Chapter 5

Nickel-Catalyzed Conversion of Enol Triflates to Alkenyl Halides◊

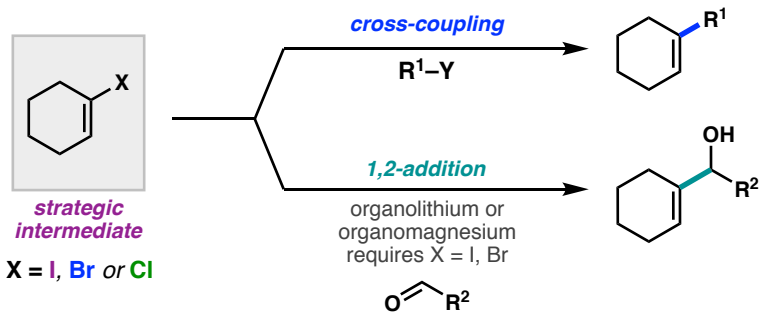
5.1 INTRODUCTION

Alkenyl halides are versatile functional groups that can be used in a variety of carbon–carbon and carbon–heteroatom bond-forming reactions.[1] For example, alkenyl halides are commonly employed as substrates in transition metal-catalyzed cross-coupling reactions or are converted to nucleophiles via metal-halogen exchange for 1,2-additions to carbonyl compounds (Scheme 5.1).[2] These transformations render alkenyl halides as indispensable functional group handles for synthetic disconnections. Furthermore, the alkenyl halide moiety appears in some natural products and bioactive molecules.[3,4]

◊ Portions of this chapter have been reproduced from a manuscript in preparation and the supporting information found therein. This work was conducted with Julie Hofstra and Alex Shimozono, graduate students in the Reisman lab.

While acyclic alkenyl halides are easily prepared from the corresponding alkyne[5–9] or aldehyde,[10,11] most cyclic alkenyl halides are synthesized from the corresponding ketone. The most direct method is the Barton reaction (and variations thereof),[12–17] which proceeds through an intermediate hydrazine (Scheme 5.2a). 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.[11]

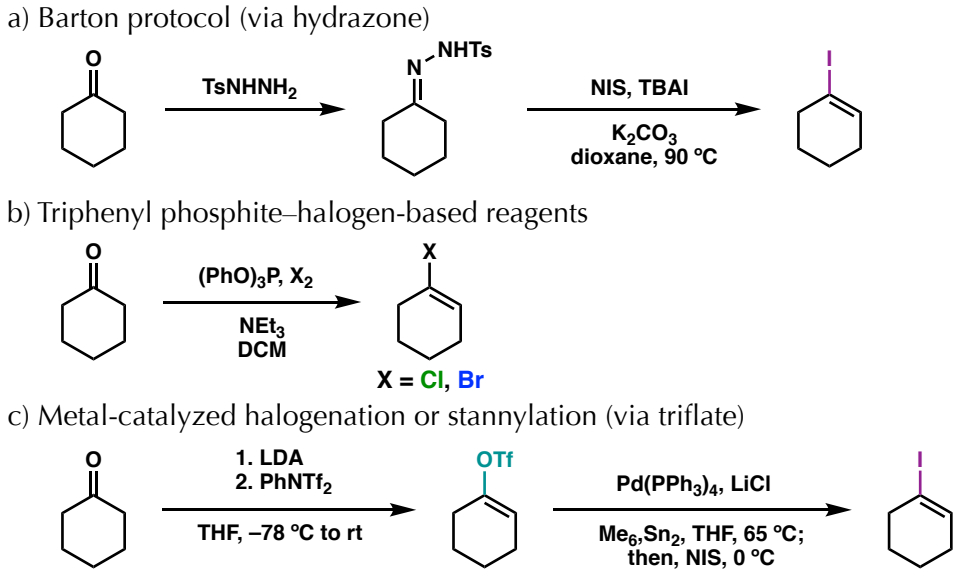
Scheme 5.1. *Synthetic utility of alkenyl halides.*



As a result, enol 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, enol triflates cannot be directly converted to the corresponding alkenyllithium or -magnesium 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 enol triflate, 2) conversion of the triflate to the alkenyl stannane, and 3) conversion of the stannane to the alkenyl halide[18] (Scheme 5.2c). Direct, mild methods to convert enol triflates to alkenyl halides, without

proceeding through organostannane intermediates, can streamline the preparation of these valuable intermediates.

