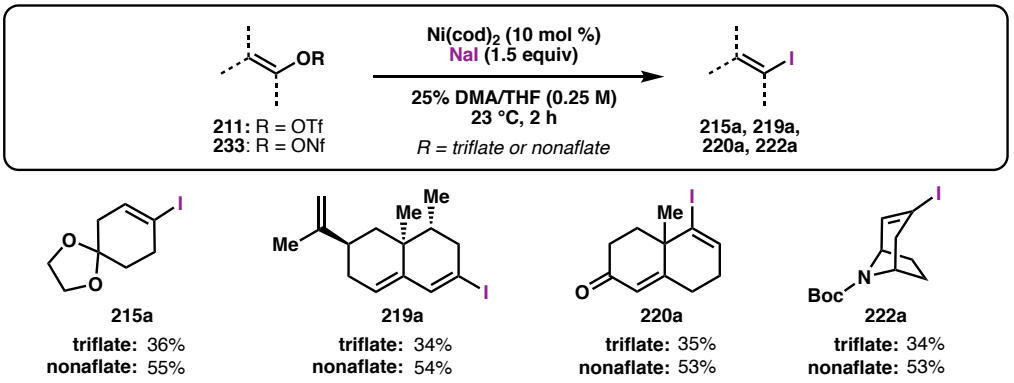
Reactions are conducted on 0.3 mmol scale under N_2. Isolated yields are provided. **225b** was conducted with 5 mol % $Ni(cod)_2$. **221b** and **221c** were conducted on 0.1 mmol scale. Yields for **217a**, **223a**, **224a**, and **225a** were determined by NMR on 0.1 mmol scale.

proceeded with the most consistently high yields across different substrate classes. Under these conditions, 1-arylvinyl triflates (**228**–**231**) provided the corresponding bromides and iodides in good yields; however, in the presence of chloride salts, elimination of the triflate by LiCl to give the aryl acetylenes outcompeted chlorination, a process previously reported by Li and coworkers.[36] The use of tetrabutylammonium salts did not improve the desired transformation. For non-styrenyl triflates, the yield of alkenyl iodide was most substrate-dependent. For example, cyclopentenyl triflates (**224**, **225**) were poor substrates for alkenyl iodide formation, but gave good yields of the alkenyl chlorides. The alkenyl iodide formation typically worked best for unactivated cyclohexenyl and cycloheptenyl triflates.

For several substrates, alkenyl iodide formation from the triflate was poor yielding (**215**, **219**, **220**, and **222**). Schoenebeck and coworkers recently reported a Ni-catalyzed trifluoromethyltiolation of alkenyl triflates and found lower yielding substrates could be rescued via the use of the corresponding alkenyl nonaflates.[34] Alkenyl nonaflates are not only more stable than their corresponding alkenyl triflates, but the calculated $\Delta G^{\ddagger}$ suggests a 0.4 kcal/mol decrease in the barrier for oxidative addition.[34,37] We were pleased to find that the use of alkenyl nonaflates could be used to improve the yield of lower yielding substrates with nearly a 20% increase in product yield (Figure 5.5).

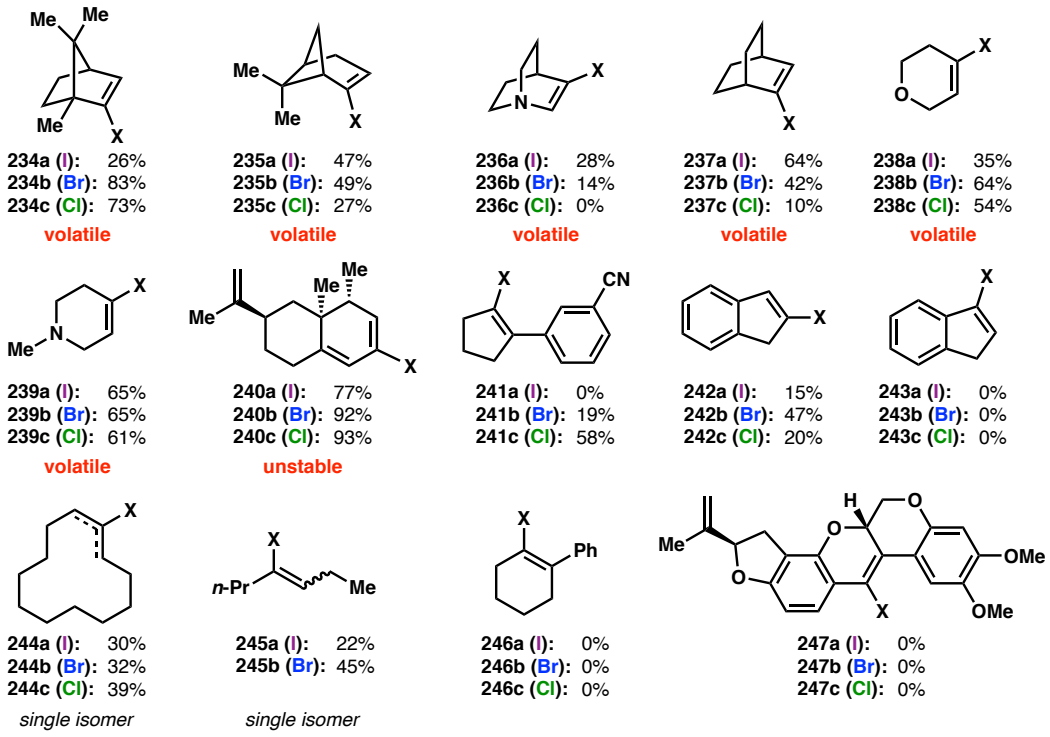
Although the alkenyl triflate halogenation tolerates a variety of functional groups, the reaction does possess some limitations (Figure 5.6). For instance, a variety of fused bicycles were evaluated and the alkenyl halide products were formed in moderate to low yields. The alkenyl triflate derived from camphor provided the desired bromide (**234b**) and chloride (**234c**) in good yields; however, the formation of the iodide (**234a**) was low

Figure 5.5 *Evaluation of alkenyl nonaflate iodination.*



yielding. Furthermore, isolation of the bicyclic compounds was difficult due to purification difficulties (coelution with homocoupling) and product volatility. Dienyl halide **240** was formed in excellent yield; however, the product isomerized to **219** upon standing and during purification. Other substrates provided geometric constraints. Typically, five-

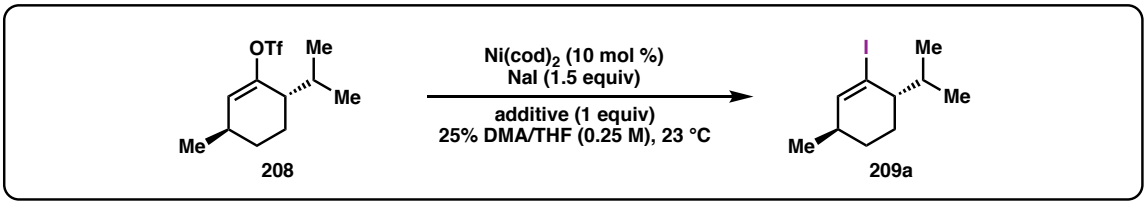
Figure 5.6 *Substrates possessing purification difficulties and diminished yields.*



membered rings did not undergo full conversion (**241**, **242**, and **243**). Linear alkenyl triflates that were added as a mixture of isomers converged to a single isomer during the reaction; however, the yield was still fairly low (**244** and **245**). Finally, tetrasubstituted alkenes failed to provide the desired alkenyl halide product (**246** and **247**).

Lastly, given the observation of competitive halide exchange, we conducted a robustness screen to determine what coupling handles could be tolerated (Figure 5.7). When a variety of additives were added to the reaction, some were fully recovered while others were consumed. Competitive halide exchange was observed for alkyl bromides (including activated benzylic bromides) in addition to aryl bromides and aryl iodides. Aryl chlorides, aryl triflates, aryl boronic esters, and benzylic chlorides were tolerated under the reaction conditions, although the yield of **209a** was diminished in some cases.

Figure 5.7 *Evaluation of added coupling handles.*

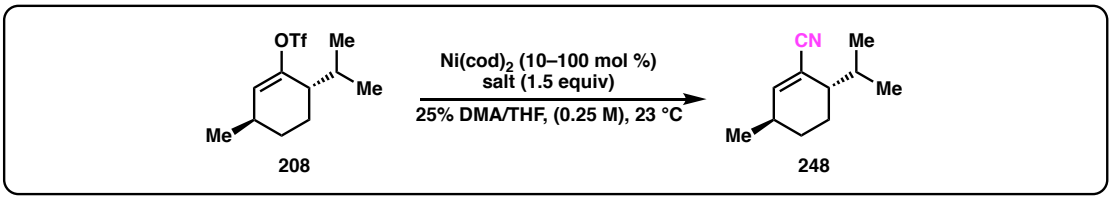


Additive	none	I, OMe	Br, OMe	Cl, OMe	OTf, OMe	Bpin	*n*-Pr, Br, *n*-Pr	Me, Br	Me, Cl
Recovery of Additive	–	19%	37%	65%	100%	100%	47%	32%	87%
Yield of Alkenyl Iodide	77%	31%*	37%	72%	29%	73%	31%	0%	59%
Other Products from Additive	–	71% ArBr	25% ArI	–	–	–	13% alkyl I	76% BnI	–

*LiBr in place of NaI, yield is of alkenyl bromide

Fluoride and cyanide salts were also evaluated in addition to the reported halogenations (X = I, Br, Cl). In all cases, fluorination failed to provide the desired product (F^- sources included NaF, LiF, and TBAF). However, the use of NaCN and TBACN provided the desired alkenyl nitrile **248** under the optimized reaction conditions (Table 5.5), albeit in trace yield (<5%). A variety of solvents were then screened, and alkenyl nitrile **248** was obtained in 18% yield when the reaction was run in DMSO (entries 1–6); the reactions, however, exhibited poor conversion. When stoichiometric $Ni(cod)_2$ was used, **248** was formed in 50% yield (entry 7). The use of tetrabutylammonium cyanide, which eliminated possible metal cation effects, also produced **248** in low yield (entry 8).

Table 5.5. *Evaluation of conditions for alkenyl nitrile formation.*



				Cyanation	
Entry	Ni (%)	Salt	Solvent	Yield (%)	Triflate (%)
1	10	NaCN	DMA	15	46
2	10	NaCN	DMF	2	77
3	10	NaCN	MeOH	0	82
4	10	NaCN	DMSO	18	33
5	10	NaCN	MeCN	2	75
6	10	NaCN	DMPU	16	16
7	100	NaCN	25% DMA/THF	50	6
8	10	TBACN	25% DMA/THF	16	16

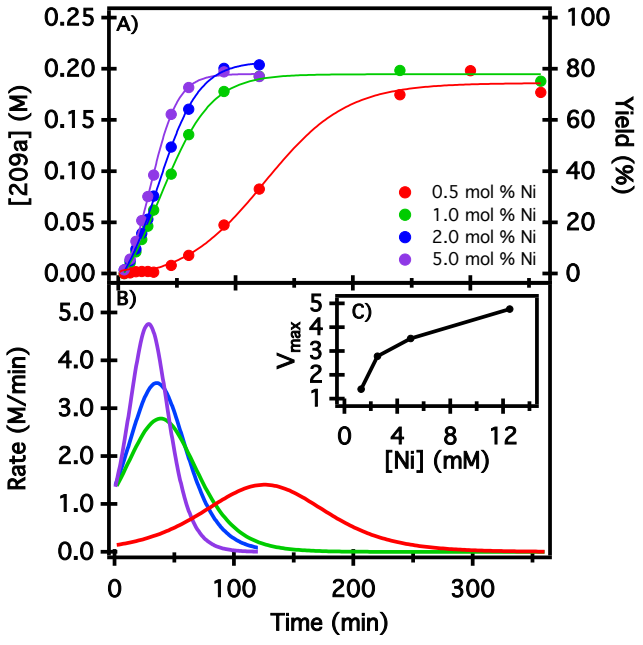
5.4 MECHANISTIC INVESTIGATIONS

To better understand the Ni-catalyzed halogenation of alkenyl triflates, and the iodination in particular, a series of mechanistic experiments were performed.

5.4.1 Kinetics

We began by studying the kinetics of the iodination reaction with $Ni(cod)_2$. The reaction was first conducted at a variety of Ni loadings (5–20 mol % $Ni(cod)_2$) which all displayed identical reaction profiles, suggesting a zero-order rate dependence on Ni. However, further lowering the catalyst loading (0.5–5 mol %) revealed a positive rate dependence on Ni (Figure 5.8a). Excitingly, the iodination of **208** could be run with loadings as low as 0.5 mol % $Ni(cod)_2$, which provided a comparable yield of **209a** as long as the reaction was given sufficient time to obtain full conversion. At low catalyst loadings (e.g. 0.5 mol %) the reaction also exhibited a prominent induction period, which complicated initial rate kinetic analysis. Blackmond and coworkers have demonstrated the use of sigmoidal fits to extract V_{max} data from reactions exhibiting induction periods.[38] In

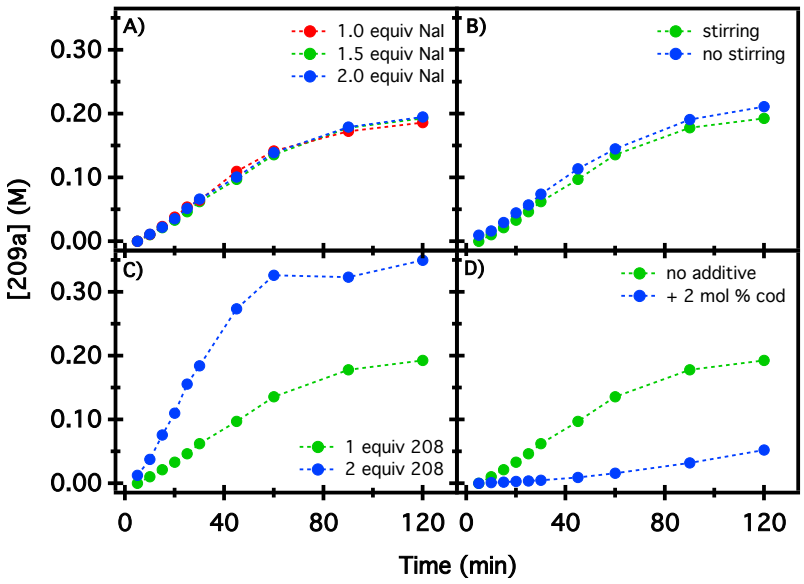
Figure 5.8 *Analysis of alkenyl iodide as a function of time, determination of V_{max}, and observation of positive order rate on [Ni].*



order to process our data, each run in Figure 5.8a was fit with a sigmoid fit in Igor Pro software, which were subsequently plotted over the existing data points. The derivative of each fit was calculated in Excel to give the rate of the product formation as a function of time (Figure 5.8b). The maximum rate was extracted from the respective plots (V_{max}). PlottingV_{max} vs. [Ni] revealed that the reaction has a positive-order dependence on [Ni] that negatively deviates from first order at higher [Ni] (Figure 5.8c), suggesting the formation of dimeric (or higher order) off-cycle species at higher [Ni].

We also evaluated the kinetic profile of the reaction while altering a number of other parameters (Figure 5.9). No change in the rate of iodination of **208** was observed when the amount of NaI was increased beyond 1 equivalent when conducted at 1 mol % $Ni(cod)_2$ (Figure 5.9a). Altering the stir rate of the reaction (stirring vs. no stirring) also displayed no rate dependence on the iodination of **208**, suggesting that the reaction does not proceed via a hetereogenous process (Figure 5.9b). When the concentration of alkenyl

Figure 5.9 *Kinetic profile of alkenyl iodide with a series of reaction variations.*

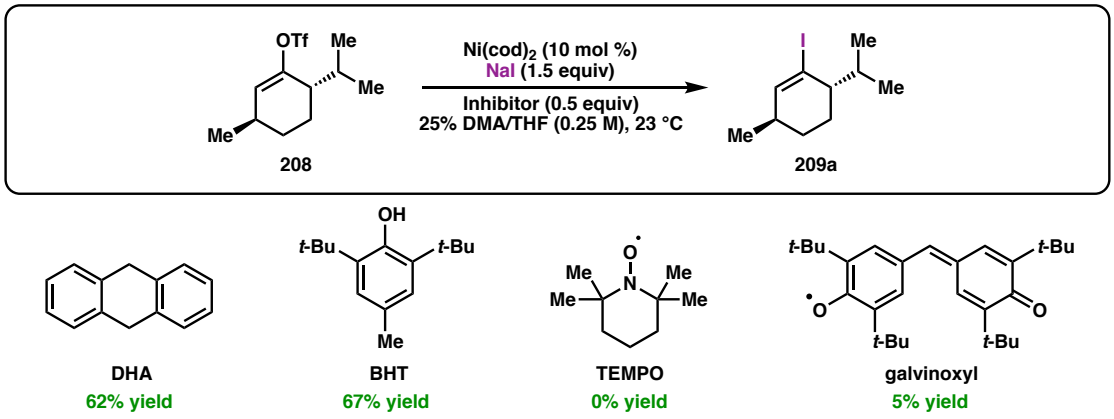


triflate was doubled (from 0.25 M to 0.5 M) while maintaining the concentration of NaI (0.375 M), the rate of product formation over time (reported as M/min) approximately doubled, indicating that substrate is present in the rate determining step of the reaction (Figure 5.9c). Finally, the addition of exogenous cyclooctadiene was found to inhibit the reaction rate, therefore we speculate that ligand dissociation could be the source of the induction period (Figure 5.9d). When the reaction with exogenous cyclooctadiene was run for 14 hours, **209a** was formed in 80% yield, indicating that cyclooctadiene does not inhibit overall reactivity.

5.4.2 Radical Inhibitors

A variety of radical inhibitors and free radicals were added to the reaction (Figure 5.10). With the addition of radical inhibitors such as DHA and BHT, alkenyl iodide **209a** was produced in slightly diminished yield. However, when free radicals such as TEMPO and galvinoxyl were added, reaction conversion ceased. Given these results, it is possible that a radical species is present in the mechanism or that added free radicals are able to bind to the active Ni catalyst and shut down productive reactivity.

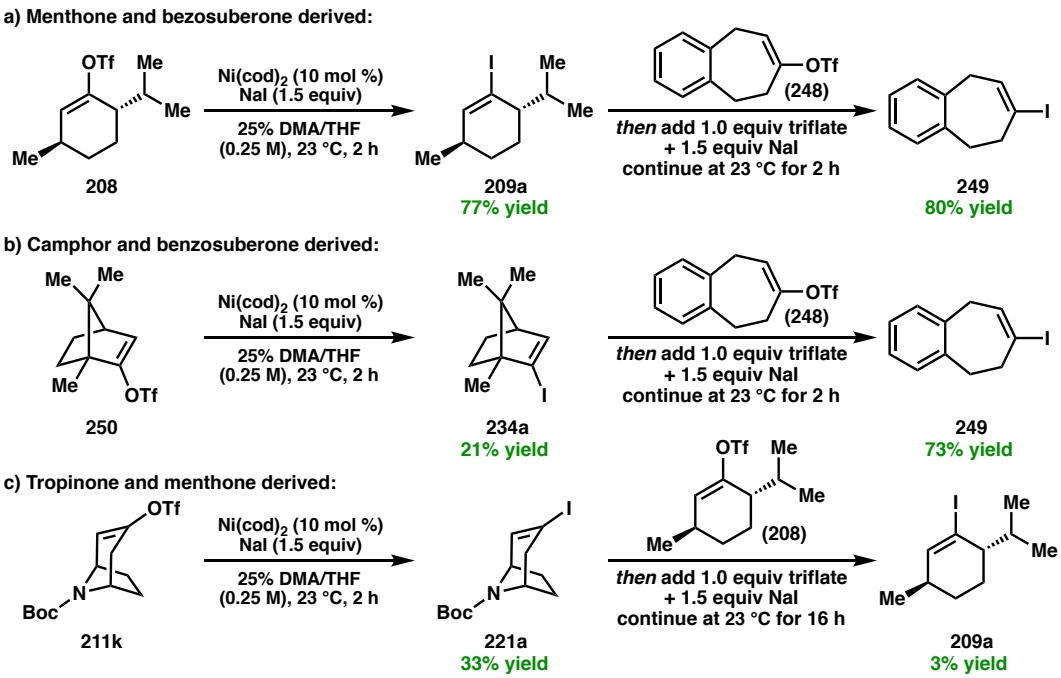
Figure 5.10 *Evaluation of radical inhibitors.*



5.4.3 Investigating Catalyst Inhibition

During the evaluation of substrate scope, typically products which were formed in low yield were typically met with poor conversion of the starting material. In order to investigate whether catalyst deactivation was occurring, a series of batch experiments and kinetic studies were conducted. A series of alkenyl triflates were converted to the desired alkenyl halides for 2 hours before an additional alkenyl triflate and added NaI was added to the reaction (Scheme 5.4). In some cases, the second triflate underwent full conversion and provided the alkenyl iodide (Scheme 5.4a–b); however, in some cases reactivity had ceased (Scheme 5.4c).

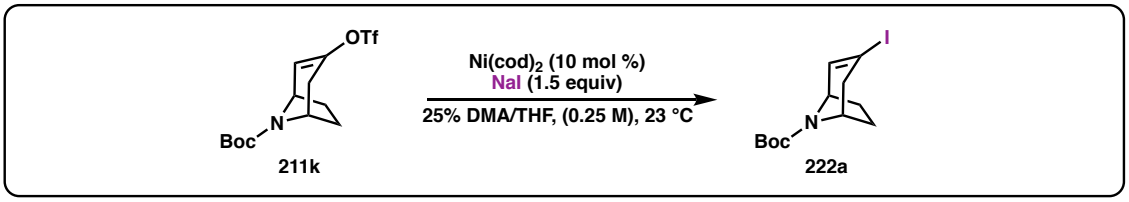
Scheme 5.4 *Investigation of catalyst deactivation by sequential substrate addition.*



Further experimental conditions were evaluated to improve the conversion of alkenyl triflate **211k** (Table 5.6). Unfortunately, attempts to improve the yield of low-

yielding reactions (due to incomplete conversion of starting material) with $Ni(cod)_2$ as the catalyst were ultimately unsuccessful: addition of excess $Ni(cod)_2$ did not improve the yield of **222a** and instead afforded additional diene side product (entry 2). The homocoupled diene product was isolated and added to the halogenation reactions; however, it did not inhibit product formation when included at 5 mol % and 10 mol % loadings (entries 3–4). Finally, added NaI or increased reaction time also showed no improvement (entries 5–6).

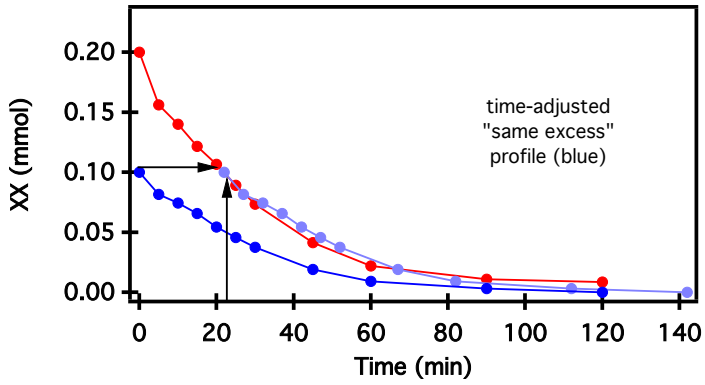
Table 5.6. *Evaluation of conditions to improve low yielding substrates.*



		Iodination		
Entry	Conditions	Yield (%)	Triflate (%)	Diene (%)
1	2 h	38	31	9
2	2 h, then add $Ni(cod)_2$ for 16 h	40	20	12
3	+ 5 mol % diene	35	41	11
4	+ 10 mol % diene	37	42	15
5	2 h, then add NaI for 16 h	36	39	8
7	18 h	37	38	8

We then turned back to kinetics to study the possibility of catalyst inhibition by reaction progress kinetics analysis, a method recently described by Blackmond and coworkers, where a "same excess" reaction was conducted and analyzed (Figure 5.11).[38,39] Only 0.1 mmol of **208** was added instead of 0.2 mmol, and the data was offset by the time it required the 0.2 mmol reaction to have 0.1 mmol of remaining starting material. The kinetic traces overlay nicely for the remainder of the reaction, indicating that no catalyst is decomposing during the course of the reaction.

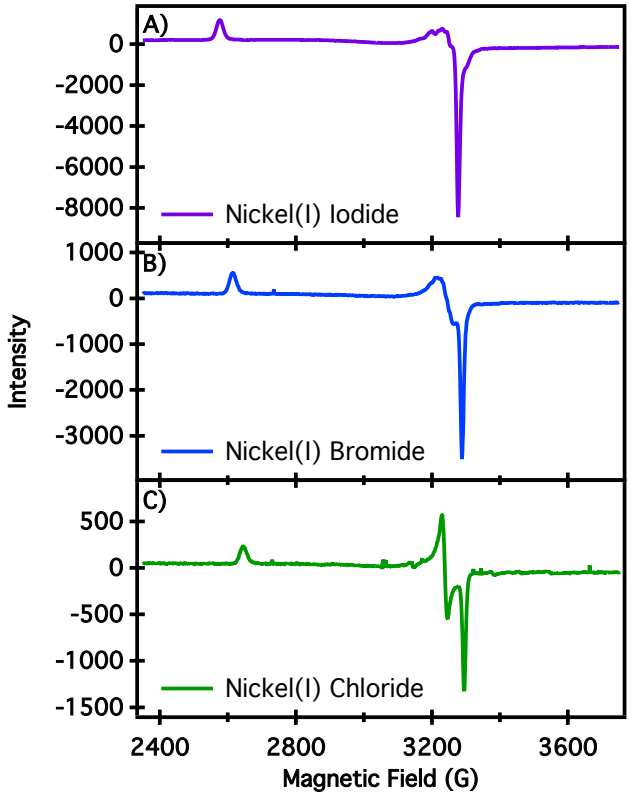
Figure 5.11 *Same excess kinetic profile indicating no catalyst decomposition.*



5.4.4 EPR Spectroscopy

Given the likelihood that radical species may be present during the course of the reaction, we decided to analyze the crude reaction by EPR spectroscopy (Figure 5.12).

Figure 5.12 *EPR spectra of Ni(I) halides*



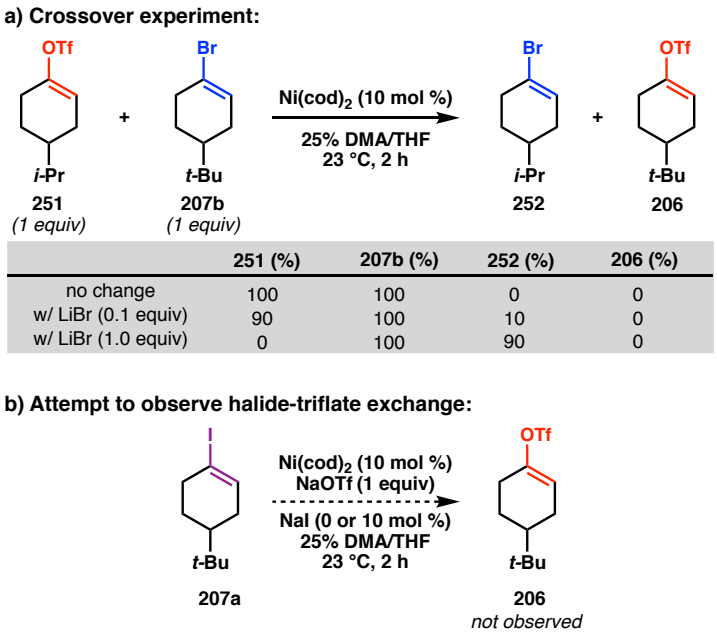
When the iodination reaction of **208** was monitored by EPR with 5 mol % $Ni(cod)_2$, a Ni(I) signal grew in over the course of the reaction, reaching a maximum concentration at 30 minutes before disappearing (Figure 5.12a). When the reaction was instead conducted with LiBr or LiCl, the EPR signal was present as well, albeit with decreased intensity and alterations in the spectral features, both in the observed hyperfine coupling and shift in g-value (Figure 5.12b–c). This suggests that the observed Ni(I) species contains the halogen nucleus. Differences in the electronegativity and polarizability of the halogens could result in differences in spin-orbit coupling and alter the level of hyperfine coupling observed (most prominent for iodide). Furthermore, the observation that increased Δg occurs as the halide size increases could possibly be due to different HOMO–LUMO spacings in the molecular orbital energy levels. The Ni(I) signals shown in Figure 5.12 were then successfully reproduced by mixing a solution of $Ni(cod)_2$ with the corresponding alkenyl halide, resulting in oxidative addition to form the Ni(I) halide complexes and alkenyl homocoupling which was observed by ^1H NMR. While this observed Ni(I) signal could potentially be active in the catalytic cycle, quantification of this species with an external standard of $CuSO_4$ in 1:9 ethylene glycol/H_2O provided the result that only 2% of the total Ni content (i.e. 2% x 5% = 0.1 mol % Ni(I)) resided as this particular Ni(I) species.

5.4.5 Crossover Experiments

Finally, a crossover experiment was designed to evaluate the reversibility of alkenyl halide formation (Figure 5.13). Treatment of a 1:1 mixture of **251** and **207b** with $Ni(cod)_2$ (10 mol %) in 1:3 DMA/THF at 23 °C resulted in complete recovery of **251** and **207b**, without detection of crossover products **252** or **206** (Figure 5.13a). Addition of 0.1 or 1.0

equivalents LiBr resulted in conversion of **251** to **252** in 10% and 90% yield, respectively. No **206** was detected at any point in either reaction. Furthermore, the subjection of alkenyl iodide **207a** to $Ni(cod)_2$ (10 mol %) and metal triflate salts (e.g. NaOTf) did not result in alkenyl triflate formation (Figure 5.13b).

Figure 5.13 *Crossover experiments to probe reversible alkenyl triflate formation.*

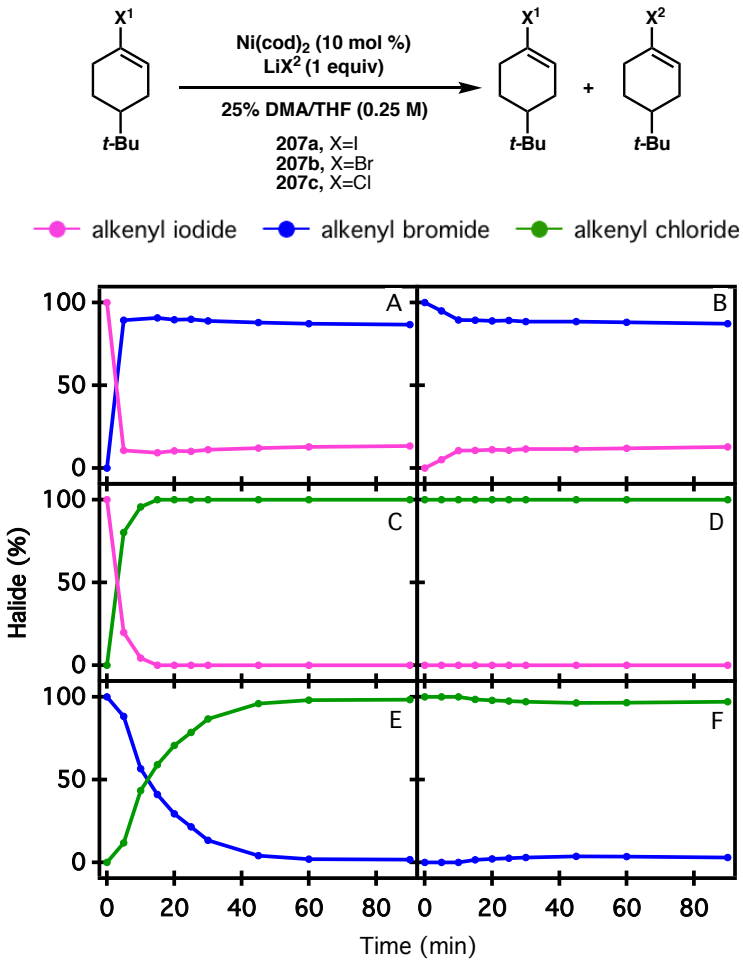


	251 (%)	207b (%)	252 (%)	206 (%)
no change	100	100	0	0
w/ LiBr (0.1 equiv)	90	100	10	0
w/ LiBr (1.0 equiv)	0	100	90	0

Interestingly, no evidence of oxidative addition was observed by ^1H NMR when alkenyl triflate **208** and $Ni(cod)_2$ (5 mol %) were mixed in the presence or absence of NaOTf. However, upon addition of a metal halide salt, conversion of **208** to alkenyl halide **209a** was observed. This is in contrast to the oxidative addition of aryl triflates which have previously been shown undergo oxidative addition to (dppf)Ni(cod) to form Ni(I) complexes.[40,41] Taken together, these results suggest that oxidative addition of the alkenyl triflate is irreversible, or that halide exchange for triflate in the oxidative addition complex is rapid and irreversible. In either scenario, the fact that the enol triflate is irreversibly

consumed enables the reaction to proceed in good yield to the respective alkenyl halides. This is in contrast to Ni-catalyzed halide exchange reactions, which are thermodynamically driven equilibrium processes (Figure 5.14).[29] For example, after 2 h, an 85:15 mixture of **207a**:**207b** is obtained for both the Ni-catalyzed reactions of **207b** with LiI, or **207a** with LiBr (Figure 5.14a–b). Although the formation of alkenyl chloride **207c** appears to be the

Figure 5.14 *Ratios in terms of percentages for halide cross-over experiments:* ***A)*** *alkenyl iodide + LiBr,* ***B)*** *alkenyl bromide + LiI,* ***C)*** *alkenyl iodide + LiCl,* ***D)*** *alkenyl chloride + LiI,* ***E)*** *alkenyl bromide + LiCl, and* ***F)*** *alkenyl chloride + LiBr.*

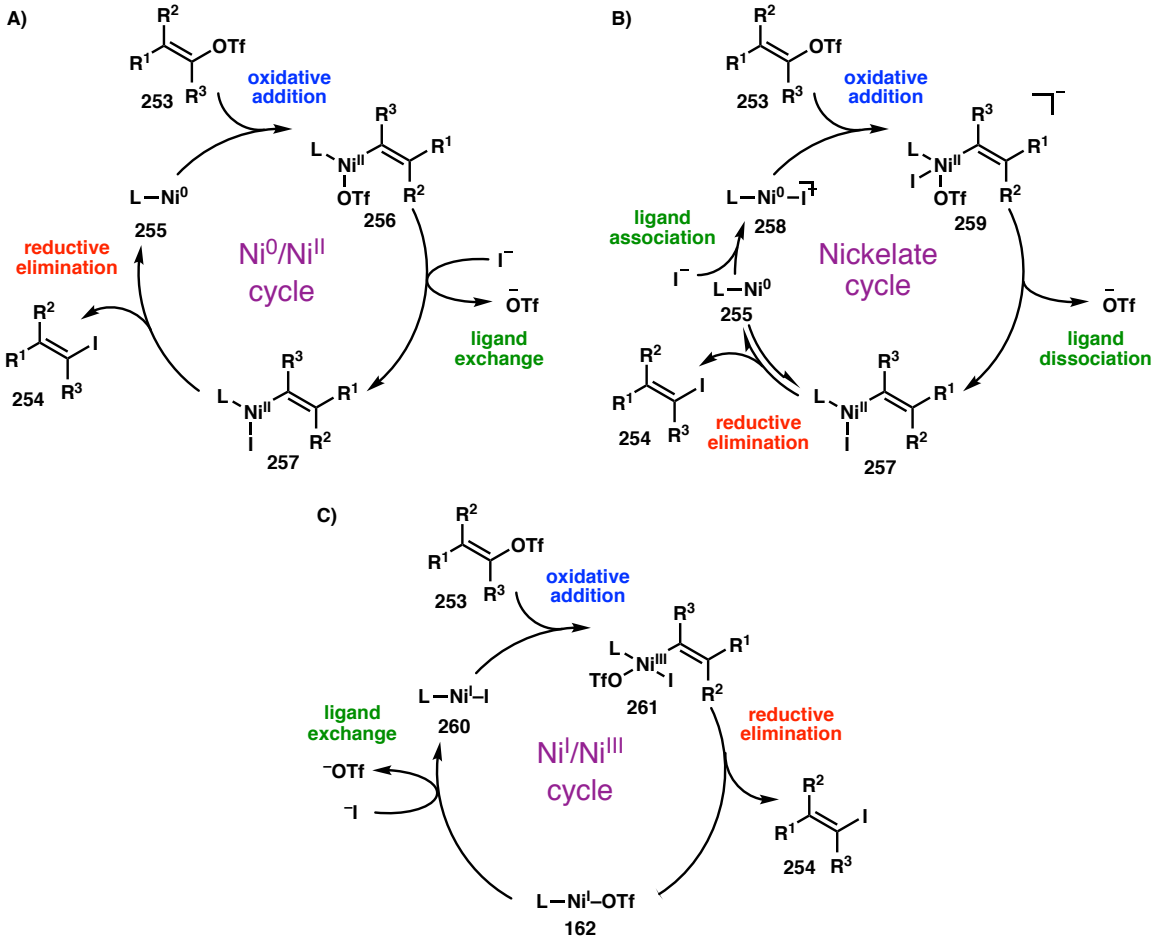


most thermodynamically favorable, when a mixture of alkenyl chloride **207c** and LiBr is monitored by GC, trace amounts of alkenyl bromide **207b** are formed, indicating that alkenyl chloride can undergo oxidative addition with Ni(0) (Figure 5.14f).

5.4.6 Potential Reaction Mechanisms

Given the experimental mechanistic results, we hypothesize three different mechanisms may be operative for the conversion of alkenyl triflates to alkenyl halides (Figure 5.15). In all cases, the formation of L–Ni(0) (**255**) proceeds via cod dissociation, owing to the observed induction period. One mechanistic possibility is a Ni(0)/Ni(II)

Figure 5.15 *Possible mechanisms for the Ni-catalyzed alkenyl triflate halogenation.*



catalytic cycle which has been previously proposed for the cyanation of phenol derivatives (Figure 5.15a).[42] Monoligated Ni(0) complex **255** may undergo oxidative addition to the alkenyl triflate to form Ni(II) complex **256**. Ligand exchanged followed by reductive elimination from Ni(II) complex **257** can then afford the desired alkenyl iodide **254**. However, one shortcoming of this mechanism is that it does not account for the observation that alkenyl triflate oxidative addition does not occur in the absence of iodide. Consequently, a mechanism proceeding through a nickelate intermediates could be at play (Figure 5.15b). Kochi and coworkers previously assigned EPR spectra to a phosphine bound Ni(I) species that formed a nickelate complex upon addition of iodide.[29] It is possible that a Ni(0) nickelate complex **258** could form upon the addition of iodide via ligand association. Oxidative addition, ligand dissociation, and reductive elimination may form the desired alkenyl iodide (**254**). Lastly, given the observation of Ni(I) by EPR spectroscopy, a Ni(I)/Ni(III) catalytic cycle may be operative as well (Figure 5.15c). While our mechanistic investigations have not resulted in conclusive evidence for a particular pathway, these results shed light onto the complex and enigmatic reactivity of Ni-catalyzed halogenation reactions.

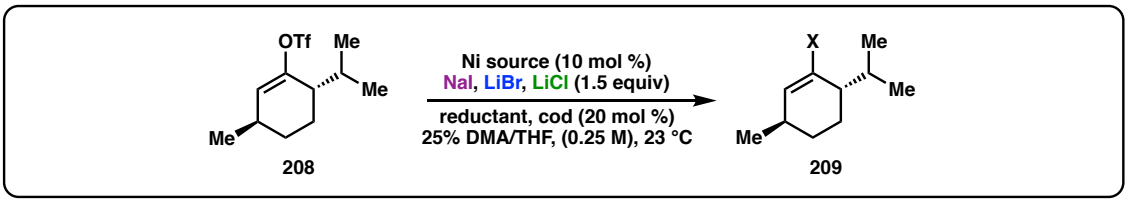
5.5 EVALUATION OF NI(II) PRECATALYSTS

5.5.1 Optimization

At this stage, we had successfully developed the $Ni(cod)_2$-catalyzed conversion of alkenyl triflates and nonaflates to alkenyl chlorides, bromides, and iodides. A broad substrate scope and good functional group tolerance were demonstrated, and a number of

mechanistic studies were performed in order to probe the reaction mechanism. However, $Ni(cod)_2$ is not bench stable and rather expensive compared to Ni(II) sources.[43] Therefore, we also investigated the use of Ni(II) salts with *in situ* reduction by Mn or Zn in order to prepare the alkenyl halides investigated in our earlier studies (Table 5.7). Reports by Inokawa and Brandsma previously demonstrated that active catalysts in Ni-mediated halogen exchange reactions of alkenyl halides were successfully prepared with the use of NiX_2 salts (anhydrous or hydrated) and Zn dust as the reductant[30,31] When NiX_2 salts were pre-reduced in the presence of excess Mn followed by filtration of the reduced catalyst, no conversion of **208** was observed (entry 1). However, upon the addition of 20 mol % cod, both Mn and Zn delivered the alkenyl halide products, albeit in variable yields (entries 2–3). In order to streamline the reaction process, Zn was directly added to the reactions in substoichiometric quantities (entry 4–6). Notably, the chlorination did not proceed to

Table 5.7. *Evaluation of Ni(II) halide salts for the halogenation of alkenyl triflates.*



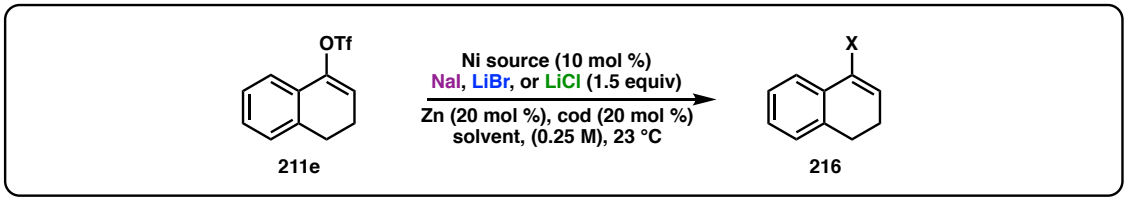
				Iodination	Bromination	Chlorination
Entry	Solvent	Ni Source	reductant	Yield (%)	Yield (%)	Yield (%)
1[a,b]	25% DMA/THF	NiX_2	excess Mn	0	0	0
2[a]	25% DMA/THF	NiX_2	excess Mn	4	41	63
3[a]	25% DMA/THF	NiX_2	excess Zn	4	37	57
4	25% DMA/THF	NiX_2	10 mol % Zn	28	84	0
5	25% DMA/THF	NiX_2	20 mol % Zn	25	85	0
6	25% DMA/THF	NiX_2	100 mol % Zn	14	24	0
7	DMA	NiX_2	20 mol % Zn	62	83	0
8	25% DMA/THF	NiX_2(dme)	20 mol % Zn	—	87	87

[a]Ni catalyst is pre-reduced with 3 equiv Zn, then filtered and added to the reaction. [b]No cod added.

provide the desired product due to insoluble nature of $NiCl_2$. In order to address the low solubility, DMA was evaluated as a solvent. While the chlorination still did not proceed, the iodination reaction improved under these conditions (entry 7). Changing the Ni halide source to the use of $NiX_2(dme)$, which is inherently much more soluble in organic solvents, provided the alkenyl bromide and chloride in 87% yield. Unfortunately, $NiI_2(dme)$ is not commercially available, although it can be made in the laboratory and was not investigated in this study.[44,45]

A series of other non-halide Ni precatalyst were evaluated, which could potentially provide for a more general reaction system (Table 5.8). While reduced $Ni(acac)_2$ successfully formed the alkenyl bromide **216b**, iodination failed under these conditions. Neither the bromination or iodination worked with $Ni(OTf)_2$, likely due to its poor solubility. Finally, the use of $Ni(OAc)_2{\cdot}4H_2O$ successfully provided alkenyl bromide **216b**

Table 5.8. *Evaluation of additional Ni(II) sources.*



				Iodination	Bromination	Chlorination
Entry	Solvent	Ni Source	Time (h)	Yield (%)	Yield (%)	Yield (%)
1	DMA	$Ni(acac)_2$	2	4	97	—
2	25% DMA/THF	$Ni(acac)_2$	2	4	91	—
3	DMA	$Ni(OTf)_2$	2	5	0	—
4	DMA	$Ni(OAc)_2{\cdot}4H_2O$	2	0	39	—
5	25% DMA/THF	$Ni(OAc)_2{\cdot}4H_2O$	2	33	95	99
6[a]	25% DMA/THF	$Ni(OAc)_2{\cdot}4H_2O$	2	57	—	—
7[a]	25% DMA/THF	$Ni(OAc)_2{\cdot}4H_2O$	5	83	—	—
8[a]	25% DMA/THF	$Ni(OAc)_2{\cdot}4H_2O$	16	95	—	—

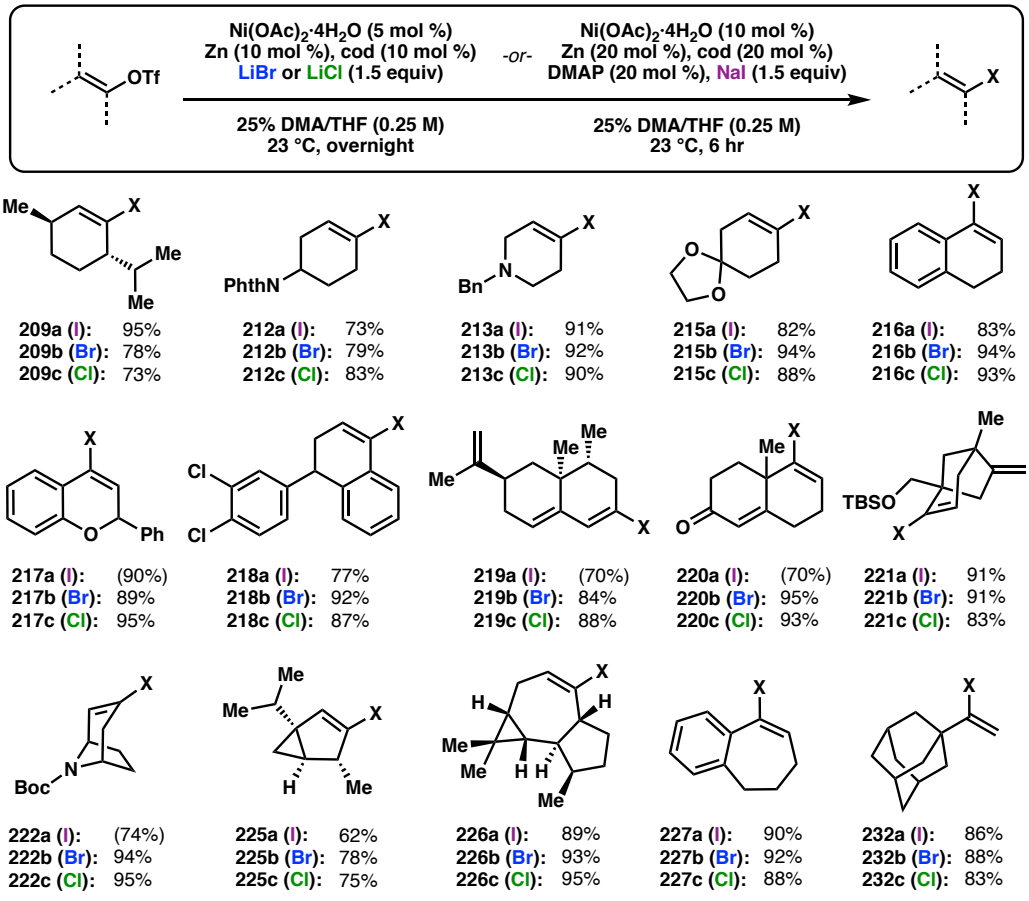
[a]20 mol % DMAP added.

in 95% yield and alkenyl iodide **216a** in a promising 33% yield (entry 5). The addition of 20 mol % DMAP, a ligand employed in reductive cross-couplings by Gong and coworkers,[46,47] afforded a higher yield of the **216a** (entry 6). Finally, running the reaction for an extended period of time furnished alkenyl iodide **216a** in 95% yield (entry 8).

5.5.2 Substrate Scope

With the Ni(II) conditions in hand, the scope was reevaluated (Figure 5.16). Most substrates saw an increase in yield over the Ni(0) conditions, in part due to improvements

Figure 5.16 *Evaluation of substrate scope with Ni(II).*



Reactions are conducted on 0.3 mmol scale under N_2. Isolated yields are provided; yields in parenthesis are ^{1}H NMR yields for substrates who could not be purified to >95% purity. Iodinations for **215a**, **217a**, **219a**, **220a**, **222a**, and **225a** conducted with 5 equiv NaI for 36 h in the absence of cod. Bromination and chlorination for **225b** and **225c** were conducted with 10 mol % DMAP instead of 10 mol % cod.

in conversion and increased recovery of mass balance. Under the Ni(II) conditions, the iodination reactions unfortunately were more prone towards the production of protodetriflation/protodehalogenation products (alkene) and some alkenyl halides could not be purified to >95% purity (**217a**, **219a**, **220a**, and **222a**); instead NMR yields are reported. Styrenyl bromides and iodides also produced significant quantities of alkene side products as well as the rearranged α-halo ketones under these reaction conditions.

5.6 CONCLUSION

In conclusion, a mild Ni-catalyzed halogenation of alkenyl triflates and alkenyl nonaflates has been developed with the use of commercially available $Ni(cod)_2$ and simple halide salts. By modifying the halide salt, alkenyl iodides, bromides, and chlorides can be readily obtained. The reaction proceeds at room temperature with the use of cod as the ancillary ligand, is amenable to gram scale preparation, and exhibits good functional group tolerance. Nevertheless, the reaction was still remarkably sensitive and required a glovebox to obtain reproducible and consistent yields. Attempts to translate the reaction to a benchtop setup were successful when $Ni(cod)_2$ was briefly exposed to air; however, the reaction was extremely sensitive to trace oxygen content in the reaction flask which inhibited the active catalyst and resulted in diminished yields. Further development of conditions that employ Ni(II) and a stoichiometric Zn reductant also successfully delivered the desired alkenyl halide products; however, in some cases product purification was challenging due to inseparable alkene byproducts. The analogous Ni(II) reactions also exhibited comparable high sensitivity to trace oxygen. A series of mechanistic experiments,

including evaluation via EPR, indicated the presence of a Ni(I) radical intermediate in the reaction; however, additional studies are required to fully elucidate the mechanism of this transformation.

5.7 EXPERIMENTAL SECTION

5.7.1 Materials and Methods

Unless otherwise stated, reactions were performed under a N_2 atmosphere using freshly dried solvents. Tetrahydrofuran (THF) and methylene chloride (CH_2Cl_2) were dried by passing through activated alumina columns. Diisopropylamine (*i*-Pr_2NH) was distilled over calcium hydride prior to use. Anhydrous dimethylacetamide (DMA), sodium iodide (NaI), lithium bromide (LiBr), and lithium chloride (LiCl) were purchased from Aldrich and stored under N_2. $Ni(cod)_2$ was purchased from Strem and stored in the glovebox at –20 °C. Unless otherwise stated, chemicals and reagents were used as received. All reactions were monitored by thin-layer chromatography using EMD/Merck silica gel 60 F254 pre-coated plates (0.25 mm) and were visualized by UV, CAM, or $KMnO_4$ staining. Flash column chromatography was performed as described by Still et al.[48] using silica gel (230-400 mesh, Silicycle). Purified compounds were dried on a high vacuum line (0.2 torr) to remove trace solvent. Optical rotations were measured on a Jasco P-2000 polarimeter using a 100 mm path-length cell at 589 nm. ^1H and ^{13}C NMR spectra were recorded on a Bruker Avance III HD with Prodigy cyroprobe (at 400 MHz and 101 MHz, respectively), a Varian 400 MR (at 400 MHz and 101 MHz, respectively), or a Varian Inova 500 (at 500 MHz and 126 MHz, respectively). ^1H and ^{19}F NMR spectra were also recorded on a Varian Inova 300 (at

300 MHz and 282 MHz, respectively). NMR data is reported relative to internal $CHCl_3$ (^1H, δ = 7.26), $CDCl_3$ (^{13}C, δ = 77.0), CD_3CN (^1H, δ = 1.94), CD_3CN (^{13}C, δ = 1.32), and C_6F_6 (^{19}F, δ = -161.64). Data for ^1H NMR spectra are reported as follows: chemical shift (δ ppm) (multiplicity, coupling constant (Hz), integration). Multiplicity and qualifier abbreviations are as follows: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad. IR spectra were recorded on a Perkin Elmer Paragon 1000 spectrometer and are reported in frequency of absorption (cm^{-1}). HRMS were acquired from the Caltech Mass Spectral Facility using fast-atom bombardment (FAB), electrospray ionization (ESI-TOF), or electron impact (EI).

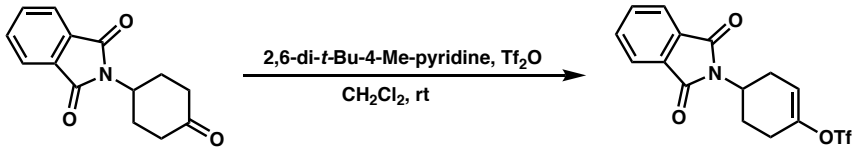
5.7.2 Optimization of Reaction Parameters

A 1-dram vial equipped with a stir bar was brought into a N_2-filled glovebox. The vial was charged with NaI, LiBr, or LiCl (0.15 mmol, 1.5 equiv) and $Ni(cod)_2$ (2.8 mg, 0.01 mmol, 0.1 equiv). Anhydrous DMA (0.1 mL) and THF (0.3 mL) were added, resulting in a clear yellow solution. Enol triflate (0.1 mmol, 1 equiv) was added neat, turning the reaction dark red (NaI) or aqua blue (LiBr or LiCl) over several minutes. The vial was sealed with a Teflon cap and brought out of the glovebox to stir on the bench (480 rpm) for two hours at room temperature. The reaction was quenched by eluting through a small plug of silica gel (5 cm of silica in a large glass pipette) with 40% Et_2O/pentane (10 mL collected). The crude reaction mixture was concentrated under reduced pressure and analyzed by NMR with tetrachloronitrobenzene as an external standard.

5.7.3 Substrate Preparation

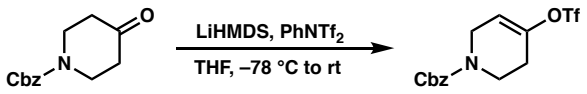
5.7.3.1 Alkenyl Triflates

4-(1,3-dioxoisoindolin-2-yl)cyclohex-1-en-1-yl trifluoromethanesulfonate (211a)



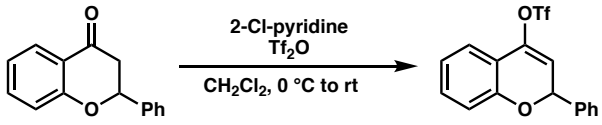
To a round bottom flask was added 2-(4-oxocyclohexyl)isoindoline-1,3-dione (730 mg, 3.0 mmol, 1.0 equiv), 2,6-di-*tert*-butyl-4-methylpyridine (924 mg, 4.5 mmol, 1.5 equiv), CH_2Cl_2 (10 mL), and trifluoromethanesulfonic anhydride (757 μL, 4.5 mmol, 1.5 equiv). The reaction was stirred overnight, then diluted with hexanes, filtered over Celite, and eluted with CH_2Cl_2. The organic filtrate was washed with H_2O and brine, and the aqueous layer was extracted with CH_2Cl_2. The combined organic layers were dried with $MgSO_4$, filtered, and concentrated. The product was purified by column chromatography (silica, 30% EtOAc/hexanes) to yield 752 mg (67% yield) of **211a** as a white solid. $\mathbf{R_f}$ = 0.30 (silica, 30% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.83 (dd, *J* = 5.5, 3.0 Hz, 2H), 7.77 – 7.66 (m, 2H), 5.78 (dt, *J* = 5.9, 2.3 Hz, 1H), 4.43 (dddd, *J* = 12.7, 10.8, 5.5, 3.1 Hz, 1H), 3.07 (dddt, *J* = 17.3, 10.7, 4.3, 2.3 Hz, 1H), 2.81 – 2.68 (m, 1H), 2.68 – 2.54 (m, 1H), 2.52 – 2.40 (m, 1H), 2.39 – 2.26 (m, 1H), 1.92 (dddd, *J* = 12.5, 5.9, 3.8, 1.8 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 168.2, 148.2, 134.3, 131.9, 123.4, 118.6 (q, $J_{C\text{-}F}$ = 320.2 Hz), 116.9, 45.6, 27.7, 26.7, 26.1. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -73.7. **FTIR (NaCl, thin film, cm^{-1}):** 1704, 1698, 1418, 1385, 1249, 1196, 1139, 1112, 876, 718. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{15}H_{13}F_3O_5NS$ $[M+H]^+$: 376.0467; found: 376.0467.

Benzyl 4-(((trifluoromethyl)sulfonyl)oxy)-3,6-dihydropyridine-1(2*H*)-carboxylate (211c)



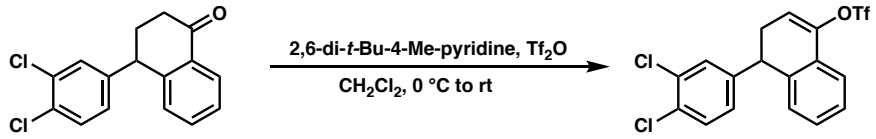
Benzyl 4-oxopiperidine-1-carboxylate (1.17 g, 5.0 mmol, 1.0 equiv) was added to a round-bottom flask and placed under an atmosphere of N_2. THF (25 mL) was added and the reaction was cooled to –78 °C. LiHMDS (5.5 mL, 1 M in THF, 5.5 mmol, 1.1 equiv) was added dropwise and allowed to stir for 30 minutes before N-phenyl-bis(trifluoromethanesulfonimide) (1.88 g, 5.25 mmol, 1.05 equiv) was added in one portion. The reaction was allowed to reach room temperature and stir overnight. The reaction was then quenched with saturated aq. NH_4Cl (50 mL) and extracted with Et_2O (2 x 50 mL). The combined organic layers were dried with $MgSO_4$, filtered, and concentrated. The product was purified by column chromatography (silica, 20% Et_2O/hexanes) to yield 901 mg (49% yield) of **211c** as a colorless oil. $\mathbf{R_f}$ = 0.30 (silica, 30% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, d_3-MeCN, 65 °C):** δ 7.39 (s, 1H), 7.38 (s, 2H), 7.37 – 7.30 (m, 1H), 5.91 – 5.85 (m, 1H), 5.18 – 5.14 (m, 2H), 4.14 – 4.06 (m, 2H), 3.69 (t, J = 5.8 Hz, 2H), 2.47 (ttt, J = 5.7, 2.8, 1.3 Hz, 2H). **^{13}C NMR (101 MHz, d_3-MeCN, 65 °C):** δ 156.2, 148.4, 138.5, 129.7, 129.2, 129.0, 117.4, 68.3, 43.1, 41.9, 29.0. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -71.7. **FTIR (NaCl, thin film, cm^{-1}):** 3035, 2953, 1714, 1418, 1366, 1281, 1211, 1142, 1116, 1065, 872, 766, 698, 611. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{14}H_{14}F_3NO_5S$ $[M+H]^+$: 366.0623; found: 366.0613.

2-phenyl-2*H*-chromen-4-yl trifluoromethanesulfonate (211f)



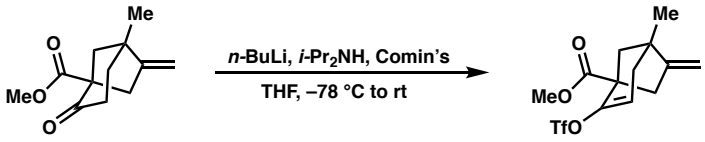
To a flame dried, N_2-filled round bottom flask was added 2-phenylchroman-4-one (500 mg, 2.9 mmol, 1.0 equiv), 2-chloropyridine (304 mg, 2.7 mmol, 1.2 equiv), and CH_2Cl_2 (8 mL). The reaction was cooled to 0 °C before trifluoromethanesulfonic anhydride (0.45 mL, 2.7 mmol, 1.2 equiv) was added. The reaction was allowed to reach room temperature and continued to stir overnight. The reaction was then cooled to 0 °C, saturated aq. $NaHCO_3$ was slowly added until gas evolution ceased, and then H_2O (25 mL) was added. The crude mixture was extracted with CH_2Cl_2 (2 x 50 mL). The combined organic layers were dried with $MgSO_4$, filtered, and concentrated. The product was purified by column chromatography (silica, 4% EtOAc/hexanes) to yield 421 mg (53% yield) of **211f** as a pale solid. $\mathbf{R_f}$ = 0.60 (silica, 10% Et_2O/hexanes, $KMnO_4$) **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.49 – 7.44 (m, 2H), 7.44 – 7.35 (m, 3H), 7.30 (dd, *J* = 7.7, 1.6 Hz, 1H), 7.26 (td, *J* = 8.1, 7.7, 1.6 Hz, 1H), 6.99 (td, *J* = 7.6, 1.1 Hz, 1H), 6.86 (dd, *J* = 8.1, 1.0 Hz, 1H), 6.12 (d, *J* = 3.8 Hz, 1H), 5.85 (d, *J* = 3.8 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 153.9, 143.2, 138.8, 131.9, 129.2, 129.0, 127.1, 121.70, 121.67, 118.5 (q, $J_{C\text{-}F}$ = 320.5 Hz), 116.6, 116.4, 113.1, 77.4 **^{19}F NMR (282 MHz, $CDCl_3$):** δ -73.4. **FTIR (NaCl, thin film, cm^{-1}):** 3068, 3036, 1667, 1607, 1485, 1455, 1428, 1354, 1248, 1222, 1139, 1032, 935, 883, 858, 758, 698. **HRMS (FAB, *m/z*):** calc'd for $C_{16}H_{11}F_3O_4S$ $[M+\cdot]^+$: 356.0330; found: 356.0304.

4-(3,4-dichlorophenyl)-3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (211g)



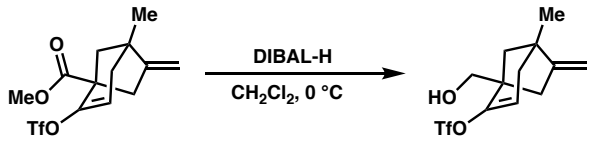
To a round bottom flask was added 4-(3,4-dichlorophenyl)-3,4-dihydronaphthalen-1(2*H*)-one (1.46 g, 5.0 mmol, 1.0 equiv), 2,6-di-*tert*-butyl-4-methylpyridine (1.13 g, 5.5 mmol, 1.1 equiv), and CH_2Cl_2 (15 mL). The reaction was cooled to 0 °C before trifluoromethanesulfonic anhydride (1.0 mL, 6.0 mmol, 1.2 equiv) was added. The reaction was allowed to reach room temperature and stirred for 30 minutes before being concentrated. The reaction mixture was then suspended in hexanes, filtered over a plug of Celite, and eluted with additional hexanes. The solution was concentrated and the product was purified by column chromatography (silica, 2% Et_2O/hexanes) to yield 2.09 g (99% yield) of **211g** as a colorless oil. $\mathbf{R_f}$ = 0.23 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.47 (dd, *J* = 7.6, 1.3 Hz, 1H), 7.39 (d, *J* = 8.3 Hz, 1H), 7.35 (tdd, *J* = 7.7, 1.4, 0.6 Hz, 1H), 7.32 – 7.26 (m, 2H), 7.03 (ddd, *J* = 8.3, 2.2, 0.5 Hz, 1H), 6.94 – 6.89 (m, 1H), 5.97 (t, *J* = 4.8 Hz, 1H), 4.18 (t, *J* = 7.9 Hz, 1H), 2.89 (ddd, *J* = 17.4, 7.4, 4.8 Hz, 1H), 2.72 (ddd, *J* = 17.3, 8.6, 4.9 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 146.2, 143.2, 137.4, 132.8, 131.2, 130.8, 130.3, 130.0, 128.7, 128.4, 127.9, 127.7, 121.9, 118.7 (q, $J_{C\text{-}F}$ = 320.4 Hz), 116.0, 42.4, 30.8 **^{19}F NMR (282 MHz, $CDCl_3$):** δ -73.5. **FTIR (NaCl, thin film, cm^{-1}):** 1658, 1470, 1422, 1249, 1213, 1140, 1066, 1019, 895, 765, 612. **HRMS (EI, *m/z*):** calc'd for $C_{17}H_{11}Cl_2F_3O_3S$ $[M+\cdot]^+$: 421.9758; found: 421.9755.

Methyl (1*s*,5*r*)-5-methyl-6-methylene-2-(((trifluoromethyl)sulfonyl)oxy)bicycle-[3.2.1]oct-2-ene-1-carboxylate (S31)



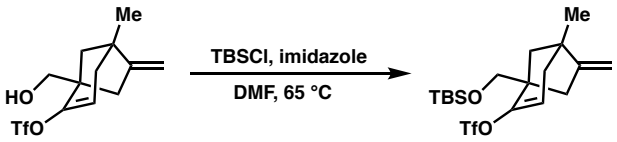
To a flame dried, N_2 filled round bottom flask was added methyl (1*s*,5*r*)-5-methyl-6-methylene-2-oxobicyclo[3.2.1]octane-1-carboxylate (670 mg, 3.0 mmol, 1 equiv) and THF (15 mL). The reaction was cooled to –78 °C (dry ice/acetone) before LDA (0.75M in THF, 4.8 mL, 3.6 mmol, 1.2 equiv) was added via cannula. The reaction mixture was stirred for 30 minutes before Comin's reagent (1M in THF, 3.45 mL, 3.45 mmol, 1.15 equiv) was added via cannula. After 1 hour, the reaction was quenched by addition of saturated aq. $NaHCO_3$ (20 mL) and warmed to room temperature. The crude mixture was extracted with Et_2O (3 x 15 mL) and the combined organic layers were dried over $MgSO_4$, filtered and concentrated. The product was purified by column chromatography (silica, 5% EtOAc/hexanes) to yield 865 mg (81% yield) of **S31** as a clear oil. $\mathbf{R_f}$ = 0.54 (silica, 10% EtOAc/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.63 (dd, *J* = 4.9, 2.6 Hz, 1H), 5.02 (ddd, *J* = 2.5, 1.7, 0.8 Hz, 1H), 4.96 (dd, *J* = 3.0, 1.9 Hz, 1H), 3.76 (s, 3H), 3.11 – 2.92 (m, 2H), 2.37 (dd, *J* = 17.3, 2.7 Hz, 1H), 2.17 (ddd, *J* = 11.0, 2.7, 0.8 Hz, 1H), 2.11 – 2.02 (m, 1H), 1.96 (dd, *J* = 11.0, 1.5 Hz, 1H), 1.26 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 171.1, 155.2, 149.6, 120.0 (q, $J_{C\text{-}F}$ = 319.9 Hz), 116.5, 107.7, 52.8, 52.6, 48.2, 44.7, 42.9, 41.9, 23.9. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -74.4. **FTIR (NaCl, thin film, cm^{-1}):** 2959, 1744, 1420, 1299, 1249, 1209, 1142, 1071, 1029, 265, 623. **HRMS (FAB, *m/z*):** calc'd for $C_{13}H_{15}F_3O_3S$ $[M+NH_4]^+$: 358.0931; found: 358.0924.

(1*r*,5*r*)-1-(hydroxymethyl)-5-methyl-6-methylenebicyclo[3.2.1]oct-2-en-2-yl trifluoromethanesulfonate (S32)



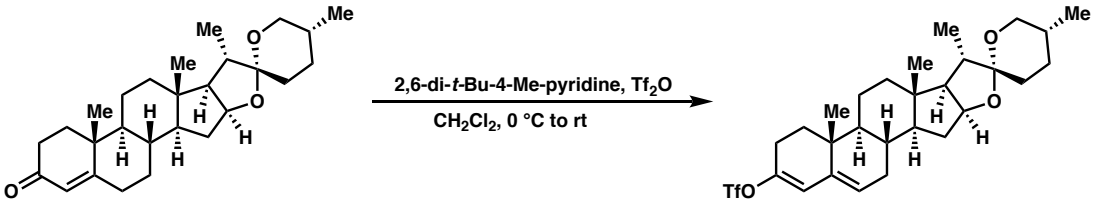
To a flame dried, N_2 filled round bottom flask was added **S31** (783 mg, 2.3 mmol, 1 equiv) and CH_2Cl_2 (23 mL). The reaction was cooled to 0 °C before DIBAL (1.23 mL, 6.9 mmol, 3 equiv) was added slowly. After 45 minutes, the reaction was quenched by addition of 1M HCl (6 mL) and warmed to room temperature. The crude mixture was diluted with water (20 mL) and extracted with CH_2Cl_2 (3 x 15 mL). The combined organic layers were washed with saturated aq. $NaHCO_3$ (30 mL), then brine (30 mL), and dried over $MgSO_4$, filtered and concentrated. The product was purified by column chromatography (silica, 10% to 20% EtOAc/hexanes) to yield 670 mg (93% yield) of **S32** as a clear oil. $\mathbf{R_f}$ = 0.36 (silica, 20% EtOAc/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.61 (dd, *J* = 4.7, 2.7 Hz, 1H), 4.97 (ddd, *J* = 2.4, 1.4, 0.7 Hz, 1H), 4.94 (dd, *J* = 3.0, 1.7 Hz, 1H), 3.99 (dd, *J* = 11.3, 5.3 Hz, 1H), 3.59 (dd, *J* = 11.3, 5.7 Hz, 1H), 2.78 (ddt, *J* = 15.8, 3.2, 1.7 Hz, 1H), 2.41 – 2.29 (m, 2H), 2.08 – 1.98 (m, 2H), 1.74 – 1.67 (m, 2H), 1.25 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 156.6, 153.1, 118.7 (q, $J_{C\text{-}F}$ = 319.8 Hz), 117.2, 107.1, 64.5, 48.4, 47.4, 44.3, 43.1, 42.3, 24.4. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -74.2. **FTIR (NaCl, thin film, cm^{-1}):** 3390 (br), 3076, 2959, 2880, 1668, 1416, 1211, 1142, 1030, 871, 621. **HRMS (FAB, *m/z*):** calc'd for $C_{11}H_{11}F_3O_3S$ $[M+H]^+$: 330.0981; found: 330.0981.

(1*r*,5*r*)-1-(((*tert*-butyldimethylsilyl)oxy)methyl)-5-methyl-6-methylenebicyclo[3.2.1]oct-2-en-2-yl trifluoromethanesulfonate (211j)



To a round bottom flask was added **211j** (576 mg, 1.8 mmol, 1 equiv), imidazole (251 mg, 3.7 mmol, 2 equiv), DMF (18 mL), and TBSCl (333 mg, 2.2 mmol, 1.2) equiv). The reaction was heated to 65 °C for 12 hours, cooled to room temperature and quenched by addition of saturated aq. NH_4Cl (20 mL). The crude mixture was extracted with EtOAc (3 x 20 mL, then the combined organic layers were washed with saturated aq. $NaHCO_3$ (30 mL), then saturated aq. NH_4Cl (3 x 30 mL), dried over $MgSO_4$, filtered and concentrated. The product was purified by column chromatography (silica, hexanes to 3% EtOAc/Hexanes) to yield 738 mg (94% yield) of **211j** as a white solid. $\mathbf{R_f}$ = 0.27 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.55 (dd, *J* = 4.7, 2.7 Hz, 1H), 4.95 (ddd, *J* = 2.5, 1.5, 0.8 Hz, 1H), 4.92 (dd, *J* = 3.1, 1.7 Hz, 1H), 3.90 (d, *J* = 10.1 Hz, 1H), 3.51 (d, *J* = 10.1 Hz, 1H), 2.69 (ddt, *J* = 15.8, 3.1, 1.6 Hz, 1H), 2.43 – 2.35 (m, 1H), 2.32 (dd, *J* = 17.1, 2.7 Hz, 1H), 2.06 – 1.97 (m, 1H), 1.91 (dd, *J* = 11.0, 2.8 Hz, 1H), 1.69 (dd, *J* = 10.9, 1.5 Hz, 1H), 1.24 (s, 3H), 0.89 (s, 9H), 0.05 (s, 6H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 157.3, 153.6, 120.1 (q, $J_{C\text{-}F}$ = 319.3 Hz), 116.3, 106.7, 64.0, 48.4, 47.6, 43.8, 43.0, 42.4, 26.0, 24.5, 18.5, -5.5. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -74.4. **FTIR (NaCl, thin film, cm^{-1}):** 3076, 2957, 2860, 1668, 1473, 1418, 1246, 1211, 1144, 1101, 1031, 874, 840, 778, 620. **HRMS (FAB, *m/z*):** calc'd for $C_{18}H_{29}F_3O_4S$ $[M+H]^+$: 427.1581; found: 427.1568.

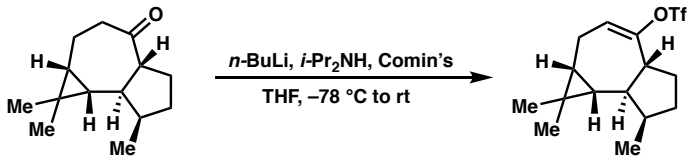
(5'*R*,6a*R*,6b*S*,8a*S*,8b*R*,9*S*,10*R*,11a*S*,12a*S*,12b*S*)-5',6a,8a,9-tetramethyl-1,3',4',5,5',6,6a,6b,-6',7,8,8a,8b,9,11a,12,12a,12b-octadecahydrospiro[naphtho[2',1':4,5]indeno[2,1-*b*]furan-10,2'-pyran]-4-yl trifluoromethanesulfonate (211l)



To a round bottom flask was added (5'*R*,6a*R*,6b*S*,8a*S*,8b*R*,9*S*,10*R*,11a*S*,12a*S*,12b*S*)-5',6a,8a,9-tetramethyl-1,3',4',5,5',6,6a,6b,6',7,8,8a,8b,9,11a,12,12a,12b-octadecahydro-spiro-[naphtha[2',1':4-,5]indeno[2,1-*b*]furan-10,2'-pyran]-4(3*H*)-one (661 mg, 1.8 mmol, 1.0 equiv), 2,6-di-*tert*-butyl-4-methylpyridine (395 mg, 2.16 mmol, 1.2 equiv), and CH_2Cl_2 (5.0 mL). The reaction was cooled to 0 °C and trifluoromethanesulfonic anhydride (296 μL, 1.98 mmol, 1.1 equiv) was added. The reaction was stirred at room temperature overnight, then washed with saturated aq. $NaHCO_3$ (50 mL) and extracted with CH_2Cl_2 (2 x 100 mL). The combined organic layers were dried with $MgSO_4$, filtered, and concentrated. The product was purified by column chromatography (silica, 5 to 10% Et_2O/hexanes) to yield 488 mg (50% yield) of **211l** as a white solid. $\mathbf{R_f}$ = 0.40 (silica, 10% Et_2O/hexanes, $KMnO_4$). $[\boldsymbol{a}]_D^{25}$ = –125° (c = 1.0, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.99 (d, *J* = 2.2 Hz, 1H), 5.57 (dd, *J* = 5.1, 2.9 Hz, 1H), 4.42 (ddd, *J* = 8.6, 7.5, 6.3 Hz, 1H), 3.47 (ddd, *J* = 10.8, 4.6, 2.0 Hz, 1H), 3.37 (t, *J* = 10.9 Hz, 1H), 2.63 – 2.48 (m, 1H), 2.40 – 2.30 (m, 1H), 2.23 (dt, *J* = 18.8, 5.2 Hz, 1H), 1.99 (ddd, *J* = 11.8, 7.5, 5.4 Hz, 1H), 1.95 – 1.51 (m, 11H), 1.51 – 1.39 (m, 2H), 1.32 (ddd, *J* = 13.7, 11.9, 6.4 Hz, 2H), 1.26 – 1.11

(m, 2H), 1.09 – 0.99 (m, 1H), 0.99 (s, 6H), 0.81 (s, 3H), 0.79 (d, J = 6.3 Hz, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 147.1, 138.2, 128.1, 120.6, 118.7 (q, $J_{C\text{-}F}$ = 319.9 Hz), 109.5, 80.9, 67.0, 62.2, 56.6, 47.8, 41.8, 40.5, 39.8, 35.0, 33.9, 32.2, 31.9, 31.5, 31.3, 30.4, 28.9, 25.7, 21.2, 18.8, 17.3, 16.5, 14.7. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -73.8. **FTIR (NaCl, thin film, cm^{-1}):** 3054, 2947, 2306, 1640, 1456, 1380, 1266, 1214, 1140, 1051, 919, 829, 740. **HRMS (FAB, *m/z*):** calc'd for $C_{28}H_{40}F_3O_5S$ $[M+H]^+$: 545.2549; found: 545.2536.

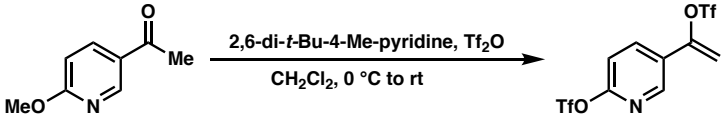
(1a*R*,4a*R*,7*R*,7a*S*,7b*S*)-1,1,7-trimethyl-1a,2,4a,5,6,7,7a,7b-octahydro-1*H*-cyclopropa[*e*]azulen-4-yl trifluoromethanesulfonate (211m)



To a round bottom flask was added diisopropyl amine (337 μL, 2.4 mmol, 1.2 equiv) and THF (6 mL). The solution was cooled to 0 °C, then *n*-butyllithium (960 μL, 2.5 M in hexanes, 2.4 mmol, 1.2 equiv) was added and stirred for 30 minutes before being cooled to –78 °C. (1a*R*,4a*R*,7*R*,7a*S*,7b*S*)-1,1,7-Trimethyldecahydro-4*H*-cyclopropa[*e*]azulen-4-one (412 mg, 2.0 mmol, 1.0 equiv) was added and stirred for 30 minutes before N-(5-chloro-2-pyridyl)bis(trifluoromethanesulfonimide) (942 mg, 2.4 mmol, 1.2 equiv) was added in one portion. The reaction was allowed to reach room temperature and stir overnight. The reaction was quenched with H_2O and extracted with Et_2O (2 x 50 mL). The combined organic layers were dried with $MgSO_4$, filtered, and concentrated. The product was purified by column chromatography (silica, hexanes) to yield 386 mg (57% yield) of **211m** as a colorless oil which solidified in the freezer. $\mathbf{R}_f$ = 0.49 (silica, hexanes, $KMnO_4$)

$[\alpha]_D^{25}$ = –93° (c = 1.0, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.74 (ddd, *J* = 9.3, 2.9, 2.1 Hz, 1H), 2.79 (tdd, *J* = 11.3, 5.4, 2.0 Hz, 1H), 2.29 (dddd, *J* = 17.3, 9.3, 7.0, 0.8 Hz, 1H), 2.24 – 2.11 (m, 1H), 2.11 – 1.90 (m, 3H), 1.70 (td, *J* = 11.7, 8.4 Hz, 1H), 1.56 – 1.41 (m, 1H), 1.24 (dtd, *J* = 13.1, 8.5, 4.3 Hz, 1H), 1.05 (d, *J* = 1.1 Hz, 6H), 0.97 (ddd, *J* = 10.1, 9.3, 7.0 Hz, 1H), 0.92 (d, *J* = 7.2 Hz, 3H), 0.65 (dd, *J* = 11.5, 9.2 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 154.6, 120.1, 118.7 (q, $J_{C\text{-}F}$ = 319.9 Hz), 48.0, 43.1, 34.4, 32.0, 29.8, 28.5, 25.7, 25.6, 20.3, 18.7, 18.0, 15.3. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -74.3. **FTIR (NaCl, thin film, cm^{-1}):** 2957, 2872, 1672, 1457, 1415, 1246, 1208, 1145, 984, 941, 865. **HRMS (FAB, *m/z*):** calc'd for $C_{15}H_{21}F_3O_3S$ $[M+\cdot]^+$: 338.1164; found: 338.1164.

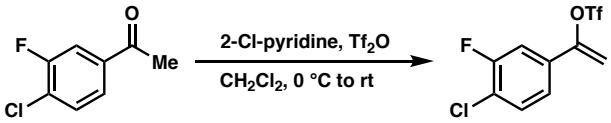
1-(6-(((trifluoromethyl)sulfonyl)oxy)pyridin-3-yl)vinyl trifluoromethanesulfonate (211p)



To a round bottom flask was added 1-(6-methoxypyridin-3-yl)ethan-1-one (756 mg, 5.0 mmol, 1.0 equiv), 2,6-di-*tert*-butyl-4-methylpyridine (2.26 g, 11 mmol, 2.2 equiv), and CH_2Cl_2 (15 mL). The reaction was cooled to 0 °C before trifluoromethanesulfonic anhydride (2.0 mL, 12.0 mmol, 2.4 equiv) was added. The reaction was allowed to reach room temperature and stir overnight. The reaction was then cooled to 0 °C and saturated aq. $NaHCO_3$ was added slowly until gas evolution ceased, then H_2O (25 mL) was added. The crude mixture was extracted with Et_2O (2 x 50 mL). The combined organic layers were dried with $MgSO_4$, filtered, and concentrated. The product was purified by column chromatography (silica, 20% Et_2O/hexanes) to yield 544 mg (27% yield) of **211p** as a light

orange oil. $\mathbf{R_f}$ = 0.33 (silica, 30% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 8.59 (dd, *J* = 2.6, 0.7 Hz, 1H), 8.03 (dd, *J* = 8.6, 2.6 Hz, 1H), 7.30 – 7.23 (m, 1H), 5.75 (d, *J* = 4.5 Hz, 1H), 5.61 (d, *J* = 4.6 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 156.6, 149.0, 145.9, 138.0, 129.3, 118.7 (q, J_{C-F} = 320.6 Hz), 118.6 (q, J_{C-F} = 320.4 Hz), 115.4, 108.0. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -72.8, -73.3. **FTIR (NaCl, thin film, cm^{-1}):** 1648, 1588, 1474, 1427, 1212, 1138, 943, 890, 819. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_9H_5F_6O_6NS_2$ $[M+H]^+$: 401.9541; found: 401.9551.

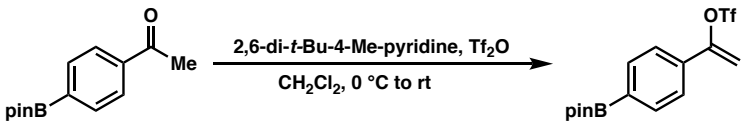
1-(4-chloro-3-fluorophenyl)vinyl trifluoromethanesulfonate (211q)



To a flame dried, N_2 filled round bottom flask was added 1-(4-chloro-3-fluorophenyl)vinyl trifluoromethanesulfonate (500 mg, 2.9 mmol, 1.0 equiv), 2-chloropyridine (428 mg, 3.8 mmol, 1.3 equiv), and CH_2Cl_2 (10 mL). The reaction was cooled to 0 °C before trifluoromethanesulfonic anhydride (0.58 mL, 3.5 mmol, 1.2 equiv) was added. The reaction was allowed to reach room temperature and continued to stir overnight. The reaction was then cooled to 0 °C and saturated aq. $NaHCO_3$ was added slowly until gas evolution ceased, then H_2O (25 mL) was added. The crude mixture was extracted with CH_2Cl_2 (2 x 50 mL). The combined organic layers were dried with $MgSO_4$, filtered, and concentrated. The product was purified by column chromatography (silica, hexanes) to yield 434 mg (49% yield) of **211q** as a light yellow oil. $\mathbf{R_f}$ = 0.31 (silica, hexanes, UV). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.46 (dd, *J* = 8.4, 7.3 Hz, 1H), 7.32 (dd, *J* = 9.6, 2.1 Hz, 1H), 7.29 (ddd, *J* = 8.4, 2.1, 0.9 Hz, 1H), 5.64 (d, *J* = 4.3 Hz, 1H), 5.47 (d, *J* = 4.3 Hz, 1H). **^{13}C**

NMR (101 MHz, $CDCl_3$): 158.3 (d, J_{C-F} = 250.3 Hz), 151.3 (d, J_{C-F} = 2.7 Hz), 132.6 (d, J_{C-F} = 7.2 Hz), 131.4, 123.5 (d, J_{C-F} = 17.7 Hz), 121.8 (d, J_{C-F} = 3.9 Hz), 118.6 (q, J_{C-F} = 320.3 Hz), 113.8 (d, J_{C-F} = 23.7 Hz), 106.0. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -73.5, -113.2 (dd, J_{F-H} = 9.3, 7.3 Hz). **FTIR (NaCl, thin film, cm^{-1}):** 1647, 1575, 1492, 1423, 1296, 1244, 1216, 1141, 1080, 955, 916, 803, 607. **HRMS (FAB, *m/z*):** calc'd for $C_9H_5ClF_4O_3S$ $[M+\cdot]^+$: 303.9584; found: 303.9592.

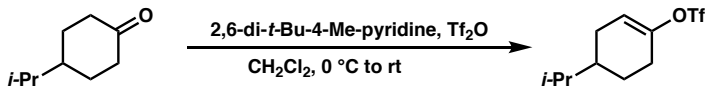
1-(4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)vinyl trifluoromethanesulfonate (211r)



To a round bottom flask was added 1-(4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)ethan-1-one (984 mg, 4.0 mmol, 1.0 equiv), 2,6-di-*tert*-butyl-4-methylpyridine (904 mg, 4.4 mmol, 1.1 equiv), and CH_2Cl_2 (12 mL). The reaction was cooled to 0 °C before trifluoromethanesulfonic anhydride (808 μL, 4.8 mmol, 1.2 equiv) was added. The reaction was allowed to reach room temperature and continued to stir overnight. The reaction was concentrated and the product was purified by column chromatography (silica, 5% EtOAc/hexanes) to yield 742 mg (49% yield) of **211r** as a blue oil. $\mathbf{R_f}$ = 0.51 (silica, 10% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.89 – 7.81 (m, 2H), 7.56 – 7.51 (m, 2H), 5.67 (d, *J* = 4.0 Hz, 1H), 5.41 (d, *J* = 4.0 Hz, 1H), 1.35 (s, 12H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 153.6, 135.3, 134.4, 124.5, 118.6 (q, J_{C-F} = 320.2 Hz), 105.1, 84.3, 25.0. *(Note: carbon bonded to boron not observed.)* **^{19}F NMR (282 MHz, $CDCl_3$):** δ -73.7.

FTIR (NaCl, thin film, cm^{-1}): 2981, 1646, 1612, 1423, 1402, 1362, 1225, 1143, 1096, 939, 829, 660, 605. **HRMS (FAB, *m/z*):** calc'd for $C_{15}H_{15}BF_3O_5S$ $[M+\cdot]^+$: 378.0920; found: 378.0946.

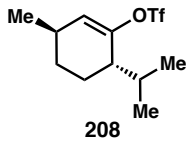
4-isopropylcyclohex-1-en-1-yl trifluoromethanesulfonate (251)



To a flame dried, N_2-filled round bottom flask was added 4-isopropylcyclohexan-1-one (1.8 g, 12.5 mmol, 1.0 equiv), 2,6-di-*tert*-butyl-4-methylpyridine (3.0 g, 14.4 mmol, 1.15 equiv), and CH_2Cl_2 (83 mL). The reaction was cooled to 0 °C before trifluoromethanesulfonic anhydride (2.3 mL, 2.7 mmol, 1.2 equiv) was added. The reaction was warmed to room temperature and continued overnight. The reaction was cooled to 0 °C, saturated aq. $NaHCO_3$ was slowly added until gas evolution ceased, and then H_2O (25 mL) was added. The crude mixture was extracted with CH_2Cl_2 (2 x 50 mL). The combined organic layers were dried with $MgSO_4$, filtered, and concentrated. The product was purified by column chromatography (silica, hexanes) to yield 2.3 g (68% yield) of **251** as a clear oil. $\mathbf{R_f}$ = 0.49 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.74 (dt, J = 5.2, 2.6 Hz, 1H), 2.46 – 2.34 (m, 1H), 2.34 – 2.25 (m, 1H), 2.25 – 2.14 (m, 1H), 1.98 – 1.84 (m, 2H), 1.61 – 1.49 (m, 1H), 1.49 – 1.29 (m, 2H), 0.91 (d, J = 3.0 Hz, 3H), 0.90 (d, J = 3.0 Hz, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 149.4, 118.6 (q, $J_{C\text{-}F}$ = 320.1 Hz), 118.3, 39.0, 31.7, 28.1, 27.4, 26.2, 20.0, 19.7. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -73.9. **FTIR (NaCl, thin film, cm^{-1}):** 2962, 2933, 2876, 1693, 1418, 1248, 1209, 1144, 1053, 1022, 879, 853, 615. **HRMS (EI, *m/z*):** calc'd for $C_{10}H_{15}F_3O_3S$ $[M+\cdot]^+$: 272.0694; found: 272.0681.

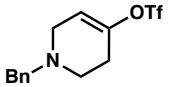
Other Alkeny Triflates Prepared from Literature

Alkenyl triflate **208** was prepared according to a literature procedure reported by Paquette and coworkers.[49]



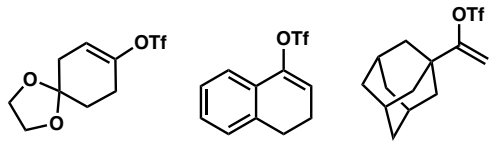
208

Alkenyl triflate **211b** was prepared according to a literature procedure reported by Stadler and coworkers.[50]



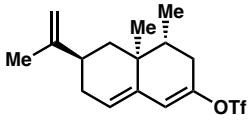
211b

Alkenyl triflates **211d**, **211e**, and **211u** were prepared according to a literature procedure reported by Yuan, Yi, and coworkers.[51]



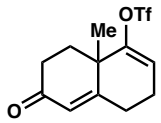
211d **211e** **211u**

Alkenyl triflate **211h** was prepared according to a literature procedure reported by Buchwald and coworkers.[52]



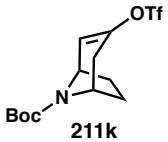
211h

Alkenyl triflate **211i** was prepared according to a literature procedure reported by Lett and coworkers.[53]



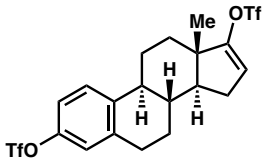
211i

Alkenyl triflate **211k** was prepared according to a literature procedure reported by Takahashi and coworkers.[54]



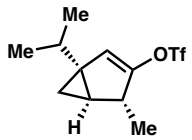
211k

Alkenyl triflate **211m** was prepared according to a literature procedure reported by Wang and coworkers.[55]



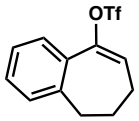
211m

Alkenyl triflate **211n** was prepared according to a literature procedure reported by Wada and coworkers.[56]



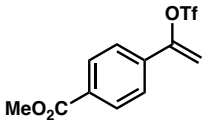
211n

Alkenyl triflate **211p** was prepared according to a literature procedure reported by Xu, Tang, and coworkers.[57]



211p

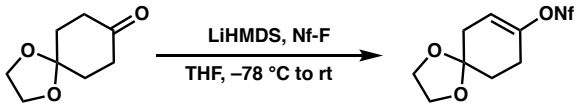
Alkenyl triflate **211q** was prepared according to a literature procedure reported by Kamimura and coworkers.[58]



211q

5.7.3.2 Alkenyl Nonaflates

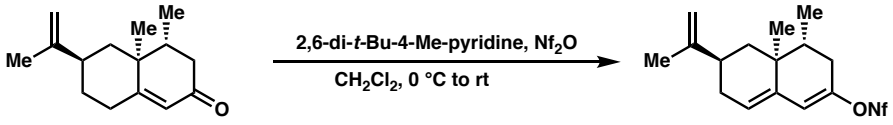
1,4-dioxaspiro[4.5]dec-7-en-8-yl 1,1,2,2,3,3,4,4,4-nonafluorobutane-1-sulfonate (233a)



1,4-dioxaspiro[4.5]decan-8-one (1.0 g, 6.4 mmol, 1.0 equiv) was added to a flame dried round-bottom flask and placed under an atmosphere of N_2. THF (13 mL) was added and the reaction was cooled to –78 °C. LiHMDS (8.3 mL, 1 M in THF, 5.5 mmol, 1.3 equiv) was added dropwise and allowed to stir for 30 minutes before perfluorobutanesulfonylfluoride (1.27 mL, 7.0 mmol, 1.1 equiv) was added in one portion. The reaction was allowed to reach room temperature and stir overnight. The reaction was then quenched with saturated aq. NH_4Cl (50 mL) and extracted with Et_2O (2 x 50 mL). The

combined organic layers were dried with $MgSO_4$, filtered, and concentrated. The product was purified by column chromatography (silica, 10% EtOAc/hexanes) to yield 1.3 g (45 % yield) of **233a** as a colorless oil. $\mathbf{R_f}$ = 0.66 (silica, 20% Et_2O/hexanes, anisaldehyde (blue)). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.68 (tt, *J* = 4.1, 1.4 Hz, 1H), 3.98 (p, *J* = 1.7 Hz, 4H), 2.54 (dtd, *J* = 6.6, 3.4, 2.6, 1.4 Hz, 2H), 2.41 (dt, *J* = 4.8, 2.6 Hz, 2H), 1.91 (t, *J* = 6.6 Hz, 2H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 148.4, 116.1, 106.3, 64.8, 34.3, 31.2, 26.6. (*Note: nonaflate carbons omitted due to low intensity resulting from C-F splitting*). **^{19}F NMR (282 MHz, $CDCl_3$):** δ -80.55 (tt, *J* = 9.7, 2.3 Hz), -109.78 – -109.95 (m), -120.87 (dddd, *J* = 14.9, 9.8, 6.4, 2.4 Hz), -125.66 – -125.90 (m). **FTIR (NaCl, thin film, cm^{-1}):** 2965, 2890, 1691, 1422, 1240, 1144, 1070, 883. **HRMS (EI, *m/z*):** calc'd for $C_{12}H_{12}F_9O_5S$ $[M+H]^+$: 439.0261; found: 439.0276.

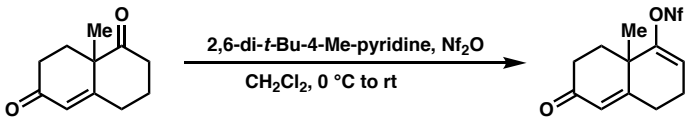
(4*R*,4a*S*,6*R*)-4,4a-dimethyl-6-(prop-1-en-2-yl)-3,4,4a,5,6,7-hexahydronaphthalen-2-yl 1,1,2,2,3,3,4,4,4-nonafluorobutane-1-sulfonate (233b)



To a round bottom flask was added (4*S*,4a*R*,6*S*)-4,4a-dimethyl-6-(prop-1-en-2-yl)-4,4a,5,6,7,8-hexahydronaphthalen-2(3*H*)-one (174 mg, 0.8 mmol, 1.0 equiv), 2,6-di-*tert*-butyl-4-methylpyridine (312 mg, 0.9 mmol, 1.1 equiv), and CH_2Cl_2 (4 mL). The reaction was cooled to 0 °C before nonafluorobutanesulfonic anhydride (465 mg, 0.8 mmol, 1.0 equiv) was added. The reaction was allowed to reach room temperature and continued to stir for 2 hours. The reaction was diluted with hexanes, filtered, and concentrated. The product was purified by column chromatography (silica, hexanes) to yield 226 mg (56%

yield) of **233b** as a colorless oil. $\mathbf{R_f}$ = 0.22 (silica, hexanes, UV). $[\boldsymbol{\alpha}]_D^{25}$ = –66° (c = 0.5, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.04 (s, 1H), 5.63 (dd, *J* = 5.3, 2.7 Hz, 1H), 4.76 (pd, *J* = 1.9, 1.3 Hz, 2H), 2.50 – 2.36 (m, 1H), 2.36 – 2.29 (m, 3H), 2.26 (td, *J* = 5.4, 1.4 Hz, 1H), 1.98 (ddd, *J* = 18.9, 11.4, 2.3 Hz, 1H), 1.79 – 1.65 (m, 5H), 1.18 (t, *J* = 12.7 Hz, 1H), 0.96 (d, *J* = 6.8 Hz, 3H), 0.93 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 149.6, 147.1, 138.5, 128.2, 120.5, 109.3, 39.7, 39.3, 37.1, 35.9, 34.3, 31.4, 30.3, 20.8, 17.3, 14.5. (*Note: nonaflate carbons omitted due to low intensity resulting from C-F splitting*). **^{19}F NMR (282 MHz, $CDCl_3$):** δ -80.57 (tt, *J* = 9.8, 2.3 Hz), -109.77 – -109.94 (m), -120.90 (dddt, *J* = 15.8, 9.7, 6.3, 3.3 Hz), -125.69 – -125.92 (m). **FTIR (NaCl, thin film, cm^{-1}):** 2969, 1644, 1416, 1238, 1142, 1058, 912. **HRMS (EI, *m/z*):** calc'd for $C_{19}H_{20}F_9O_3S$ $[M–H]^+$: 499.0989; found: 499.0965.

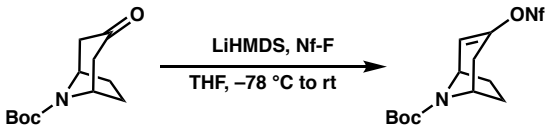
8a-methyl-6-oxo-3,4,6,7,8,8a-hexahydronaphthalen-1-yl 1,1,2,2,3,3,4,4,4-nonafluoro-butane-1-sulfonate (233c)



To a round bottom flask was added 8a-methyl-3,4,8,8a-tetrahydronaphthalene-1,6(2*H*,7*H*)-dione (142 mg, 0.8 mmol, 1.0 equiv), 2,6-di-tert-butyl-4-methylpyridine (312 mg, 0.9 mmol, 1.1 equiv), and CH_2Cl_2 (4 mL). The reaction was cooled to 0 °C before nonafluorobutansulfonic anhydride (465 mg, 0.8 mmol, 1.0 equiv) was added. The reaction was allowed to reach room temperature and continued to stir for 2 hours. The reaction was diluted with hexanes, filtered, and concentrated. The product was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield 270 mg (73% yield) of **233c** as a white

solid. $\mathbf{R_f}$ = 0.32 (silica, 25% Et_2O/hexanes, UV). **^{1}H NMR (400 MHz, $CDCl_3$)**: δ 6.15 (d, *J* = 2.3 Hz, 1H), 5.89 – 5.82 (m, 1H), 2.81 (ddd, *J* = 15.4, 7.3, 6.2 Hz, 1H), 2.74 – 2.35 (m, 5H), 2.07 (ddd, *J* = 13.6, 5.9, 1.6 Hz, 1H), 1.75 – 1.61 (m, 1H), 1.25 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 213.0, 148.2, 136.4, 127.4, 119.4, 44.7, 35.2, 28.9, 25.1, 24.9, 22.7. (*Note: nonaflate carbons omitted due to low intensity resulting from C-F splitting*) **^{19}F NMR (282 MHz, $CDCl_3$):** δ -80.57 (tt, *J* = 9.8, 2.3 Hz), -109.67 – -109.85 (m), -120.88 (dtd, *J* = 14.8, 7.1, 6.5, 4.2 Hz), -125.68 – -125.92 (m). **FTIR (NaCl, thin film, cm^{-1}):** 2969, 2936, 1715, 1664, 1420, 1353, 1203, 1144, 1061, 880. **HRMS (EI, *m/z*):** calc'd for $C_{15}H_{13}F_9O_4S$ $[M+\cdot]^+$: 460.0391; found: 460.0375.

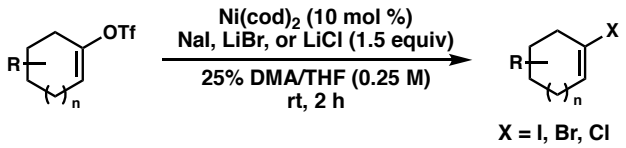
tert-butyl (1_r_,5_s_)-3-(((perfluorobutyl)sulfonyl)oxy)-8-azabicyclo[3.2.1]oct-2-ene-8-carboxylate (233d)



To a flame dried round-bottom flask under an inert atmosphere was added *tert*-butyl (1*R*,5*S*)-3-oxo-8-azabicyclo[3.2.1]octane-8-carboxylate (1.17 g, 5.0 mmol, 1.0 equiv). THF (9 mL) was added and the reaction was cooled to –78 °C. LiHMDS (5.5 mL, 1 M in THF, 5.5 mmol, 1.1 equiv) was added dropwise and allowed to stir for 30 minutes before perfluorobutanesulfonylfluoride (1.88 g, 5.25 mmol, 1.05 equiv) was added in one portion. The reaction was allowed to reach room temperature and stir overnight. The reaction was then quenched with saturated aq. NH_4Cl (50 mL) and extracted with Et_2O (2 x 50 mL). The combined organic layers were dried with $MgSO_4$, filtered, and concentrated. The product

was purified by column chromatography (silica, 10-20% Et_2O/hexanes) to yield 2.1 g (95% yield) of **233d** as an off white solid. $\mathbf{R_f}$ = 0.59 (silica, 75% Et_2O/hexanes, anisaldehyde (blue)). **^{1}H NMR (400 MHz, d_3-MeCN, 65 °C):** δ 6.19 (ddd, *J* = 5.8, 1.9, 1.1 Hz, 1H), 4.53 – 4.45 (m, 1H), 4.44 – 4.36 (m, 1H), 3.08 – 2.95 (m, 1H), 2.23 (dddd, *J* = 13.6, 7.4, 6.3, 1.7 Hz, 1H), 2.16 (dt, *J* = 17.0, 1.2 Hz, 1H), 2.04 – 1.96 (m, 2H), 1.81 – 1.69 (m, 1H), 1.45 (s, 9H). **^{13}C NMR (101 MHz, d_3-MeCN, 65 °C):** δ 154.9, 149.1, 125.3, 80.9, 53.6, 53.5, 37.6, 35.2, 30.4, 28.7. (*Note: nonaflate carbons omitted due to low intensity resulting from C-F splitting*) **^{19}F NMR (376 MHz, d_3-MeCN, 65 °C):** δ -81.46 (tt, *J* = 9.7, 2.8 Hz), -109.99 (ddp, *J* = 16.8, 10.7, 2.7 Hz), -121.10 – -121.26 (m), -125.91 – -126.07 (m). (*Note: not standardized with internal C_6F_6*). **FTIR (NaCl, thin film, cm^{-1}):** 3188, 3076, 2981, 1697, 1416, 1326, 1243, 1064, 875. **HRMS (EI, *m/z*):** calc'd for $C_{16}H_{19}F_9O_5SN$ $[M+H]^+$: 508.0843; found: 508.0840.

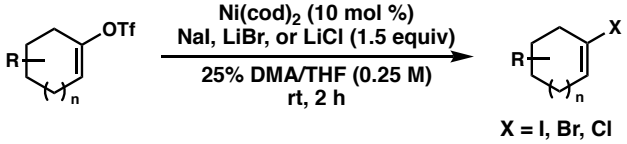
5.7.4 Ni-Catalyzed Halogenation



General Procedure 1: Enol Triflate Halogenation on 0.3 mmol scale.

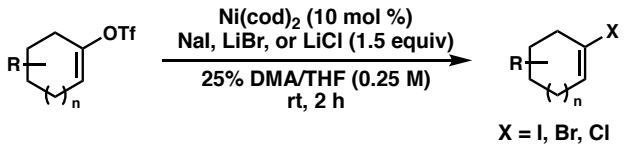
A 2-dram vial was equipped with a stir bar and brought into a N_2-filled glovebox. The vial was charged with NaI, LiBr, or LiCl (0.45 mmol, 1.5 equiv) and $Ni(cod)_2$ (8.3 mg, 0.03 mmol, 0.1 equiv). Anhydrous DMA (0.3 mL) and THF (0.9 mL) were added, resulting in a clear yellow solution. Enol triflate (0.3 mmol, 1 equiv) was added in one portion, turning the reaction dark red (NaI) or aqua blue (LiBr or LiCl) over several minutes. The vial was

sealed with Teflon cap and brought out of the glovebox. The reaction was allowed to stir on the bench (480 rpm) for two hours at room temperature. Reaction was quenched by addition of water and Et_2O. The organic layer was separated and extracted with 2 x 10 mL Et_2O, then washed once with brine (20 mL). The combined organic layers were dried with $MgSO_4$, filtered, and concentrated under reduced pressure. The crude reaction was purified by silica gel chromatography to afford the desired product.



General Procedure 2: Enol Triflate Halogenation on 6.0 mmol scale.

A 100 mL Schlenk flask was equipped with a stir bar and brought into a N_2-filled glovebox. The vial was charged with NaI, LiBr, or LiCl (9.0 mmol, 1.5 equiv) and $Ni(cod)_2$ (166 mg, 0.6 mmol, 0.1 equiv). Anhydrous DMA (6 mL) and THF (18 mL) were added, resulting in a clear yellow solution. Enol triflate (6.0 mmol, 1 equiv) was added in one portion, turning the reaction dark red (NaI) or aqua blue (LiBr or LiCl) over several minutes. The Schlenk flask was sealed with a Kontes valve and brought out of the glovebox. The reaction was allowed to stir on the bench (480 rpm) for two hours at room temperature. Reaction was quenched by addition of water and Et_2O. The organic layer was separated and extracted with 2 x 200 mL Et_2O, then washed once with brine (400 mL). The combined organic layers were dried with $MgSO_4$, filtered, and concentrated under reduced pressure. The crude reaction was purified by silica gel chromatography to afford the desired product.

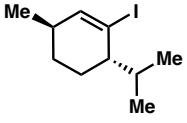


General Procedure 3: Enol Nonaflate Halogenation on 0.3 mmol scale.

A 2-dram vial was equipped with a stir bar and brought into a N_2-filled glovebox. The vial was charged with NaI, LiBr, or LiCl (0.45 mmol, 1.5 equiv) and $Ni(cod)_2$ (8.3 mg, 0.03 mmol, 0.1 equiv). Anhydrous DMA (0.3 mL) and THF (0.9 mL) were added, resulting in a clear yellow solution. Enol nonaflate (0.3 mmol, 1 equiv) was added in one portion, turning the reaction dark red (NaI) or aqua blue (LiBr or LiCl) over several minutes. The vial was sealed with Teflon cap and brought out of the glovebox. The reaction was allowed to stir on the bench (480 rpm) for two hours at room temperature. Reaction was quenched by addition of water and Et_2O. The organic layer was separated and extracted with 2 x 10 mL Et_2O, then washed once with brine (20 mL). The combined organic layers were dried with $MgSO_4$, filtered, and concentrated under reduced pressure. The crude reaction was purified by silica gel chromatography to afford the desired product.

5.7.5 Characterization of Reaction Products

(3*R*,6*S*)-1-iodo-6-isopropyl-3-methylcyclohex-1-ene (209a)

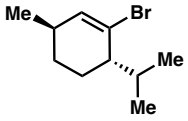


Prepared from (3*R*,6*S*)-6-isopropyl-3-methylcyclohex-1-en-1-yl trifluoromethanesulfonate (**208**, 143.2 mg, 0.3 mmol) and sodium iodide (112.5 mg, 0.75 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **209a** (96 mg, 73% yield) as a colorless oil. $\mathbf{R}_f = 0.79$ (silica, pentane, $KMnO_4$). $[\alpha]_D^{25} = -47°$ (c = 0.5, $CHCl_3$). **^{1}H NMR (400 MHz,**

$CDCl_3$): δ 6.36 (d, *J* = 1.2 Hz, 1H), 2.35 – 2.14 (m, 3H), 1.89 – 1.79 (m, 1H), 1.68 (dddd, *J* = 13.3, 5.9, 4.5, 3.0 Hz, 1H), 1.54 – 1.42 (m, 1H), 1.18 (tdd, *J* = 13.1, 10.2, 3.1 Hz, 1H), 0.97 (d, *J* = 7.0 Hz, 3H), 0.94 (d, *J* = 6.8 Hz, 3H), 0.72 (d, *J* = 6.7 Hz, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 146.8, 109.2, 48.7, 35.7, 32.4, 30.9, 23.0, 21.5, 20.5, 15.1. **FTIR (NaCl, thin film, cm^{-1}):** 2958, 2868, 1617, 1457, 1367, 1314, 944, 852, 782, 703. **HRMS (EI, *m/z*):** calc'd for $C_{10}H_{17}I$ $[M+\cdot]^+$: 264.0375; found: 264.0392.

Prepared from (3*R*,6*S*)-6-isopropyl-3-methylcyclohex-1-en-1-yl trifluoromethanesulfonate (**208**, 1.70 g, 6.0 mmol) and sodium iodide (1.3 g, 9.0 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **209a** (1.12 g, 71% yield) as a colorless oil.

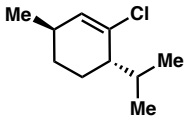
(3*R*,6*S*)-1-bromo-6-isopropyl-3-methylcyclohex-1-ene (209b)



Prepared from (3*R*,6*S*)-6-isopropyl-3-methylcyclohex-1-en-1-yl trifluoromethanesulfonate (**208**, 85.9 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **209b** (52 mg, 80% yield) as a colorless oil. $\mathbf{R}_f$ = 0.77 (silica, hexanes, $KMnO_4$). $[\alpha]_D^{25}$ = –26° (c = 1.0, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.99 (td, *J* = 2.0, 1.0 Hz, 1H), 2.39 (ddt, *J* = 13.7, 6.8, 3.4 Hz, 1H), 2.32 (ddtd, *J* = 9.8, 5.8, 3.8, 1.8 Hz, 1H), 2.24 – 2.12 (m, 1H), 1.85 – 1.71 (m, 2H), 1.51 – 1.39 (m, 1H), 1.14 (tdd, *J* = 12.4, 10.1, 2.6 Hz, 1H), 0.98 (d, *J* = 7.1 Hz, 3H), 0.93 (d, *J* = 7.0 Hz, 3H), 0.75 (d, *J* = 6.8 Hz, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 137.8, 129.5, 47.0, 33.9, 30.8, 29.6, 23.2, 21.6, 20.3, 15.4. **FTIR (NaCl, thin film, cm^{-1}):** 2959, 2930, 2870,

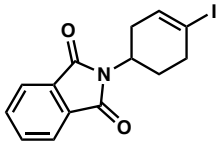
2854, 1634, 1458, 1387, 1318, 949, 851, 791. **HRMS (EI, *m/z*):** calc'd for $C_{10}H_{17}Br$ $[M+\cdot]^+$: 216.0514; found: 216.0532.

(3*R*,6*S*)-1-chloro-6-isopropyl-3-methylcyclohex-1-ene (209c)



Prepared from (3*R*,6*S*)-6-isopropyl-3-methylcyclohex-1-en-1-yl trifluoromethanesulfonate (**208**, 85.9 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **209c** (37 mg, 72% yield) as a colorless oil. $\mathbf{R_f}$ = 0.87 (silica, hexanes, $KMnO_4$). $[\alpha]_D^{25} = -11°$ (c = 0.5, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.73 (td, *J* = 2.0, 1.0 Hz, 1H), 2.37 (m, 1H), 2.27 (ddtd, *J* = 9.7, 5.7, 3.8, 1.9 Hz, 1H), 2.23 – 2.14 (m, 1H), 1.84 – 1.71 (m, 2H), 1.48 – 1.35 (m, 1H), 1.16 – 1.04 (m, 1H), 0.98 (d, *J* = 7.0 Hz, 3H), 0.93 (d, *J* = 7.0 Hz, 3H), 0.76 (d, *J* = 6.8 Hz, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 136.5, 133.3, 45.8, 32.5, 30.8, 28.2, 22.8, 21.8, 20.3, 15.7. **FTIR (NaCl, thin film, cm^{-1}):** 2960, 2870, 1642, 1454, 1368, 957, 851, 812, 727. **HRMS (EI, *m/z*):** calc'd for $C_{10}H_{17}Cl$ $[M+\cdot]^+$: 172.1019; found: 172.1032.

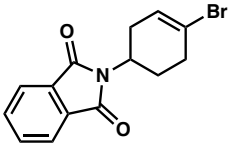
2-(4-iodocyclohex-3-en-1-yl)isoindoline-1,3-dione (212a)



Prepared from 4-(1,3-dioxoisoindolin-2-yl)cyclohex-1-en-1-yl trifluoromethanesulfonate (**211a**, 113 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10 to 25% Et_2O/hexanes) to yield **212a** (53 mg, 50% yield) as a white solid. $\mathbf{R_f}$ = 0.40 (silica, 30% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.81 (tt, *J* = 5.1, 2.4 Hz, 2H), 7.76 – 7.66 (m, 2H), 6.29 (dq, *J* = 5.7,

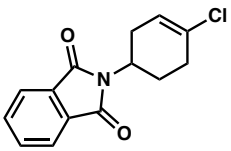
1.9 Hz, 1H), 4.44 (dqd, *J* = 11.5, 5.5, 3.1 Hz, 1H), 3.06 – 2.92 (m, 1H), 2.82 – 2.61 (m, 3H), 2.19 (dtd, *J* = 16.8, 5.7, 5.0, 3.0 Hz, 1H), 1.78 – 1.66 (m, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 168.3, 135.5, 134.1, 132.0, 123.3, 95.1, 45.7, 39.9, 32.3, 28.9. **FTIR (NaCl, thin film, cm^{-1}):** 1700, 1458, 1395, 1380, 1109, 990, 874, 716. **HRMS (FAB, *m/z*):** calc'd for $C_{14}H_{12}NO_2I$ $[M+H]^+$: 353.9991; found: 353.9979.

2-(4-bromocyclohex-3-en-1-yl)isoindoline-1,3-dione (212b)



Prepared from 4-(1,3-dioxoisoindolin-2-yl)cyclohex-1-en-1-yl trifluoromethanesulfonate (**211a**, 113 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10 to 25% Et_2O/hexanes) to yield **212b** (65 mg, 71% yield) as a white solid. $\mathbf{R}_f$ = 0.36 (silica, 30% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.86 – 7.78 (m, 2H), 7.75 – 7.67 (m, 2H), 6.01 (dtd, *J* = 5.9, 2.3, 0.9 Hz, 1H), 4.42 (dddd, *J* = 12.6, 11.1, 5.5, 3.2 Hz, 1H), 3.01 – 2.89 (m, 1H), 2.79 – 2.63 (m, 2H), 2.63 – 2.51 (m, 1H), 2.25 – 2.14 (m, 1H), 1.88 – 1.76 (m, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 168.3, 134.1, 132.0, 127.0, 123.3, 121.3, 46.0, 35.4, 30.4, 27.9. **FTIR (NaCl, thin film, cm^{-1}):** 1695, 1464, 1396, 1111, 992, 919, 875, 717. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{14}H_{12}NO_2Br$ $[M+H]^+$: 306.0130; found: 306.0121.

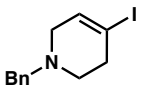
2-(4-chlorocyclohex-3-en-1-yl)isoindoline-1,3-dione (212c)



Prepared from 4-(1,3-dioxoisoindolin-2-yl)cyclohex-1-en-1-yl trifluoromethanesulfonate (**211a**, 113 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was

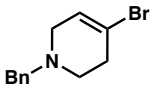
purified by column chromatography (silica, 10 to 25% Et_2O/hexanes) to yield **212c** (72 mg, 92% yield) as a white solid. $\mathbf{R_f}$ = 0.36 (silica, 30% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.85 – 7.79 (m, 2H), 7.74 – 7.68 (m, 2H), 5.80 (dtt, *J* = 5.9, 2.4, 0.7 Hz, 1H), 4.46 – 4.36 (m, 1H), 2.97 (dddt, *J* = 16.6, 11.0, 4.4, 2.3 Hz, 1H), 2.72 (tdd, *J* = 12.5, 11.8, 5.8 Hz, 1H), 2.66 – 2.55 (m, 1H), 2.49 – 2.40 (m, 1H), 2.27 – 2.18 (m, 1H), 1.90 – 1.82 (m, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 168.3, 134.1, 132.0, 131.4, 123.3, 122.7, 46.2, 33.0, 29.1, 27.1. **FTIR (NaCl, thin film, cm^{-1}):** 1700, 1465, 1378, 1112, 995, 920, 876, 717. **HRMS (FAB, *m/z*):** calc'd for $C_{14}H_{12}NO_2Cl$ $[M+H]^+$: 262.0635; found: 262.0636.

1-benzyl-4-iodo-1,2,3,6-tetrahydropyridine (213a)



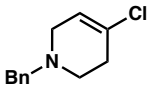
Prepared from 1-benzyl-1,2,3,6-tetrahydropyridin-4-yl trifluoromethanesulfonate (**211b**, 96 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield **213a** (62 mg, 69% yield) as a light yellow oil. $\mathbf{R_f}$ = 0.31 (silica, 10% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.35 – 7.22 (m, 5H), 6.26 (td, *J* = 3.5, 1.7 Hz, 1H), 3.56 (s, 2H), 3.04 – 3.00 (m, 2H), 2.61 (m, 4H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 138.0, 135.3, 129.2, 128.5, 127.4, 93.2, 62.3, 55.7, 51.7, 39.8. **FTIR (NaCl, thin film, cm^{-1}):** 2920, 2800, 2752, 1494, 1454, 1363, 1340, 1054, 960, 729, 698. **HRMS (FAB, *m/z*):** calc'd for $C_{12}H_{14}IN$ $[M+H–H_2]^+$: 298.0093; found: 298.0081.

1-benzyl-4-bromo-1,2,3,6-tetrahydropyridine (213b)



Prepared from 1-benzyl-1,2,3,6-tetrahydropyridin-4-yl trifluoromethanesulfonate (**211b**, 96 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 5% to 10 Et_2O/hexanes) to yield **213b** (60 mg, 79% yield) as a light yellow oil. $\mathbf{R_f}$ = 0.60 (silica, 20% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.37 – 7.24 (m, 5H), 5.99 (tt, *J* = 3.5, 1.6 Hz, 1H), 3.59 (s, 2H), 3.01 (dt, *J* = 3.7, 2.8 Hz, 2H), 2.66 (td, *J* = 5.7, 0.6 Hz, 2H), 2.58 – 2.52 (m, 2H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 138.0, 129.1, 128.4, 127.4, 126.8, 119.9, 62.0, 54.1, 50.9, 35.8. **FTIR (NaCl, thin film, cm^{-1}):** 3062, 3027, 2924, 2802, 2756, 1659, 1493, 1454, 1365, 1346, 1056, 995, 965, 822, 732, 698. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{12}H_{14}BrN$ $[M+H]^+$: 252.0388; found: 252.0404.

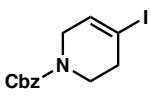
1-benzyl-4-chloro-1,2,3,6-tetrahydropyridine (213c)



Prepared from 1-benzyl-1,2,3,6-tetrahydropyridin-4-yl trifluoromethanesulfonate (**211b**, 96 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 5 to 10% Et_2O/hexanes) to yield **213c** (50 mg, 80% yield) as a light yellow oil. $\mathbf{R_f}$ = 0.56 (silica, 20% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.36 – 7.25 (m, 5H), 5.76 (tt, *J* = 3.5, 1.6 Hz, 1H), 3.60 (s, 2H), 3.03 (dt, *J* = 3.6, 2.8 Hz, 2H), 2.67 (t, *J* = 5.7 Hz, 2H), 2.43 (ttd, *J* = 5.7, 2.8, 1.5 Hz, 2H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 138.1, 130.3, 129.1, 128.4, 127.4, 122.5, 62.0, 52.9, 50.2, 33.5. **FTIR (NaCl, thin film, cm^{-1}):** 3062, 6027, 2925, 2801, 2759, 1666, 1494, 1454, 1365, 1350,

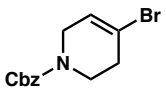
1059, 998, 972, 824, 735, 698. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{12}H_{14}ClN$ $[M+H]^+$: 208.0893; found: 208.0881.

benzyl 4-iodo-3,6-dihydropyridine-1(2*H*)-carboxylate (214a)



Prepared from benzyl 4-(((trifluoromethyl)sulfonyl)oxy)-3,6-dihydro-pyridine-1(2*H*)-carboxylate (**211c**, 110 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield **214a** (61 mg, 60% yield) as a colorless oil. $\mathbf{R_f}$ = 0.25 (silica, 10% EtOAc/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, *d*$_3$-MeCN, 65 °C):** δ 7.61 – 7.11 (m, 5H), 6.38 – 6.30 (m, 1H), 5.13 (s, 2H), 3.97 (q, *J* = 3.0 Hz, 2H), 3.58 (t, *J* = 5.7 Hz, 2H), 2.69 – 2.49 (m, 2H). **^{13}C NMR (101 MHz, *d*$_3$-MeCN, 65 °C):** δ 156.4, 138.6, 135.5, 129.7, 129.1, 128.9, 92.7, 68.1, 47.7, 43.7, 39.9. **FTIR (NaCl, thin film, cm^{-1}):** 3032, 2932, 2838, 1704, 1428, 1361, 1335, 1273, 1231, 1108, 1044, 1027, 964, 697. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{13}H_{14}INO_2$ $[M+H]^+$: 344.0148; found: 344.0154.

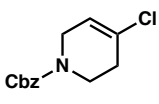
benzyl 4-bromo-3,6-dihydropyridine-1(2*H*)-carboxylate (214b)



Prepared from benzyl 4-(((trifluoromethyl)sulfonyl)oxy)-3,6-dihydro-pyridine-1(2*H*)-carboxylate (**211c**, 110 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield **214b** (81 mg, 91% yield) as a colorless oil. $\mathbf{R_f}$ = 0.36 (silica, 30% EtOAc/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, *d*$_3$-MeCN, 65 °C):** δ 7.38 (m, 4H), 7.33 (m, 1H), 6.06 (tt, *J* = 3.4, 1.7 Hz, 1H), 5.14 (s,

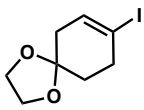
2H), 3.96 (q, *J* = 3.0 Hz, 2H), 3.63 (t, *J* = 5.8 Hz, 2H), 2.53 (ttd, *J* = 5.6, 2.7, 1.6 Hz, 2H). **^{13}C NMR (101 MHz, *d*$_3$-MeCN, 65 °C):** δ 156.2, 138.5, 129.6, 129.1, 128.9, 127.1, 120.2, 68.0, 46.1, 43.0, 35.9. **FTIR (NaCl, thin film, cm^{-1}):** 2934, 1698, 1428, 1361, 1336, 1274, 1230, 1111, 1027, 964, 757, 698. **HRMS (FAB, *m/z*):** calc'd for $C_{13}H_{14}BrNO_2$ $[M+H]^+$: 296.0286; found: 296.0285.

benzyl 4-chloro-3,6-dihydropyridine-1(2*H*)-carboxylate (214c)



Prepared from benzyl 4-(((trifluoromethyl)sulfonyl)oxy)-3,6-dihydropyridine-1(2*H*)-carboxylate (**211c**, 110 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield **214c** (65 mg, 86% yield) as a colorless oil. **R$_f$** = 0.36 (silica, 30% EtOAc/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, *d*$_3$-MeCN, 65 °C):** δ 7.41 – 7.36 (m, 4H), 7.36 – 7.31 (m, 1H), 5.84 (tt, *J* = 3.4, 1.6 Hz, 1H), 5.14 (s, 2H), 3.99 (q, *J* = 2.9 Hz, 2H), 3.64 (t, *J* = 5.8 Hz, 2H), 2.41 (ttd, *J* = 5.7, 2.7, 1.5 Hz, 2H). **^{13}C NMR (101 MHz, *d*$_3$-MeCN, 65 °C):** δ 156.2, 138.5, 131.0, 129.7, 129.1, 128.9, 122.9, 68.0, 44.9, 42.4, 33.6. **FTIR (NaCl, thin film, cm^{-1}):** 3033, 2940, 1698, 1497, 1428, 1362, 1276, 1233, 1112, 1049, 971, 813, 764, 699. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{13}H_{14}ClNO_2$ $[M+H]^+$: 252.0791; found: 252.0807.

8-iodo-1,4-dioxaspiro[4.5]dec-7-ene (215a)

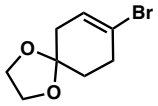


Prepared from 1,4-dioxaspiro[4.5]dec-7-en-8-yl trifluoromethanesulfonate (**211d**, 86.5 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column

chromatography (silica, 10% Et_2O/pentane) to yield **215a** (29 mg, 36% yield) as a colorless oil.

Prepared from 1,4-dioxaspiro[4.5]dec-7-en-8-yl 1,1,2,2,3,3,4,4,4-nonafluorobutane-1-sulfonate (**233a**, 131.4 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 3. The crude residue was purified by column chromatography (silica, 0.5% trimethylamine/10% EtOAc/pentane) to yield **215a** (44 mg, 55% yield) as a colorless oil. $\mathbf{R_f}$ = 0.45 (silica, 10% EtOAc/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.18 (tt, *J* = 3.9, 1.7 Hz, 1H), 3.97 (s, 4H), 2.70 (tq, *J* = 6.5, 2.2 Hz, 2H), 2.30 (dddd, *J* = 4.0, 3.3, 2.3, 1.2 Hz, 2H), 1.80 (tt, *J* = 6.5, 0.9 Hz, 2H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 134.7, 106.1, 95.0, 64.6, 39.6, 38.7, 33.8. **FTIR (NaCl, thin film, cm^{-1}):** 2882, 1651, 1429, 1366, 1252, 1114, 1059, 1022, 914, 860, 650. **HRMS (FAB, *m/z*):** calc'd for $C_8H_{11}IO_2$ $[M+H]^+$: 266.9882; found: 266.9885.

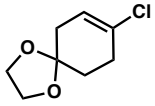
8-bromo-1,4-dioxaspiro[4.5]dec-7-ene (215b)



Prepared from 1,4-dioxaspiro[4.5]dec-7-en-8-yl trifluoromethanesulfonate (**211d**, 86.5 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10% Et_2O/pentane) to yield **251b** (48 mg, 73% yield) as a colorless oil. $\mathbf{R_f}$ = 0.41 (silica, 10% EtOAc/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.90 (tt, *J* = 4.0, 1.6 Hz, 1H), 3.97 (s, 4H), 2.62 (ttd, *J* = 6.5, 2.4, 1.6 Hz, 2H), 2.29 (dtt, *J* = 4.1, 2.4, 0.9 Hz, 2H), 1.84 (tt, *J* = 6.6, 0.9 Hz, 2H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 126.2, 121.2, 106.4, 64.7, 37.7, 34.3, 32.8. **FTIR (NaCl, thin film, cm^{-1}):** 2883, 1652, 1430,

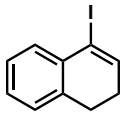
1368, 1255, 1117, 1060, 1024, 929, 862, 654. **HRMS (EI, *m/z*):** calc'd for $C_8H_{11}BrO_2$ $[M+\cdot]^+$: 217.9942; found: 217.9933.

8-chloro-1,4-dioxaspiro[4.5]dec-7-ene (215c)



Prepared from 1,4-dioxaspiro[4.5]dec-7-en-8-yl trifluoromethanesulfonate (**211d**, 86.5 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10% Et_2O/pentane) to yield **215c** (44 mg, 83% yield) as a colorless oil. $\mathbf{R_f}$ = 0.38 (silica, 10% EtOAc/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.69 (tt, *J* = 4.1, 1.6 Hz, 1H), 3.98 (s, 4H), 2.51 (tq, *J* = 6.5, 2.0 Hz, 2H), 2.36 – 2.29 (m, 2H), 1.91 – 1.81 (m, 2H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 131.4, 121.8, 106.8, 64.7, 36.4, 32.0, 31.9. **FTIR (NaCl, thin film, cm^{-1}):** 2933, 2884, 1659, 1433, 1370, 1336, 1251, 1203, 1119, 1062, 1028, 985, 944, 864, 666. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_8H_{11}ClO_2$ $[M+H]^+$: 175.0526; found: 175.0521.

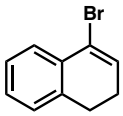
4-iodo-1,2-dihydronaphthalene (216a)



Prepared from 3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (**211e**, 93.5 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **216a** (38 mg, 49% yield) as a colorless oil. $\mathbf{R_f}$ = 0.65 (silica, hexanes, UV). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.43 (dd, *J* = 7.5, 1.3 Hz, 1H), 7.27 – 7.20 (m, 1H), 7.17 (td, *J* = 7.4, 1.4 Hz, 1H), 7.05 – 7.00 (m, 1H), 6.83 (t, *J* = 4.8 Hz, 1H), 2.85 (t, *J* = 8.0 Hz, 2H), 2.36 (ddd, *J* = 9.1, 7.4, 4.9 Hz, 2H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 140.2,

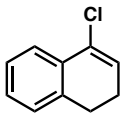
135.9, 134.4, 130.9, 128.4, 127.4, 127.1, 98.1, 27.9, 27.2. **FTIR (NaCl, thin film, cm^{-1}):** 3059, 2934, 2882, 2827, 1604, 1476, 1448, 1314, 1276, 938, 805, 756, 727. **HRMS (EI, *m/z*):** calc'd for $C_{10}H_9I$ $[M+\cdot]^+$: 255.9749; found: 255.9744.

4-bromo-1,2-dihydronaphthalene (216b)



Prepared from 3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (**211e**, 93.5 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **216b** (48 mg, 77% yield) as a colorless oil. $\mathbf{R_f}$ = 0.62 (silica, hexanes, UV). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.57 (dd, *J* = 7.5, 1.4 Hz, 1H), 7.26 (td, *J* = 7.6, 1.5 Hz, 1H), 7.21 (td, *J* = 7.4, 1.5 Hz, 1H), 7.11 (dq, *J* = 7.8, 1.2 Hz, 1H), 6.46 (t, *J* = 4.8 Hz, 1H), 2.85 (t, *J* = 8.1 Hz, 2H), 2.38 (ddd, *J* = 9.1, 7.4, 4.9 Hz, 2H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 136.4, 133.2, 130.8, 128.4, 127.4, 126.9, 126.6, 121.5, 27.7, 25.6. **FTIR (NaCl, thin film, cm^{-1}):** 3059, 2937, 2884, 2831, 1690, 1615, 1479, 1450, 1316, 1169, 948, 809, 758, 730. **HRMS (EI, *m/z*):** calc'd for $C_{10}H_9Br$ $[M+\cdot]^+$: 207.9888; found: 207.9876.

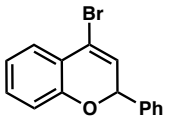
4-chloro-1,2-dihydronaphthalene (216c)



Prepared from 3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (**211e**, 93.5 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **216c** (39 mg, 80% yield) as a colorless oil. $\mathbf{R_f}$ = 0.56 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.57 (dd, *J* = 7.5, 1.5 Hz, 1H), 7.28 – 7.23 (m, 1H), 7.21 (td, *J* = 7.4, 1.6 Hz, 1H), 7.16 – 7.11 (m, 1H), 6.18 (t, *J* = 4.8 Hz, 1H), 2.84 (t, *J*

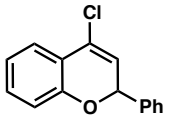
= 8.0 Hz, 2H), 2.40 (ddd, *J* = 9.1, 7.5, 4.8 Hz, 2H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 136.5, 132.5, 130.6, 128.3, 127.4, 126.8, 126.1, 124.2, 27.7, 24.3. **FTIR (NaCl, thin film, cm^{-1}):** 3063, 2938, 2887, 2832, 1621, 1482, 1451, 1319, 1172, 964, 814, 760, 732. **HRMS (EI, *m/z*):** calc'd for $C_{10}H_9Cl$ $[M+\cdot]^+$: 164.0393; found: 164.0382.

4-bromo-2-phenyl-2*H*-chromene (217b)



Prepared from 2-phenyl-2*H*-chromen-4-yl trifluoromethanesulfonate (**211f**, 107 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10% PhMe/hexanes) to yield **217b** (65 mg, 75% yield) as a yellow oil. *Note: This compound decomposes readily at room temperature.* $\mathbf{R_f}$ = 0.69 (silica, 10% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.46 (ddd, *J* = 7.7, 2.6, 1.5 Hz, 3H), 7.43 – 7.33 (m, 3H), 7.23 – 7.17 (m, 1H), 6.97 (td, *J* = 7.6, 1.2 Hz, 1H), 6.81 (dd, *J* = 8.1, 1.2 Hz, 1H), 6.21 (d, *J* = 3.7 Hz, 1H), 5.91 (d, *J* = 3.7 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 153.4, 139.6, 131.1, 128.9, 128.9, 127.2, 127.1, 126.5, 121.7, 121.1, 118.4, 116.2, 78.8. **FTIR (NaCl, thin film, cm^{-1}):** 1645, 1605, 1478, 1464, 1450, 1374, 1223, 1116, 1062, 756, 697. **HRMS (FAB, *m/z*):** calc'd for $C_{15}H_{11}BrO$ $[M+H-H_2]^+$: 284.9915; found: 284.9917.

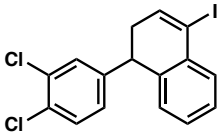
4-chloro-2-phenyl-2*H*-chromene (217c)



Prepared from 2-phenyl-2*H*-chromen-4-yl trifluoromethanesulfonate (**211f**, 107 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column

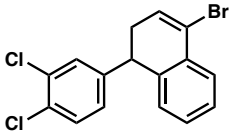
chromatography (silica, 10% PhMe/hexanes) to yield **217c** (48 mg, 66% yield) as a colorless oil. *Note: This compound decomposes readily at room temperature.* $\mathbf{R_f}$ = 0.68 (silica, 10% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.52 – 7.47 (m, 1H), 7.47 – 7.43 (m, 2H), 7.42 – 7.35 (m, 3H), 7.21 (ddd, *J* = 8.1, 7.4, 1.6 Hz, 1H), 6.98 (td, *J* = 7.6, 1.2 Hz, 1H), 6.84 (dd, *J* = 8.1, 1.1 Hz, 1H), 5.97 (s, 2H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 153.6, 139.8, 131.0, 128.9, 128.9, 128.3, 127.2, 124.7, 122.0, 121.6, 120.4, 116.2, 78.1. **FTIR (NaCl, thin film, cm^{-1}):** 1634, 1605, 1481, 1451, 1328, 1224, 1118, 1064, 981, 914, 852, 754, 697. **HRMS (FAB, *m/z*):** calc'd for $C_{15}H_{11}ClO$ $[M+\cdot]^+$: 242.0498; found: 242.0518.

4-iodo-1-(3,4-dichlorophenyl)-1,2-dihydronaphthalene (218a)



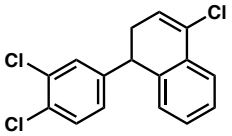
Prepared from 4-(3,4-dichlorophenyl)-3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (**211g**, 127.0 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **218a** (63 mg, 52% yield) as a white solid. $\mathbf{R_f}$ = 0.44 (silica, hexanes, UV). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.54 (dd, *J* = 7.8, 1.2 Hz, 1H), 7.37 (d, *J* = 8.3 Hz, 1H), 7.33 – 7.26 (m, 2H), 7.17 (td, *J* = 7.5, 1.3 Hz, 1H), 6.98 (ddd, *J* = 8.3, 2.2, 0.5 Hz, 1H), 6.77 – 6.72 (m, 2H), 4.16 – 4.09 (m, 1H), 2.70 (ddd, *J* = 16.8, 7.0, 4.9 Hz, 1H), 2.59 (ddd, *J* = 16.8, 8.9, 4.8 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 143.6, 137.9, 136.8, 134.2, 132.6, 131.5, 130.9, 130.6, 130.3, 129.0, 127.9, 127.8, 127.6, 98.0, 43.1, 35.2. **FTIR (NaCl, thin film, cm^{-1}):** 3059, 2932, 2876, 2827, 1603, 1561, 1470, 1447, 1396, 1132, 1030, 910, 862, 822, 879, 730. **HRMS (FAB, *m/z*):** calc'd for $C_{16}H_{11}ICl_2$ $[M+\cdot]^+$: 399.9283; found: 399.9279.

4-bromo-1-(3,4-dichlorophenyl)-1,2-dihydronaphthalene (218b)



Prepared from 4-(3,4-dichlorophenyl)-3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (**211g**, 127.0 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **218b** (83 mg, 78% yield) as a white solid. $\mathbf{R_f}$ = 0.35 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.67 (dd, *J* = 7.7, 1.3 Hz, 1H), 7.37 (d, *J* = 8.3 Hz, 1H), 7.31 (tdd, *J* = 7.7, 1.3, 0.6 Hz, 1H), 7.28 (d, *J* = 2.1 Hz, 1H), 7.20 (td, *J* = 7.5, 1.3 Hz, 1H), 7.00 (ddd, *J* = 8.3, 2.2, 0.5 Hz, 1H), 6.81 (dt, *J* = 7.4, 1.2 Hz, 1H), 6.38 (t, *J* = 4.8 Hz, 1H), 4.18 – 4.09 (m, 1H), 2.72 (ddd, *J* = 16.9, 7.1, 4.9 Hz, 1H), 2.60 (ddd, *J* = 16.9, 9.0, 4.8 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 143.7, 137.4, 133.0, 132.7, 130.9, 130.7, 130.4, 129.0, 128.7, 127.82, 127.75, 127.70, 127.2, 121.5, 43.0, 33.7. **FTIR (NaCl, thin film, cm^{-1}):** 3062, 2879, 1618, 1468, 1448, 1397, 1132, 1030, 871, 822, 760. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{16}H_{11}BrCl_2$ $[M+H]^+$: 352.9499; found: 352.9485.

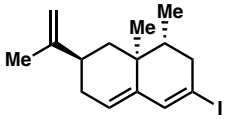
4-chloro-1-(3,4-dichlorophenyl)-1,2-dihydronaphthalene (218c)



Prepared from 4-(3,4-dichlorophenyl)-3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (**211g**, 127.0 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **218c** (69 mg, 75% yield) as a white solid. $\mathbf{R_f}$ = 0.55 (silica, hexanes, UV). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.70 (dd, *J* = 7.7, 1.3 Hz, 1H), 7.38 (d, *J* = 8.3 Hz, 1H), 7.33 (tdd, *J* = 7.7, 1.4, 0.6 Hz, 1H), 7.30 – 7.28 (m, 1H), 7.22 (td, *J* = 7.5, 1.4 Hz, 1H), 7.01 (ddd, *J* = 8.3, 2.2, 0.5 Hz, 1H), 6.85 (dt, *J* =

7.6, 1.2 Hz, 1H), 6.13 (t, *J* = 4.8 Hz, 1H), 4.17 – 4.09 (m, 1H), 2.76 (ddd, *J* = 17.0, 7.2, 4.9 Hz, 1H), 2.64 (ddd, *J* = 16.9, 9.0, 4.7 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 143.8, 137.4, 132.6, 132.3, 130.9, 130.7, 130.6, 130.3, 129.0, 127.8, 127.7, 127.6, 124.7, 124.0, 43.0, 32.5. **FTIR (NaCl, thin film, cm^{-1}):** 3063, 2880, 1625, 1559, 1468, 1449, 1398, 1133, 1030, 980, 878, 814, 762, 735. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{16}H_{11}Cl_3$ $[M+H]^+$: 309.0005; found: 309.0005.

(2*R*,8*R*,8a*S*)-6-iodo-8,8a-dimethyl-2-(prop-1-en-2-yl)-1,2,3,7,8,8a-hexahydronaphthalene (219a)

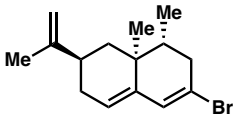


Prepared from (4*R*,4a*S*,6*R*)-4,4a-dimethyl-6-(prop-1-en-2-yl)-3,4,4a,5,6,7-hexahydronaphthalen-2-yl trifluoromethanesulfonate (**211h**, 105.1 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **219a** (34 mg, 34% yield) as a colorless oil. *Note: This compound decomposes readily at room temperature.*

Prepared from (4*R*,4a*S*,6*R*)-4,4a-dimethyl-6-(prop-1-en-2-yl)-3,4,4a,5,6,7-hexahydronaphthalen-2-yl 1,1,2,2,3,3,4,4,4-nonafluorobutane-1-sulfonate (**233b**, 150 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 3. The crude residue was purified by column chromatography (silica, pentane) to yield **219a** (54 mg, 54% yield) as a colorless oil. $\mathbf{R_f}$ = 0.63 (silica, hexanes, $KMnO_4$). $[\boldsymbol{\alpha}]_D^{25}$ = –155° (c = 1.0, $CHCl_3$). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 6.58 (d, *J* = 2.4 Hz, 1H), 5.41 (dd, *J* = 5.4, 2.8 Hz, 1H), 4.80 – 4.70 (m, 2H), 2.54 (dd, *J* = 18.4, 5.2 Hz, 1H), 2.40 (dddd, *J* = 16.9, 8.5,

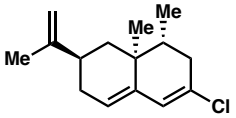
4.3, 2.4 Hz, 2H), 2.23 (dddd, *J* = 20.0, 6.8, 5.1, 2.3 Hz, 1H), 2.01 – 1.85 (m, 1H), 1.79 – 1.65 (m, 5H), 1.20 – 1.11 (m, 1H), 0.92 (d, *J* = 0.7 Hz, 3H), 0.86 (d, *J* = 6.9 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 150.0, 142.8, 139.1, 124.4, 109.0, 95.1, 46.1, 41.5, 40.0, 37.1, 35.5, 31.1, 20.8, 17.6, 14.2. **FTIR (NaCl, thin film, cm^{-1}):** 3079, 2967, 2912, 1644, 1615, 1441, 1372, 1157, 888, 783. **HRMS (FAB, *m/z*):** calc'd for $C_{15}H_{21}I$ $[M+H-H_2]^+$: 327.0610; found: 327.0598.

(2*R*,8*R*,8a*S*)-6-bromo-8,8a-dimethyl-2-(prop-1-en-2-yl)-1,2,3,7,8,8a-hexahydronaphthalene (219b)



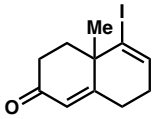
Prepared from (4*R*,4a*S*,6*R*)-4,4a-dimethyl-6-(prop-1-en-2-yl)-3,4,4a,5,6,7-hexahydronaphthalen-2-yl trifluoromethanesulfonate (**211h**, 105.1 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **219b** (55 mg, 82% yield) as a colorless oil which solidified in the freezer to give a white solid. *Note: This compound decomposes readily at room temperature.* $\mathbf{R_f}$ = 0.57 (silica, hexanes, $KMnO_4$). $[\alpha]_D^{25}$ = –172° (c = 1.0, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.30 (d, *J* = 2.3 Hz, 1H), 5.45 (dd, *J* = 5.3, 2.8 Hz, 1H), 4.79 – 4.71 (m, 2H), 2.48 – 2.29 (m, 3H), 2.22 (dt, *J* = 18.6, 5.3 Hz, 1H), 1.99 – 1.87 (m, 1H), 1.75 (t, *J* = 1.1 Hz, 3H), 1.74 – 1.67 (m, 2H), 1.21 – 1.10 (m, 1H), 0.92 (d, *J* = 0.7 Hz, 3H), 0.90 (d, *J* = 6.8 Hz, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 150.0, 141.7, 131.0, 124.3, 121.0, 109.0, 41.9, 40.8, 40.0, 37.2, 35.6, 31.2, 20.8, 17.6, 14.4. **FTIR (NaCl, thin film, cm^{-1}):** 2959, 2914, 1643, 1620, 1442, 1376, 1349, 1154, 1005, 902, 888, 792, 632. **HRMS (FAB, *m/z*):** calc'd for $C_{15}H_{21}Br$ $[M+H-H_2]^+$: 279.0748; found: 279.0744.

(2*R*,8*R*,8a*S*)-6-chloro-8,8a-dimethyl-2-(prop-1-en-2-yl)-1,2,3,7,8,8a-hexahydronaphthalene (219c)



Prepared from (4*R*,4a*S*,6*R*)-4,4a-dimethyl-6-(prop-1-en-2-yl)-3,4,4a,5,6,7-hexahydronaphthalen-2-yl trifluoromethanesulfonate (**211h**, 105.1 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **219c** (60 mg, 85% yield) as a colorless oil. *Note: This compound decomposes readily at room temperature.* $\mathbf{R_f}$ = 0.63 (silica, hexanes, $KMnO_4$). $[\boldsymbol{\alpha}]_D^{25}$ = –165° (c = 1.0, $CHCl_3$). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 6.09 (dt, *J* = 1.7, 0.9 Hz, 1H), 5.44 (ddd, *J* = 5.2, 2.1, 0.8 Hz, 1H), 4.75 (p, *J* = 1.1 Hz, 2H), 2.47 – 2.37 (m, 1H), 2.29 – 2.21 (m, 3H), 2.00 – 1.92 (m, 1H), 1.76 (t, *J* = 1.2 Hz, 3H), 1.75 – 1.71 (m, 1H), 1.71 (s, 1H), 1.17 (td, *J* = 12.7, 0.8 Hz, 1H), 0.93 – 0.90 (m, 6H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 150.0, 141.0, 130.5, 126.9, 124.0, 109.0, 40.0, 39.9, 39.5, 37.2, 35.7, 31.3, 20.8, 17.6, 14.5. **FTIR (NaCl, thin film, cm^{-1}):** 3080, 2967, 2912, 1644, 1618, 1442, 1373, 1155, 1014, 888, 824, 635. **HRMS (EI, *m/z*):** calc'd for $C_{15}H_{21}Cl$ $[M+\cdot]^+$: 236.1332; found: 236.1356.

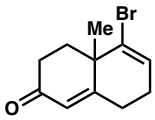
5-iodo-4a-methyl-4,4a,7,8-tetrahydronaphthalen-2(3*H*)-one (220a)



Prepared from 8a-methyl-6-oxo-3,4,6,7,8,8a-hexahydronaphthalen-1-yl trifluoromethanesulfonate (**211i**, 93.1 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 5% Et_2O/hexanes) to yield **220a** (30 mg, 35% yield) as a colorless oil. *Note: This compound decomposes readily at room temperature.*

Prepared from 8a-methyl-6-oxo-3,4,6,7,8,8a-hexahydronaphthalen-1-yl 1,1,2,2,3,3,4,4,4-nonafluorobutane-1-sulfonate (**233c**, 138 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 3. The crude residue was purified by column chromatography (silica, 5-10% Et_2O/hexanes) to yield **220a** (46 mg, 53% yield) as a colorless oil. $\mathbf{R_f}$ = 0.24 (silica, 10% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 6.68 (dt, *J* = 2.6, 0.8 Hz, 1H), 5.66 – 5.58 (m, 1H), 2.76 (ddd, *J* = 15.5, 7.3, 5.9 Hz, 1H), 2.72 (s, 2H), 2.63 – 2.53 (m, 1H), 2.49 – 2.40 (m, 1H), 2.36 (ddd, *J* = 15.5, 7.3, 6.7 Hz, 1H), 1.87 – 1.80 (m, 1H), 1.71 (dddd, *J* = 13.5, 11.5, 6.5, 0.8 Hz, 1H), 1.22 (d, *J* = 0.6 Hz, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 214.3, 140.3, 137.7, 123.7, 96.8, 44.3, 36.6, 35.4, 31.3, 24.2, 22.8. **FTIR (NaCl, thin film, cm^{-1}):** 2926, 1711, 1443, 1322, 1047, 884. **HRMS (FAB, *m/z*):** calc'd for $C_{11}H_{13}OI$ $[M+\cdot]^+$: 288.0011 found: 287.9997.

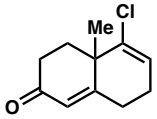
5-bromo-4a-methyl-4,4a,7,8-tetrahydronaphthalen-2(3*H*)-one (220b)



Prepared from 8a-methyl-6-oxo-3,4,6,7,8,8a-hexahydronaphthalen-1-yl trifluoromethanesulfonate (**211i**, 93.1 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 5% Et_2O/hexanes) to yield **220b** (56 mg, 78% yield) as a colorless oil. *Note: This compound decomposes readily at room temperature.* $\mathbf{R_f}$ = 0.24 (silica, 10% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.43 – 6.38 (m, 1H), 5.70 – 5.63 (m, 1H), 2.81 – 2.73 (m, 1H), 2.73 (s, 3H), 2.54 – 2.40 (m, 1H), 2.40 – 2.32 (m, 1H), 1.99 – 1.90 (m, 1H), 1.68 (dddd, *J* = 13.6, 12.2, 6.0, 0.7 Hz, 1H), 1.22 (d, *J* = 0.7 Hz, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 214.1, 139.4, 129.7, 123.6, 122.8, 44.4, 35.4,

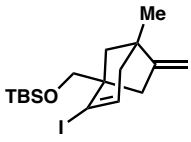
32.4, 30.5, 24.4, 22.8. **FTIR (NaCl, thin film, cm^{-1}):** 2930, 1713, 1611, 1445, 1348, 1048, 884, 750. **HRMS (FAB, *m/z*):** calc'd for $C_{11}H_{13}OBr$ $[M+\cdot]^+$: 240.0150; found: 240.0153.

5-chloro-4a-methyl-4,4a,7,8-tetrahydronaphthalen-2(3*H*)-one (220c)



Prepared from 8a-methyl-6-oxo-3,4,6,7,8,8a-hexahydronaphthalen-1-yl trifluoromethanesulfonate (**211i**, 93.1 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 5% Et_2O/hexanes) to yield **220c** (53 mg, 90% yield) as a colorless oil. *Note: This compound decomposes readily at room temperature.* $\mathbf{R_f}$ = 0.13 (silica, 10% EtOAc/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.19 (dt, *J* = 2.4, 0.7 Hz, 1H), 5.68 – 5.63 (m, 1H), 2.77 (ddd, *J* = 15.4, 7.3, 5.9 Hz, 1H), 2.68 – 2.52 (m, 2H), 2.52 – 2.45 (m, 1H), 2.45 – 2.32 (m, 2H), 1.98 (dddd, *J* = 13.6, 5.7, 1.7, 0.6 Hz, 1H), 1.72 – 1.63 (m, 1H), 1.22 (d, *J* = 0.7 Hz, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 214.1, 138.8, 132.4, 125.6, 123.4, 44.6, 35.5, 30.1, 29.8, 24.5, 22.8. **FTIR (NaCl, thin film, cm^{-1}):** 3549, 2938, 1714, 1682, 1652, 1446, 1424, 1253, 1155, 1080, 916, 733. **HRMS (EI, *m/z*):** calc'd for $C_{11}H_{13}OCl$ $[M+\cdot]^+$: 196.0655; found: 196.0663.

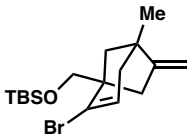
***tert*-butyl(((1*r*,5*r*)-2-iodo-5-methyl-6-methylenebicyclo[3.2.1]oct-2-en-1-yl)methoxy)-dimethylsilane (221a)**



Prepared from (1*r*,5*r*)-1-(((*tert*-butyldimethylsilyl)oxy)methyl)-5-methyl-6-methylenebicyclo[3.2.1]oct-2-en-2-yl trifluoromethanesulfonate (**211j**, 128 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica,

pentane) to yield **221a** (101 mg, 83% yield) as a colorless oil. $\mathbf{R_f}$ = 0.60 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.23 (dd, *J* = 4.8, 2.5 Hz, 1H), 4.90 (td, *J* = 1.8, 0.9 Hz, 1H), 4.88 (dd, *J* = 2.9, 1.9 Hz, 1H), 3.70 (d, *J* = 9.9 Hz, 1H), 3.49 (d, *J* = 9.9 Hz, 1H), 2.41 – 2.23 (m, 3H), 1.94 – 1.77 (m, 3H), 1.17 (s, 3H), 0.91 (s, 9H), 0.08 (s, 3H), 0.07 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 158.7, 137.8, 107.3, 106.1, 71.1, 50.0, 49.0, 46.8, 43.4, 43.3, 26.1, 24.9, 18.5, -5.1, -5.3. **FTIR (NaCl, thin film, cm^{-1}):** 2954, 2929, 2857, 1655, 1471, 1464, 1251, 1156, 1097, 1007, 879, 851, 838, 808, 776. **HRMS (FAB, *m/z*):** calc'd for $C_{17}H_{29}OISi$ $[M+H-H_2]^+$: 403.0955; found: 403.0969.

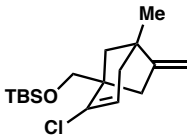
***tert*-butyl(((1*r*,5*r*)-2-bromo-5-methyl-6-methylenebicyclo[3.2.1]oct-2-en-1-yl)-methoxy)-dimethylsilane (221b)**



Prepared from (1*r*,5*r*)-1-(((*tert*-butyldimethylsilyl)oxy)methyl)-5-methyl-6-methylenebicyclo[3.2.1]oct-2-en-2-yl trifluoromethanesulfonate (**211j**, 36 mg, 0.1 mmol) and lithium bromide (13.0 mg, 0.15 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **221b** (28 mg, 78% yield) as a colorless oil. $\mathbf{R_f}$ = 0.58 (silica, hexanes, $KMnO_4$). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 5.86 (dd, *J* = 4.9, 2.5 Hz, 1H), 4.91 (t, *J* = 2.1 Hz, 1H), 4.89 – 4.86 (m, 1H), 3.82 (d, *J* = 9.9 Hz, 1H), 3.57 (d, *J* = 9.9 Hz, 1H), 2.50 – 2.43 (m, 1H), 2.42 – 2.36 (m, 1H), 2.24 (dd, *J* = 16.9, 2.5 Hz, 1H), 1.94 – 1.87 (m, 1H), 1.82 (d, *J* = 1.5 Hz, 2H), 1.19 (s, 3H), 0.90 (s, 9H), 0.07 (s, 3H), 0.06 (s, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 158.8, 129.8, 128.7, 106.1, 67.2, 50.0, 47.3, 46.8, 43.7, 43.2, 26.1, 24.8, 18.5, -5.26, -5.33. **FTIR (NaCl, thin film, cm^{-1}):** 2954, 2857, 1652, 1463, 1251,

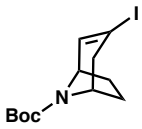
1097, 1010, 880, 839, 811, 775. **HRMS (FAB, *m/z*):** calc'd for $C_{17}H_{29}OBrSi$ $[M+H-H_2]^+$: 357.1072; found: 357.1085.

***tert*-butyl(((1*r*,5*r*)-2-chloro-5-methyl-6-methylenebicyclo[3.2.1]oct-2-en-1-yl)methoxy)-dimethylsilane (221c)**



Prepared from (1*r*,5*r*)-1-(((*tert*-butyldimethylsilyl)oxy)methyl)-5-methyl-6-methylenebicyclo[3.2.1]oct-2-en-2-yl trifluoromethanesulfonate (**211j**, 36 mg, 0.1 mmol) and lithium chloride (6.4 mg, 0.15 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **221c** (27 mg, 82% yield) as a colorless oil. $\mathbf{R_f}$ = 0.56 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.61 (dd, *J* = 4.8, 2.5 Hz, 1H), 4.89 (ddd, *J* = 7.2, 2.7, 1.8 Hz, 2H), 3.88 (d, *J* = 9.9 Hz, 1H), 3.59 (d, *J* = 9.9 Hz, 1H), 2.54 – 2.38 (m, 2H), 2.26 (dd, *J* = 16.9, 2.6 Hz, 1H), 1.97 – 1.88 (m, 1H), 1.84 – 1.73 (m, 2H), 1.20 (s, 3H), 0.90 (s, 9H), 0.06 (s, 3H), 0.06 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 158.9, 138.3, 124.0, 106.0, 65.4, 49.5, 47.2, 45.2, 43.9, 43.2, 26.0, 24.8, 18.5, -5.33, -5.34. **FTIR (NaCl, thin film, cm^{-1}):** 2954, 2858, 1656, 1471, 1252, 1098, 880, 838, 812, 776 **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{17}H_{29}OClSi$ $[M+H]^+$: 313.1754; found: 313.1732.

***tert*-butyl (1*r*,5*s*)-3-iodo-8-azabicyclo[3.2.1]oct-2-ene-8-carboxylate (222a)**

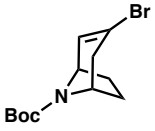


Prepared from *tert*-butyl (1*r*,5*s*)-3-(((trifluoromethyl)sulfonyl)oxy)-8-azabicyclo[3.2.1]oct-2-ene-8-carboxylate (**211k**, 402 mg, 1.2 mmol) and sodium iodide (270 mg, 1.8 mmol) according to General Procedure 1. The crude residue

was purified by column chromatography (silica, 10 to 20% Et_2O/hexanes) to yield **222a** (143 mg, 34% yield) as a colorless oil.

Prepared from *tert*-butyl (1*r*,5*s*)-3-(((perfluorobutyl)sulfonyl)oxy)-8-azabicyclo[3.2.1]oct-2-ene-8-carboxylate (**233d**, 152 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 3. The crude residue was purified by column chromatography (silica, 10 to 6% acetone/hexanes) to yield **222a** (53 mg, 53% yield) as a colorless oil. $\mathbf{R_f}$ = 0.55 (silica, 30% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, d_3-MeCN, 65 °C):** δ 6.70 – 6.65 (m, 1H), 4.23 (t, *J* = 5.6 Hz, 1H), 4.17 – 4.11 (m, 1H), 3.16 – 3.06 (m, 1H), 2.31 (dt, *J* = 17.5, 1.4 Hz, 1H), 2.26 – 2.12 (m, 1H), 1.98 – 1.81 (m, 2H), 1.76 (ddt, *J* = 15.6, 9.8, 3.8 Hz, 1H), 1.44 (d, *J* = 0.6 Hz, 9H). **^{13}C NMR (101 MHz, d_3-MeCN, 65 °C):** δ 6.70 – 6.65 (m, 1H), 4.23 (t, *J* = 5.6 Hz, 1H), 4.17 – 4.11 (m, 1H), 3.16 – 3.06 (m, 1H), 2.31 (dt, *J* = 17.5, 1.4 Hz, 1H), 2.26 – 2.12 (m, 1H), 1.98 – 1.81 (m, 2H), 1.76 (ddt, *J* = 15.6, 9.8, 3.8 Hz, 1H), 1.44 (d, *J* = 0.6 Hz, 9H). **FTIR (NaCl, thin film, cm^{-1}):** 2975, 1698, 1392, 1347, 1312, 1172, 1103, 1101, 973. **HRMS (FAB, *m/z*):** calc'd for $C_{12}H_{18}INO_2$ $[M+H]^+$: 336.0461; found: 336.0454.

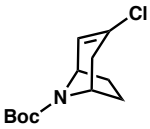
tert-butyl (1*r*,5*s*)-3-bromo-8-azabicyclo[3.2.1]oct-2-ene-8-carboxylate (222b)



Prepared from *tert*-butyl (1*r*,5*s*)-3-(((trifluoromethyl)sulfonyl)oxy)-8-azabicyclo[3.2.1]oct-2-ene-8-carboxylate (**211k**, 107 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10 to 20% Et_2O/hexanes) to yield **222b** (56 mg, 65% yield) as a colorless oil. $\mathbf{R_f}$ = 0.55 (silica, 30% Et_2O/hexanes, $KMnO_4$).

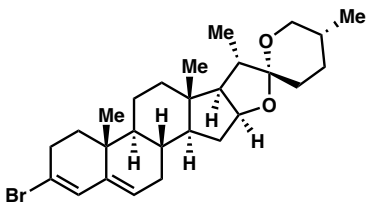
^{1}H NMR (400 MHz, d_3-MeCN, 65 °C): δ 6.38 (ddd, *J* = 5.5, 2.0, 1.4 Hz, 1H), 4.32 (td, *J* = 5.5, 1.2 Hz, 1H), 4.29 – 4.22 (m, 1H), 3.06 (ddt, *J* = 17.3, 4.3, 2.0 Hz, 1H), 2.26 – 2.13 (m, 2H), 1.99 – 1.85 (m, 2H), 1.74 (dddd, *J* = 12.9, 9.6, 6.7, 1.2 Hz, 1H), 1.45 (s, 9H). **^{13}C NMR (101 MHz, d_3-MeCN, 65 °C):** δ 155.0, 135.7, 121.0, 80.5, 56.2, 54.8, 44.8, 35.0, 30.5, 28.8. **FTIR (NaCl, thin film, cm^{-1}):** 2976, 1698, 1392, 1367, 1350, 1320, 1171, 1103, 1107, 975. **HRMS (FAB, *m/z*):** calc'd for $C_{12}H_{18}BrNO_2$ $[M+H]^+$: 288.0599; found: 288.0593.

***tert*-butyl (1r,5*s*)-3-chloro-8-azabicyclo[3.2.1]oct-2-ene-8-carboxylate (222c)**



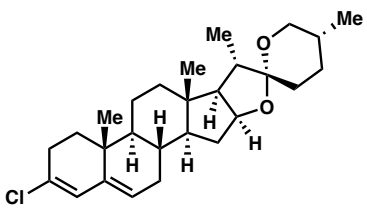
Prepared from *tert*-butyl (1*r*,5*s*)-3-(((trifluoromethyl)sulfonyl)oxy)-8-azabicyclo[3.2.1]oct-2-ene-8-carboxylate (**211k**, 107 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10 to 20% Et_2O/hexanes) to yield **222c** (61 mg, 84% yield) as a colorless oil. $\mathbf{R_f}$ = 0.55 (silica, 30% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, d_3-MeCN, 65 °C):** δ 6.16 (ddd, *J* = 5.6, 2.0, 1.3 Hz, 1H), 4.47 – 4.35 (m, 1H), 4.35 – 4.28 (m, 1H), 2.96 (ddt, *J* = 17.2, 3.9, 1.8 Hz, 1H), 2.26 – 2.14 (m, 1H), 2.09 (dt, *J* = 17.3, 1.4 Hz, 1H), 1.99 – 1.89 (m, 2H), 1.79 – 1.67 (m, 1H), 1.46 (s, 9H). **^{13}C NMR (101 MHz, d_3-MeCN, 65 °C):** δ 154.9, 131.4, 80.4, 55.0, 53.9, 42.5, 35.1, 30.5, 28.8. (*Note: one carbon under solvent*). **FTIR (NaCl, thin film, cm^{-1}):** 2976, 1694, 1638, 1392, 1323, 1256, 1168, 1103, 1015, 978, 888, 874, 775, 724. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{12}H_{18}ClNO_2$ $[M+H]^+$: 244.1104; found: 244.1098.

(5'*R*,6a*R*,6b*S*,8a*S*,8b*R*,9*S*,10*R*,11a*S*,12a*S*,12b*S*)-4-bromo-5',6a,8a,9-tetramethyl-1,3',4',5,5',6,6a,6b,6',7,8,8a,8b,9,11a,12,12a,12b-octadecahydrospiro[naphtha-[2',1':4,5]indeno[2,1-*b*]furan-10,2'-pyran] (223b)



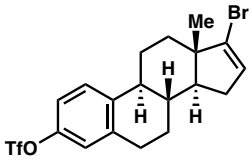
Prepared from (5'*R*,6a*R*,6b*S*,8a*S*,8b*R*,9*S*,10*R*,11a*S*,12a*S*,-12b*S*)-5',6a,8a,9-tetramethyl-1,3',4',5,5',6,6a,6b,6',7,8,8a,-8b,9,11a,12,12a,12b-octadecahydrospiro[naphtha-[2',1':4,5]indeno[2,1-*b*]furan-10,2'-pyran]-4-yl trifluoromethanesulfonate (**211l**, 163.4 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 40% Et_2O/hexanes) to yield **223b** (107 mg, 75% yield) as a white solid. $\mathbf{R_f}$ = 0.56 (silica, 10% Et_2O/hexanes, $KMnO_4$). $[\boldsymbol{a}]_D^{25}$ = –176° (c = 1.0, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.26 (d, *J* = 2.3 Hz, 1H), 5.39 (dd, *J* = 5.1, 2.9 Hz, 1H), 4.41 (ddd, *J* = 8.6, 7.5, 6.3 Hz, 1H), 3.47 (ddd, *J* = 10.9, 4.6, 2.0 Hz, 1H), 3.36 (t, *J* = 10.8 Hz, 1H), 2.67 – 2.53 (m, 1H), 2.46 (ddd, *J* = 18.4, 5.9, 1.6 Hz, 1H), 2.17 (dt, *J* = 18.7, 5.3 Hz, 1H), 1.98 (ddd, *J* = 11.8, 7.5, 5.4 Hz, 1H), 1.91 – 1.10 (m, 17H), 1.05 – 0.92 (m, 7H), 0.84 – 0.74 (m, 6H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 141.3, 131.2, 124.4, 120.9, 109.4, 80.9, 67.0, 62.2, 56.7, 48.0, 41.7, 40.5, 39.8, 35.6, 34.6, 33.2, 32.0, 31.9, 31.5, 31.3, 30.4, 28.9, 21.0, 19.1, 17.3, 16.5, 14.7. **FTIR (NaCl, thin film, cm^{-1}):** 2949, 1616, 1455, 1377, 1241, 1173, 1051, 980, 899, 734. **HRMS (FAB, *m/z*):** calc'd for $C_{27}H_{39}BrO_2$ $[M+H]^+$: 475.2035; found: 475.2049.

(5'*R*,6a*R*,6b*S*,8a*S*,8b*R*,9*S*,10*R*,11a*S*,12a*S*,12b*S*)-4-chloro-5',6a,8a,9-tetramethyl-1,3',4',5,5',6,6a,6b,6',7,8,8a,8b,9,11a,12,12a,12b-octadecahydrospiro[naphtha-[2',1':4,5]indeno[2,1-*b*]furan-10,2'-pyran] (223c)



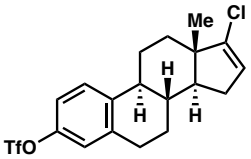
Prepared from (5'*R*,6a*R*,6b*S*,8a*S*,8b*R*,9*S*,10*R*,11a*S*,-12a*S*,12b*S*)-5',6a,8a,9-tetramethyl-1,3',4',5,5',6,6a,6b,6',7,--8,8a,8b,9,11a,12,12a,12b-octadecahydrospiro[naphtha-[2',1':4,5]indeno[2,1-*b*]furan-10,2'-pyran]-4-yl trifluoromethanesulfonate (**211l**, 163.4 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 40% Et_2O/hexanes) to yield **223c** (125 mg, 97% yield) as a white solid. $\mathbf{R_f}$ = 0.57 (silica, 10% EtOAc/hexanes, $KMnO_4$). $[\boldsymbol{a}]_D^{25}$ = –183° (c = 1.0, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.05 (d, *J* = 2.3 Hz, 1H), 5.38 (dd, *J* = 5.0, 2.9 Hz, 1H), 4.41 (ddd, *J* = 8.6, 7.6, 6.4 Hz, 1H), 3.47 (ddd, *J* = 10.9, 4.5, 2.0 Hz, 1H), 3.37 (t, *J* = 10.9 Hz, 1H), 2.50 (ddd, *J* = 17.8, 12.0, 5.8 Hz, 1H), 2.31 (ddd, *J* = 18.3, 5.9, 1.5 Hz, 1H), 2.19 (dt, *J* = 18.7, 5.3 Hz, 1H), 1.99 (ddd, *J* = 11.7, 7.5, 5.4 Hz, 1H), 1.93 – 1.50 (m, 11H), 1.50 – 1.39 (m, 2H), 1.31 (ddd, *J* = 13.5, 11.8, 6.3 Hz, 2H), 1.24 – 1.09 (m, 2H), 1.06 – 1.00 (m, 1H), 0.97 (t, *J* = 3.5 Hz, 6H), 0.84 – 0.75 (m, 6H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 140.6, 130.4, 127.1, 124.0, 109.4, 80.9, 67.0, 62.2, 56.7, 48.0, 41.7, 40.5, 39.8, 34.9, 34.7, 32.1, 31.9, 31.5, 31.4, 30.8, 30.4, 28.9, 21.1, 19.0, 17.3, 16.5, 14.7. **FTIR (NaCl, thin film, cm^{-1}):** 2950, 2906, 1622, 1450, 1380, 1350, 1240, 1170, 1070, 1050, 981, 900, 868, 734. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{27}H_{39}ClO_2$ $[M+H]^+$: 431.2717; found: 431.2716.

(8*R*,9*S*,13*S*,14*S*)-17-bromo-13-methyl-7,8,9,11,12,13,14,15-octahydro-6*H*-cyclopenta[*a*]phenanthren-3-yl trifluoromethanesulfonate (224b)



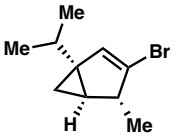
Prepared from (8*R*,9*S*,13*S*,14*S*)-13-methyl-7,8,9,11,12,13,14,15-octahydro-6*H*-cyclopenta[*a*]phenanthrene-3,17-diyl bis(trifluoromethanesulfonate) (**211m**, 160.3 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 5% to 15% PhMe/hexanes) to yield **224b** (82 mg, 59% yield) as a colorless, tacky oil. $\mathbf{R_f}$ = 0.38 (silica, 10% PhMe/hexanes, $KMnO_4$). $[\boldsymbol{a}]_D^{25}$ = 39° (c = 1.0, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.33 (dd, *J* = 8.7, 1.1 Hz, 1H), 7.03 (dd, *J* = 8.6, 2.8 Hz, 1H), 6.99 (d, *J* = 2.6 Hz, 1H), 5.88 (dd, *J* = 3.3, 1.7 Hz, 1H), 2.97 – 2.91 (m, 2H), 2.45 – 2.36 (m, 1H), 2.36 – 2.29 (m, 1H), 2.25 (ddd, *J* = 14.8, 6.3, 3.2 Hz, 1H), 2.02 (ddd, *J* = 14.8, 11.1, 1.8 Hz, 1H), 1.99 – 1.93 (m, 1H), 1.90 (ddd, *J* = 12.3, 3.7, 2.1 Hz, 1H), 1.73 (td, *J* = 11.2, 6.2 Hz, 1H), 1.69 – 1.41 (m, 4H), 0.88 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 147.7, 140.8, 139.5, 135.6, 129.1, 127.0, 121.3, 118.9 (q, $J_{C\text{-}F}$ = 320.7 Hz), 118.3, 54.9, 48.9, 44.4, 37.0, 34.6, 31.7, 29.5, 27.0, 26.2, 15.3. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -72.9. **FTIR (NaCl, thin film, cm^{-1}):** 2932, 1592, 1490, 1422, 1247, 1210, 1142, 996, 919, 882, 846. **HRMS (FAB, *m/z*):** calc'd for $C_{19}H_{20}BrF_3O_3S$ $[M+H-H_2]^+$: 465.0170; found: 465.0165.

(8*R*,9*S*,13*S*,14*S*)-17-chloro-13-methyl-7,8,9,11,12,13,14,15-octahydro-6*H*-cyclopenta[*a*]phenanthren-3-yl trifluoromethanesulfonate (224c)



Prepared from (8*R*,9*S*,13*S*,14*S*)-13-methyl-7,8,9,11,12,13,14,15-octahydro-6*H*-cyclopenta[*a*]phenanthrene-3,17-diylbis(trifluoromethanesulfonate) (**211m**, 160.3 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 1.5% EtOAc/hexanes) to yield **224c** (109 mg, 83% yield) as a colorless, tacky oil. $\mathbf{R_f}$ = 0.67 (silica, 10% EtOAc/hexanes, $KMnO_4$). $[\boldsymbol{a}]_D^{25}$ = +67° (c = 1.0, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.33 (dd, *J* = 8.8, 1.2 Hz, 1H), 7.03 (dd, *J* = 8.6, 2.8 Hz, 1H), 7.00 – 6.94 (m, 1H), 5.67 (dd, *J* = 3.3, 1.7 Hz, 1H), 2.99 – 2.88 (m, 2H), 2.46 – 2.30 (m, 2H), 2.27 (ddd, *J* = 14.7, 6.3, 3.2 Hz, 1H), 2.05 (ddd, *J* = 14.8, 11.0, 1.8 Hz, 1H), 2.00 – 1.89 (m, 2H), 1.73 (td, *J* = 11.2, 6.3 Hz, 1H), 1.68 – 1.42 (m, 4H), 0.91 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 147.7, 144.7, 140.9, 139.5, 127.0, 124.7, 121.3, 118.9 (q, $J_{C\text{-}F}$ = 320.7 Hz), 118.3, 55.1, 47.9, 44.5, 36.9, 33.8, 30.5, 29.5, 26.9, 26.1, 15.2. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -72.9. **FTIR (NaCl, thin film, cm^{-1}):** 2934, 2859, 1598, 1490, 1417, 1248, 1211, 1142, 1007, 919, 851, 822, 701, 608. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{19}H_{20}ClF_3O_3S$ $[M+H]^+$: 421.0852; found: 421.0845.

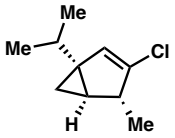
(1*S*,4*R*,5*R*)-3-bromo-1-isopropyl-4-methylbicyclo[3.1.0]hex-2-ene (225b)



Prepared from (1*S*,4*R*,5*R*)-1-isopropyl-4-methylbicyclo[3.1.0]hex-2-en-3-yl trifluoromethanesulfonate (**211n**, 85.3 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1 with the exception of 5 mol % Ni used instead of 10 mol % Ni. The crude residue was purified by column

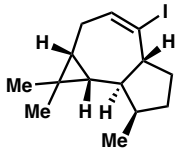
chromatography (silica, pentane) to yield **225b** (27 mg, 42% yield, 92% purity by mass) as a colorless oil. Product was determined to be 92% pure by NMR (impurity is homocoupling product) therefore the yield is adjusted 42% x 0.92 = 38% yield. $\mathbf{R_f}$ = 0.88 (silica, hexanes, $KMnO_4$). $[\boldsymbol{\alpha}]_D^{25}$ = –13° (c = 0.5, $CHCl_3$). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 5.93 (t, *J* = 1.3 Hz, 1H), 2.59 – 2.52 (m, 1H), 1.38 (p, *J* = 6.9 Hz, 1H), 1.15 – 1.11 (m, 4H), 0.99 (d, *J* = 6.8 Hz, 3H), 0.89 (d, *J* = 6.8 Hz, 3H), 0.81 – 0.78 (m, 1H), 0.28 (t, *J* = 4.2 Hz, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 133.9, 123.9, 48.5, 40.9, 31.0, 26.5, 21.5, 20.9, 20.8, 20.8. **FTIR (NaCl, thin film, cm^{-1}):** 2958, 2870, 1602, 1453, 1366, 1056, 973, 867, 832, 796, 754. **HRMS (EI, *m/z*):** calc'd for $C_{10}H_{15}Br$ $[M+\cdot]^+$: 214.0357; found: 214.0358.

(1*S*,4*R*,5*R*)-3-chloro-1-isopropyl-4-methylbicyclo[3.1.0]hex-2-ene (225c)



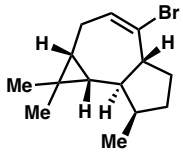
Prepared from (1*S*,4*R*,5*R*)-1-isopropyl-4-methylbicyclo[3.1.0]hex-2-en-3-yl trifluoromethanesulfonate (**211n**, 85.3 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **225c** (40 mg, 78% yield) as a colorless oil. $\mathbf{R_f}$ = 0.85 (silica, hexanes, $KMnO_4$). $[\boldsymbol{\alpha}]_D^{25}$ = +17° (c = 1.0, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.75 (t, *J* = 1.3 Hz, 1H), 2.51 (tdd, *J* = 8.0, 6.0, 0.9 Hz, 1H), 1.36 (p, *J* = 6.8 Hz, 1H), 1.14 (d, *J* = 7.1 Hz, 3H), 1.12 – 1.06 (m, 1H), 0.99 (d, *J* = 6.9 Hz, 3H), 0.89 (d, *J* = 6.8 Hz, 3H), 0.78 (dd, *J* = 7.8, 4.3 Hz, 1H), 0.27 (t, *J* = 4.2 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 134.6, 129.4, 46.8, 39.5, 31.1, 26.1, 21.6, 20.9, 20.8, 20.2. **FTIR (NaCl, thin film, cm^{-1}):** 2956, 2924, 2854, 1458, 1364, 1057, 1026. **HRMS (EI, *m/z*):** calc'd for $C_{10}H_{15}Cl$ $[M+\cdot]^+$: 170.0862; found: 170.0888.

(1a*R*,4a*R*,7*R*,7a*S*,7b*S*)-4-iodo-1,1,7-trimethyl-1a,2,4a,5,6,7,7a,7b-octahydro-1*H*-cyclopropa[*e*]azulene (226a)



Prepared from (1a*R*,4a*R*,7*R*,7a*S*,7b*S*)-1,1,7-trimethyl-1a,2,4a,5,6,7,7a,7b-octahydro-1*H*-cyclopropa[*e*]azulen-4-yl trifluoromethanesulfonate (**211o**, 101.5 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **226a** (48 mg, 75% yield) as a colorless oil. $\mathbf{R_f}$ = 0.72 (silica, hexanes, $KMnO_4$). $[\alpha]_D^{25}$ = –184° (c = 1.0, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.43 (ddd, *J* = 8.8, 3.6, 2.2 Hz, 1H), 2.77 (tdd, *J* = 11.3, 7.4, 3.3 Hz, 1H), 2.37 – 2.22 (m, 1H), 2.18 – 2.02 (m, 3H), 1.89 (dddd, *J* = 13.0, 9.8, 8.2, 3.1 Hz, 1H), 1.77 (td, *J* = 11.6, 8.4 Hz, 1H), 1.44 (dddd, *J* = 12.5, 11.4, 9.8, 8.8 Hz, 1H), 1.16 (dtd, *J* = 13.1, 8.7, 4.5 Hz, 1H), 1.03 (s, 3H), 1.02 (s, 3H), 0.97 – 0.87 (m, 4H), 0.60 (dd, *J* = 11.5, 9.3 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 138.5, 109.1, 56.7, 43.5, 36.6, 36.3, 30.9, 28.7, 26.8, 26.2, 25.8, 19.3, 18.3, 15.3. **FTIR (NaCl, thin film, cm^{-1}):** 2953, 2866, 1455, 1376, 1216, 909, 723. **HRMS (FAB, *m/z*):** calc'd for $C_{14}H_{21}I$ $[M+H–H_2]^+$: 315.0610; found: 315.0609.

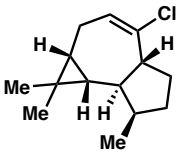
(1a*R*,4a*R*,7*R*,7a*S*,7b*S*)-4-bromo-1,1,7-trimethyl-1a,2,4a,5,6,7,7a,7b-octahydro-1*H*-cyclopropa[*e*]azulene (226b)



Prepared from (1a*R*,4a*R*,7*R*,7a*S*,7b*S*)-1,1,7-trimethyl-1a,2,4a,5,6,7,7a,7b-octahydro-1*H*-cyclopropa[*e*]azulen-4-yl trifluoromethanesulfonate (**211o**, 101.5 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **226b** (73 mg, 88% yield) as a colorless oil. $\mathbf{R_f}$ = 0.68 (silica, hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = –152° (c = 1.0, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.10 (ddd, *J* = 9.3, 3.3, 2.1 Hz, 1H), 2.77 (dddd, *J* = 18.2, 9.2, 3.7, 2.1 Hz, 1H), 2.29 – 2.10 (m, 3H), 2.04 – 1.85 (m, 2H), 1.76 (td, *J* = 11.7, 8.3 Hz, 1H), 1.46 (dddd, *J* = 12.6, 11.4, 9.8, 8.8 Hz, 1H), 1.18 (dtd, *J* = 13.1, 8.6, 4.3 Hz, 1H), 1.03 (d, *J* = 3.8 Hz, 6H), 0.97 – 0.88 (m, 4H), 0.60 (dd, *J* = 11.5, 9.3 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 130.8, 129.8, 53.7, 43.5, 35.5, 33.7, 31.3, 28.6, 26.0, 25.7, 24.5, 18.9, 18.2, 15.3. **FTIR (NaCl, thin film, cm^{-1}):** 2953, 2867, 1633, 1455, 1376, 1251, 1064, 913, 860, 732. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{14}H_{21}Br$ $[M+H–H_2]^+$: 267.0748; found: 267.0737.

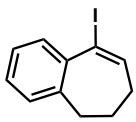
(1a*R*,4a*R*,7*R*,7a*S*,7b*S*)-4-chloro-1,1,7-trimethyl-1a,2,4a,5,6,7,7a,7b-octahydro-1*H*-cyclopropa[*e*]azulene (226c)



Prepared from (1a*R*,4a*R*,7*R*,7a*S*,7b*S*)-1,1,7-trimethyl-1a,2,4a,5,6,7,-7a,7b-octahydro-1*H*-cyclopropa[*e*]azulen-4-yltrifluoro-methanesulfonate (**211o**, 101.5 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **226c** (40 mg, 88% yield) as a colorless oil. $\mathbf{R}_f$ = 0.78 (silica, hexanes, $KMnO_4$). $[\alpha]_D^{25}$ = –174° (c = 1.0, $CHCl_3$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.84 (ddd, *J* = 9.3, 3.3, 2.1 Hz, 1H), 2.68 (dddd, *J* = 18.1, 9.2, 3.8, 2.1 Hz, 1H), 2.26 – 2.09 (m, 3H), 2.01 (ddt, *J* = 16.8, 10.4, 3.6 Hz, 1H), 1.90 (dddd, *J* = 13.1, 9.9, 8.2, 3.1 Hz, 1H), 1.75 (td, *J* = 11.7, 8.3 Hz, 1H), 1.44 (dddd, *J* = 12.6, 11.3, 9.8, 8.8 Hz, 1H), 1.19 (dtd, *J* = 13.0, 8.6, 4.3 Hz, 1H), 1.04 (s, 3H), 1.03 (s, 3H), 0.95 – 0.87 (m, 4H), 0.60 (dd, *J* = 11.5, 9.3 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 138.6, 125.6, 51.9, 43.2, 35.0, 32.1, 31.6, 28.7, 26.1, 25.8,

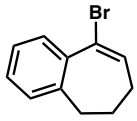
23.0, 18.8, 18.1, 15.3. **FTIR (NaCl, thin film, cm^{-1}):** 2952, 2866, 1453, 1376, 921, 748. **HRMS (EI, *m/z*):** calc'd for $C_{14}H_{21}Cl$ $[M+\cdot]^+$: 224.1332; found: 224.1306.

9-iodo-6,7-dihydro-5*H*-benzo[7]annulene (227a)



Prepared from 6,7-dihydro-5*H*-benzo[7]annulen-9-yl trifluoromethanesulfonate (**211p**, 87.7 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, hexanes) to yield **227a** (65 mg, 80% yield) as a light yellow oil. $\mathbf{R_f}$ = 0.66 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.49 (dd, *J* = 7.7, 1.3 Hz, 1H), 7.31 – 7.25 (m, 1H), 7.18 (td, *J* = 7.4, 1.4 Hz, 1H), 7.12 (dd, *J* = 7.6, 1.4 Hz, 1H), 6.95 (t, *J* = 7.5 Hz, 1H), 2.66 (t, *J* = 7.0 Hz, 2H), 2.14 (p, *J* = 7.1 Hz, 2H), 1.83 (q, *J* = 7.3 Hz, 2H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 142.1, 141.3, 139.8, 131.1, 128.5, 128.2, 126.4, 95.8, 34.8, 32.6, 28.2. **FTIR (NaCl, thin film, cm^{-1}):** 2928, 2854, 1478, 1447, 1195, 887, 763, 742, 662. **HRMS (FAB, *m/z*):** calc'd for $C_{11}H_{11}I$ $[M+\cdot]^+$: 269.9906; found: 269.9910.

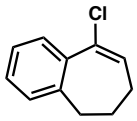
9-bromo-6,7-dihydro-5*H*-benzo[7]annulene (227b)



Prepared from 6,7-dihydro-5*H*-benzo[7]annulen-9-yl trifluoromethanesulfonate (**211p**, 87.7 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, hexanes) to yield **227b** (49 mg, 73% yield) as a light yellow oil. $\mathbf{R_f}$ = 0.51 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.58 (dd, *J* = 7.7, 1.4 Hz, 1H), 7.30 (td, *J* = 7.5, 1.6 Hz, 1H), 7.25 – 7.15 (m, 2H), 6.64 (t, *J* = 7.4 Hz, 1H), 2.68 (t, *J* = 6.9 Hz, 2H), 2.14 (p, *J* = 7.1 Hz, 2H), 1.92 (q, *J* = 7.0 Hz, 2H). **^{13}C NMR (101 MHz,**

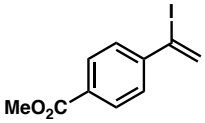
$CDCl_3$): δ 140.7, 138.8, 133.3, 129.5, 128.7, 128.4, 126.4, 120.7, 34.3, 32.7, 26.9. **FTIR (NaCl, thin film, cm^{-1}):** 3062, 2930, 2856, 1614, 1480, 1448, 1303, 1197, 897, 765, 745, 668. **HRMS (EI, *m/z*):** calc'd for $C_{11}H_{11}Br$ $[M+\cdot]^+$: 222.0044; found: 222.0042.

9-chloro-6,7-dihydro-5*H*-benzo[7]annulene (227c)



Prepared from 6,7-dihydro-5*H*-benzo[7]annulen-9-yl trifluoromethanesulfonate **211p**, 87.7 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, hexanes) to yield **227c** (38 mg, 71% yield) as a light yellow oil. $\mathbf{R_f}$ = 0.54 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.60 (dd, *J* = 7.6, 1.5 Hz, 1H), 7.30 (td, *J* = 7.5, 1.7 Hz, 1H), 7.27 – 7.22 (m, 1H), 7.20 (dd, *J* = 7.5, 1.6 Hz, 1H), 6.40 (t, *J* = 7.1 Hz, 1H), 2.69 (t, *J* = 6.7 Hz, 2H), 2.17 – 2.09 (m, 2H), 1.99 (qd, *J* = 7.1, 0.9 Hz, 2H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 141.1, 137.6, 130.7, 129.0, 128.9, 128.4, 128.3, 126.4, 33.8, 32.9, 26.0. **FTIR (NaCl, thin film, cm^{-1}):** 3059, 2934, 2858, 1620, 1483, 1449, 1322, 1304, 1201, 1169, 916, 830, 766, 748, 676. **HRMS (EI, *m/z*):** calc'd for $C_{11}H_{11}Cl$ $[M+\cdot]^+$: 178.0549; found: 178.0547.

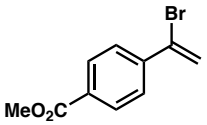
methyl 4-(1-iodovinyl)benzoate (228a)



Prepared from methyl 4-(1-(((trifluoromethyl)sulfonyl)oxy)vinyl)-benzoate (**211q**, 93.1 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 5 to 20% Et_2O/hexanes) to yield **228a** (56 mg, 64% yield) as a white solid. *Note: This compound slowly oxidizes to the α-bromo acetophenone under*

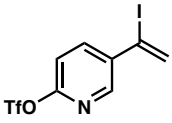
ambient conditions.[59] **R_f** = 0.25 (silica, 10% Et_2O/hexanes, UV). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.99 – 7.95 (m, 2H), 7.59 – 7.54 (m, 2H), 6.56 (d, *J* = 1.9 Hz, 1H), 6.17 (d, *J* = 1.9 Hz, 1H), 3.92 (s, 3H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 166.5, 145.8, 130.4, 129.6, 129.2, 128.2, 105.8, 52.4. **FTIR (NaCl, thin film, cm^{-1}):** 2948, 1720, 1593, 1433, 1403, 1284, 1191, 1111, 1050, 902, 861, 777, 710. **HRMS (FAB, *m/z*):** calc'd for $C_{10}H_8IO_2$ $[M+H]^+$: 288.9726; found: 288.9740.

methyl 4-(1-bromovinyl)benzoate (228b)



Prepared from methyl 4-(1-(((trifluoromethyl)sulfonyl)oxy)-vinyl)benzoate (**211q**, 93.1 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 1 to 2% Et_2O/hexanes) to yield **228b** (69 mg, 90% yield) as a white solid. *Note: This compound slowly oxidizes to the α-bromo acetophenone under ambient conditions.*[59] **R_f** = 0.47 (silica, 10% EtOAc/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 8.03 – 7.98 (m, 2H), 7.68 – 7.62 (m, 2H), 6.22 (d, *J* = 2.2 Hz, 1H), 5.88 (d, *J* = 2.2 Hz, 1H), 3.92 (s, 3H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 166.5, 142.7, 130.6, 129.9, 129.7, 127.4, 119.7, 52.4. **FTIR (NaCl, thin film, cm^{-1}):** 3429, 2952, 1727, 1606, 1436, 1406, 1281, 1191, 1110, 1016, 860, 776, 710. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{10}H_8BrO_2$ $[M+H]^+$: 240.9864; found: 240.9888.

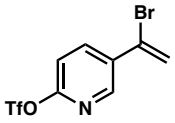
5-(1-iodovinyl)pyridin-2-yl trifluoromethanesulfonate (229a)



Prepared from 1-(6-(((trifluoromethyl)sulfonyl)oxy)pyridin-3-yl)vinyl trifluoromethanesulfonate (**211r**, 120 mg, 0.3 mmol) and sodium iodide

(67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield **229a** (62 mg, 54% yield) as a colorless oil. *Note: This compound slowly oxidizes to the α-bromo acetophenone under ambient conditions.*[59] **R_f** = 0.74 (silica, 30% EtOAc/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 8.51 (dd, *J* = 2.6, 0.7 Hz, 1H), 8.00 (dd, *J* = 8.5, 2.6 Hz, 1H), 7.13 (dd, *J* = 8.5, 0.7 Hz, 1H), 6.58 (d, *J* = 2.2 Hz, 1H), 6.25 (d, *J* = 2.1 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 155.6, 147.0, 141.0, 138.6, 130.9, 118.7 (q, J_{C-F} = 320.6 Hz), 114.6, 99.3. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -72.9. **FTIR (NaCl, thin film, cm^{-1}):** 1604, 1579, 1469, 1428, 1370, 1215, 1171, 1137, 1020, 891, 842, 717, 647. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_8H_5F_3INO_3S$ $[M+H]^+$: 379.9065; found: 379.9076.

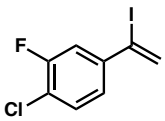
5-(1-bromovinyl)pyridin-2-yl trifluoromethanesulfonate (229b)



Prepared from 1-(6-(((trifluoromethyl)sulfonyl)oxy)pyridin-3-yl)vinyl trifluoromethanesulfonate (**211r**, 120 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield **229b** (80 mg, 80% yield) as a colorless oil. *Note: This compound slowly oxidizes to the α-bromo acetophenone under ambient conditions.*[59] **R_f** = 0.70 (silica, 30% EtOAc/hexanes, UV). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 8.58 (dd, *J* = 2.6, 0.7 Hz, 1H), 8.08 (dd, *J* = 8.5, 2.6 Hz, 1H), 7.18 (dd, *J* = 8.5, 0.6 Hz, 1H), 6.24 (d, *J* = 2.6 Hz, 1H), 5.96 (d, *J* = 2.6 Hz, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 155.8, 146.9, 140.1, 135.5, 124.9, 121.3, 118.7 (q, J_{C-F} = 320.7 Hz), 114.7. **^{19}F NMR (282 MHz, $CDCl_3$):** δ -72.9. **FTIR (NaCl, thin film, cm^{-1}):** 3105, 1615, 1582, 1470,

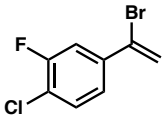
1426, 1370, 1215, 1173, 1137, 1020, 891, 621. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_8H_5F_3BrNO_3S$ $[M+H]^+$: 331.9204; found: 331.9195.

1-chloro-2-fluoro-4-(1-iodovinyl)benzene (230a)



Prepared from 1-(4-chloro-3-fluorophenyl)vinyl trifluoromethanesulfonate (**211s**, 91.4 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **230a** (58 mg, 69% yield) as a yellow oil. *Note: This compound slowly oxidizes to the α-iodo acetophenone derivative under ambient conditions.*[59] **R_f** = 0.57 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.31 – 7.23 (m, 2H), 7.21 – 7.16 (m, 1H), 6.43 (d, *J* = 2.0 Hz, 1H), 6.06 (d, *J* = 2.0 Hz, 1H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 157.5 (d, J_{C-F} = 249.4 Hz), 142.3 (d, J_{C-F} = 6.9 Hz), 130.3, 128.9, 124.4 (d, J_{C-F} = 3.5 Hz), 121.6 (d, J_{C-F} = 17.9 Hz), 116.5 (d, J_{C-F} = 22.8 Hz), 104.0 (d, J_{C-F} = 2.2 Hz). **^{19}F NMR (282 MHz, $CDCl_3$):** δ -114.9 (dd, J_{F-H} = 10.1, 7.4 Hz). **FTIR (NaCl, thin film, cm^{-1}):** 1598, 1484, 1414, 1402, 1285, 1244, 1070, 937, 901, 873, 818, 743, 733. **HRMS (EI, *m/z*):** calc'd for C_8H_5ClFI $[M+\cdot]^+$: 281.9109; found: 281.9124.

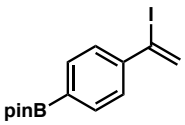
1-bromo-2-fluoro-4-(1-iodovinyl)benzene (230b)



Prepared from 1-(4-chloro-3-fluorophenyl)vinyl trifluoromethanesulfonate (**211s**, 91.4 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **230b** (52 mg, 73% yield) as a yellow oil. *Note: This compound slowly oxidizes to the α-bromo acetophenone derivative under ambient*

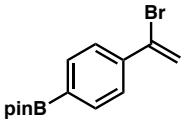
conditions.[59] **R_f** = 0.65 (silica, hexanes, UV). **^{1}H NMR (500 MHz, $CDCl_3$):** δ 7.41 – 7.35 (m, 2H), 7.32 (ddd, *J* = 8.4, 2.1, 0.7 Hz, 1H), 6.15 (d, *J* = 2.3 Hz, 1H), 5.83 (d, *J* = 2.3 Hz, 1H). **^{13}C NMR (126 MHz, $CDCl_3$):** δ 157.6 (d, J_{C-F} = 249.1 Hz), 139.0 (d, J_{C-F} = 7.2 Hz), 130.3, 128.2 (d, J_{C-F} = 2.3 Hz), 123.5 (d, J_{C-F} = 3.8 Hz), 121.7 (d, J_{C-F} = 18.0 Hz), 119.2, 115.7 (d, J_{C-F} = 23.0 Hz). **^{19}F NMR (282 MHz, $CDCl_3$):** δ -114.8 (m). **FTIR (NaCl, thin film, cm^{-1}):** 1601, 1570, 1485, 1412, 1289, 1246, 1174, 1066, 937, 892, 875, 819, 738. **HRMS (EI, *m/z*):** calc'd for C_8H_5ClFBr $[M+\cdot]^+$: 233.9247; found: 233.9228.

2-(4-(1-iodovinyl)phenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (231a)



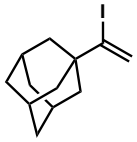
Prepared from 1-(4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-phenyl)vinyl trifluoromethanesulfonate (**211t**, 113.5 mg, 0.3 mmol) and sodium iodide (68 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 0 to 5% Et_2O/hexanes) to yield **231a** (72 mg, 68% yield) as a light yellow oil. **R_f** = 0.53 (silica, 10% EtOAc/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.77 – 7.72 (m, 2H), 7.53 – 7.48 (m, 2H), 6.51 (d, *J* = 1.8 Hz, 1H), 6.11 (d, *J* = 1.7 Hz, 1H), 1.34 (s, 12H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 144.3, 134.8, 128.0, 127.5, 107.5, 84.1, 25.0. *(Note: carbon bonded to boron not observed.)* **FTIR (NaCl, thin film, cm^{-1}):** 2978, 2930, 1607, 1398, 1360, 1324, 1269, 1210, 1144, 1092, 1018, 859, 841, 654. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{14}H_{18}BIO_2$ $[M+H]^+$: 357.0523; found: 357.0527.

2-(4-(1-bromovinyl)phenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (231b)



Prepared from 1-(4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-phenyl)vinyl trifluoromethanesulfonate (**211t**, 113.5 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, 0 to 5% Et_2O/hexanes) to yield **231b** (59 mg, 64% yield) as a light yellow oil which crystallized upon standing in the freezer. $\mathbf{R_f}$ = 0.48 (silica, 10% Et_2O/hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 7.81 – 7.76 (m, 2H), 7.62 – 7.56 (m, 2H), 6.17 (d, *J* = 2.0 Hz, 1H), 5.81 (d, *J* = 2.0 Hz, 1H), 1.35 (s, 12H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 141.0, 134.8, 131.1, 126.6, 118.5, 84.1, 25.0. *(Note: carbon bonded to boron not observed.)* **FTIR (NaCl, thin film, cm^{-1}):** 2979, 1607, 1507, 160, 1326, 1270, 1216, 1143, 1092, 1018, 859, 783, 656. **HRMS (TOF-ESI, *m/z*):** calc'd for $C_{14}H_{18}BBrO_2$ $[M+H]^+$: 309.0661; found: 309.0670.

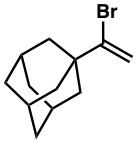
(3*r*,5*r*,7*r*)-1-(1-iodovinyl)adamantane (232a)



Prepared from 1-((3*r*,5*r*,7*r*)-adamantan-1-yl)vinyl trifluoromethanesulfonate (**211u**, 93.0 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **232a** (72 mg, 84% yield) as a colorless oil. $\mathbf{R_f}$ = 0.74 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 6.08 (d, *J* = 2.1 Hz, 1H), 5.80 (d, *J* = 2.1 Hz, 1H), 2.04 – 1.95 (m, 3H), 1.76 – 1.71 (m, 6H), 1.71 – 1.59 (m, 6H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 131.8, 122.8, 42.4, 41.8, 36.8, 28.7. **FTIR (NaCl, thin**

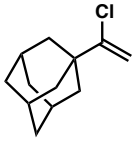
film, cm^{-1}): 2903, 2849, 1611, 1600, 1450, 1343, 1257, 1184, 1142, 1055, 894, 612. **HRMS (FAB, *m/z*):** calc'd for $C_{12}H_{17}I$ $[M+H]^+$: 289.0454; found: 289.0447.

(3*r*,5*r*,7*r*)-1-(1-bromovinyl)adamantane (232b)



Prepared from 1-((3*r*,5*r*,7*r*)-adamantan-1-yl)vinyl trifluoromethanesulfonate (**211u**, 125 mg, 0.4 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **232b** (76 mg, 78% yield) as a colorless oil. $\mathbf{R_f}$ = 0.81 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.56 (d, *J* = 2.0 Hz, 1H), 5.42 (d, *J* = 2.0 Hz, 1H), 2.03 (q, *J* = 3.2 Hz, 3H), 1.82 – 1.76 (m, 6H), 1.74 – 1.61 (m, 6H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 148.1, 113.7, 41.4, 41.1, 36.7, 28.5. **FTIR (NaCl, thin film, cm^{-1}):** 2905, 2850, 2678, 1622, 1453, 1344, 1152, 1057, 881, 716, 628. **HRMS (EI, *m/z*):** calc'd for $C_{12}H_{17}Br$ $[M+\cdot]^+$: 240.0514; found: 240.0510.

(3*r*,5*r*,7*r*)-1-(1-chlorovinyl)adamantane (232c)

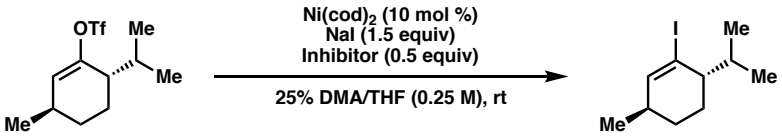


Prepared from 1-((3*r*,5*r*,7*r*)-adamantan-1-yl)vinyl trifluoromethanesulfonate (**211u**, 93.0 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 1. The crude residue was purified by column chromatography (silica, pentane) to yield **232c** (46 mg, 77% yield) as a colorless oil. $\mathbf{R_f}$ = 0.84 (silica, hexanes, $KMnO_4$). **^{1}H NMR (400 MHz, $CDCl_3$):** δ 5.13 (d, *J* = 1.5 Hz, 1H), 5.09 (d, *J* = 1.5 Hz, 1H), 2.04 (q, *J* = 3.2 Hz, 3H), 1.79 (d, *J* = 3.0 Hz, 6H), 1.76 – 1.62 (m, 6H). **^{13}C NMR (101 MHz, $CDCl_3$):** δ 153.5, 109.1, 40.7, 40.2, 36.7, 28.4. **FTIR (NaCl,**

thin film, cm^{-1}): 2904, 2851, 1618, 1452, 1344, 1165, 162, 877, 734, 666. **HRMS (EI, *m/z*):** calc'd for $C_{12}H_{17}Cl$ $[M+\cdot]^+$: 196.1019; found: 196.1040.

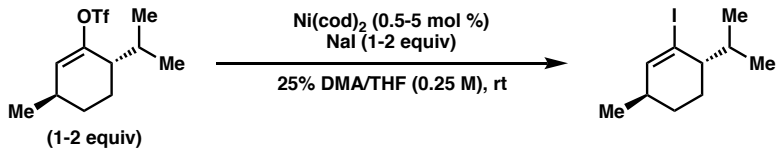
5.7.6 Mechanistic Experiments

5.7.6.1 Radical Inhibitors



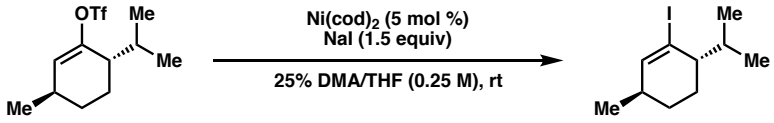
Four 1-dram vials were equipped with stir bars and brought into a N_2-filled glovebox. The vials were charged with NaI (0.15 mmol, 1.5 equiv) and $Ni(cod)_2$ (2.8 mg, 0.01 mmol, 0.1 equiv). Anhydrous DMA (0.1 mL) and THF (0.3 mL) were added, resulting in a clear yellow solution. DHA, BHT, TEMPO and Galvinoxyl were each added to one vial (0.5 equiv), then enol triflate (0.1 mmol, 1 equiv) was added in one portion. The vials were sealed with a Teflon cap and brought out of the glovebox. The reactions were allowed to stir on the bench (480 rpm) for two hours at room temperature. Reactions were quenched by filtering through a plug of silica gel, eluting with 10 mL of 40% Et_2O/Hexanes, then concentrated under reduced pressure. An NMR standard (tetrachloronitrobenzene) was added to each vial for NMR analysis.

5.7.6.2 Kinetics



A 2-dram vial equipped with a stir bar was brought into a N_2-filled glovebox. The vial was charged with NaI and $Ni(cod)_2$. Anhydrous DMA (0.5 mL) and THF (1.5 mL) were added. Undecane (32 μL) was added as an internal analytical GC standard. Alkenyl halide (0.5 mmol, 1 equiv) was added neat. The vial was sealed with a Teflon cap and allowed to stir in the glovebox (480 rpm) at room temperature. Reaction aliquots (50 μL) were taken at various time points and were quenched by addition into 1 mL hexanes in a GC vial, giving an opaque white mixture. The reaction aliquots were analyzed by GC-FID.

5.7.6.3 EPR Studies



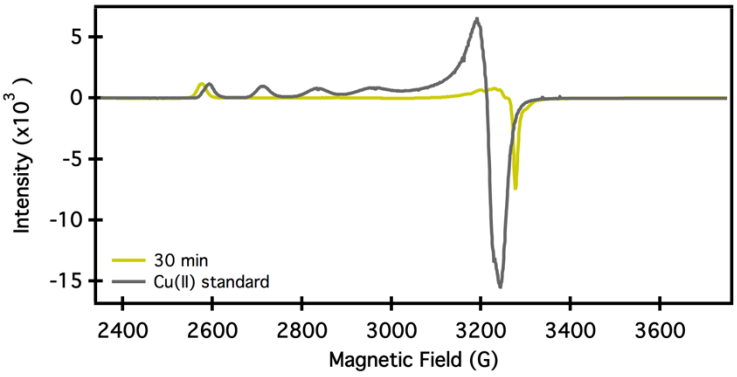
A 15 mL round-bottom flask equipped with a stir bar was brought into a N_2-filled glovebox. The vial was charged with NaI (1.2 mmol, 1.5 equiv) and $Ni(cod)_2$ (11.2 mg, 0.04 mmol, 0.05 equiv). Anhydrous DMA (0.8 mL) and THF (2.4 mL) were added. Enol triflate (0.8 mmol, 1 equiv) was added neat. The flask was sealed with a septum and allowed to stir in the glovebox (480 rpm) at room temperature. Aliquots (0.3 mL) were removed at various time points and added into EPR tubes, which were sealed and frozen at –78 ºC in a metal dewar filled with liquid nitrogen. The reaction aliquots were analyzed by EPR spectroscopy. An external standard of $CuSO_4$ in 1:9 ethylene glycol/H_2O was made and analyzed by EPR spectroscopy.

A single Ni(I) species is visible by EPR spectroscopy, which reaches a maximum concentration at 30 minutes. An additional broad Ni(II) species also forms as the reaction

proceeds, which may indicate aggregate Ni species. In order to remove contribution from the broad Ni(II) signal, baseline corrections were applied using the 'msbackadj' command in MatLab.

The spectra were processed by calculating the double integral. By comparison to the known concentration of $CuSO_4$ in Figure 5.15, the concentration of Ni(I) in the reaction was calculated to be <0.25 mM (i.e. less than 2% of all Ni added to the reaction, therefore indicating the Ni(I) species in this EPR spectrum is a trace Ni species).

Figure 5.17 *EPR of the iodination of* ***208*** *at 30 minutes compared to 12.5 mM* $CuSO_4$.



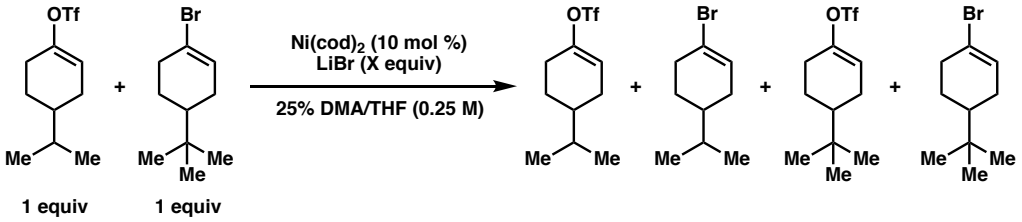
The halogenation of **208** was repeated with LiBr and LiCl to investigate the bromination and chlorination reactions. Time points were taken at 30 minutes and analyzed by EPR spectroscopy, demonstrating that the Ni(I) species observed does contain a halogen atom. The relative intensities of the spectra are I > Br > Cl.

5.7.6.4 Investigating Catalyst Death and Diene Formation

Two 1-dram vials were equipped with stir bars and brought into a N_2-filled glovebox. The vials were charged with NaI (0.15 mmol, 1.5 equiv) and $Ni(cod)_2$ (2.8 mg, 0.01 mmol, 0.1 equiv). Anhydrous DMA (0.1 mL) and THF (0.3 mL) were added, resulting in a clear

yellow solution. Enol triflate (0.1 mmol, 1 equiv) was added neat. The vials were sealed with a Teflon cap and stirred in the glovebox for two hours at room temperature. After two hours, one vial was quenched by filtering through a plug of silica gel, eluting with 10 mL of 40% Et_2O/Hexanes, then concentrated under reduced pressure. To the second vial was added an additional amount of NaI (0.15 mmol, 1.5 equiv) and a second enol triflate (0.1 mmol, 1 equiv). The vial was sealed with a Teflon cap and stirred for an additional two hours at room temperature. After two hours, the second vial was quenched by filtering through a plug of silica gel, eluting with 10 mL of 40% Et_2O/Hexanes, then concentrated under reduced pressure. An NMR standard was added to both samples for NMR analysis in order to record the yield of the first enol triflate halogenation as well as the second enol triflate halogenation. We note that in some cases, the completion of the first halogenation does not deactivate the catalyst for the second halogenation; however, in some cases the second halogenation is inhibited by the first one.

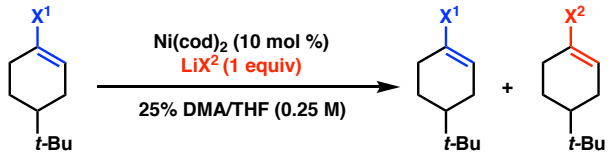
5.7.6.5 Crossover Experiments



A 2-dram vial equipped with a stir bar was brought into a N_2-filled glovebox. The vial was charged with LiBr (0–1 equiv) and $Ni(cod)_2$ (5.5 mg, 0.02 mmol, 0.1 equiv). Anhydrous DMA (0.2 mL) and THF (0.6 mL) were added, resulting in a clear yellow solution. Undecane (13 μL) was added as an internal analytical GC standard. Enol triflate (0.2 mmol,

1 equiv) was added neat, followed by alkenyl bromide (0.2 mmol, 1 equiv). The vial was sealed with a Teflon cap and allowed to stir in the glovebox (480 rpm) at room temperature. Reaction aliquots (25 µL) were taken at time points and were quenched by addition into 1 mL hexanes in a GC vial, giving an opaque white mixture. The reaction aliquots were analyzed by GC-FID against the internal standard.

5.7.6.6 Halide Competition Experiments



A 2-dram vial equipped with a stir bar was brought into a N_2-filled glovebox. The vial was charged with LiX^2 (0.5 mmol, 1 equiv) and $Ni(cod)_2$ (13.8 mg, 0.05 mmol, 0.1 equiv). Anhydrous DMA (0.5 mL) and THF (1.5 mL) were added. Undecane (32 µL) was added as an internal analytical GC standard. Alkenyl halide (RX^1) (0.5 mmol, 1 equiv) was added neat. The vial was sealed with a Teflon cap and allowed to stir in the glovebox (480 rpm) at room temperature. Reaction aliquots (50 µL) were taken at time points and were quenched by addition into 1 mL hexanes in a GC vial, giving an opaque white mixture. The reaction aliquots were analyzed by GC-FID against the internal standard.

5.7.6.7 NMR Experiments

A 1-dram vial equipped with a stir bar was brought into a N_2-filled glovebox. The vial was charged with $Ni(cod)_2$ (5.5 mg, 0.02 mmol, 1.0 equiv). Deuterated DMA (0.2 mL) and deuterated THF (0.6 mL) were added and solubilized, affording a yellow solution.

Trimethoxybenzene was added as an internal analytical NMR standard. Alkenyl triflate **208** (5.7 mg, 0.02 mmol, 1 equiv) was added neat and the reaction was stirred for 10 seconds, then the mixture was transferred to a J Young NMR tube. NMR analysis was performed at 10, 70, and 130 min against the internal standard. No oxidative addition of the enol triflate was observed; however, cod dissociation from $Ni(cod)_2$ was observed over time via NMR concomitant with the reaction turning brown in color.

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