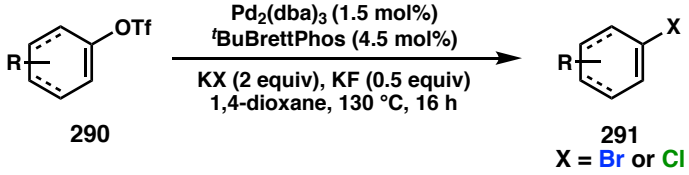
Scheme 5.2. *Methods to access alkenyl halides from ketones.*



Indeed, Buchwald has reported a Pd-catalyzed reaction to convert alkenyl triflates to alkenyl bromides and chlorides[19,20] (Scheme 5.3a); 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 $^{i}Bu_3Al$. These additives limit the functional group compatibility, particularly with common groups such as silyl ethers. More recently, Hayashi reported a Ru-catalyzed method to convert enol triflates to iodides, bromides, or chlorides that proceeds at ambient temperature (Scheme 5.3b); however, the requisite ruthenium catalyst is not commercially available and only three examples of alkenyl iodide formation are reported.[21,22]

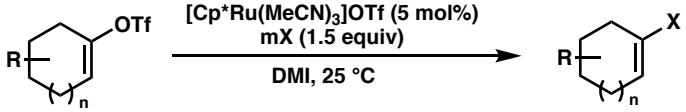
Scheme 5.3. *Alkenyl triflate-halide exchange reactions.*

a) Buchwald, 2011



290 **291**
X = Br or Cl

b) Hayashi, 2012

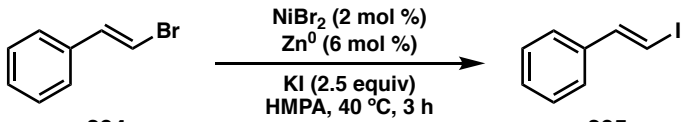


292 **293**
X = I, Br, Cl

During our investigations of Ni-catalyzed asymmetric reductive coupling reactions of alkenyl bromides (**Chapter 4**),[23,24] we observed an off-pathway halide exchange process that generated alkenyl chlorides and iodides. Whereas Ni-catalyzed aryl[25,26] and alkenyl halide exchange processes have been reported and extensively investigated (Scheme 5.4),[24,25,27,28] the corresponding reactions of enol triflates have not been developed.[29,30] Having observed promising reactivity with enol triflates,[31] we hypothesized that the appropriate Ni catalyst and inexpensive halide salts might enable the direct conversion of alkenyl triflates to alkenyl halides under mild conditions.

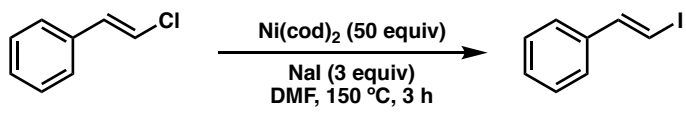
Scheme 5.4. *Ni-catalyzed alkenyl halide-halide exchange reactions.*

a) Kochi, 1978



294 **295**
95% yield

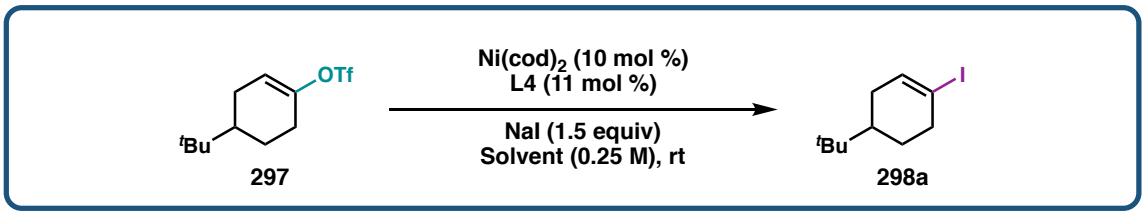
b) Brandsma, 1994

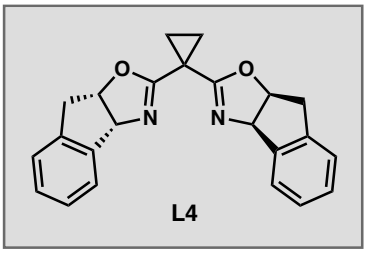


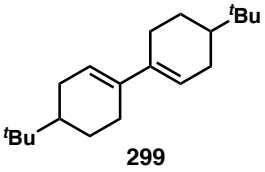
296 **295**
61% yield
80:20 E:Z

5.2 REACTION DEVELOPMENT

Table 5.1. *Initial solvent screen.*







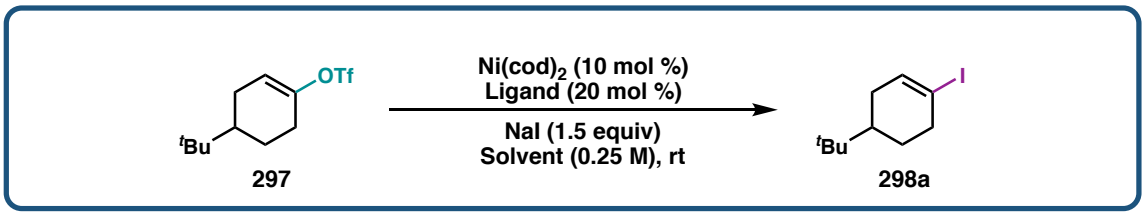
Entry	Solvent	L4	Yield 298a (%)	SM 297 (%)	HC 299 (%)
1	NMP	+	51	7	0
2	DMA	+	78	0	6
3	THF	+	71	0	0
4	MeCN	+	37	47	0
5	NMP	–	85	11	0
6	DMA	–	63	0	0
7	THF	–	9	80	0
8	MeCN	–	2	85	0

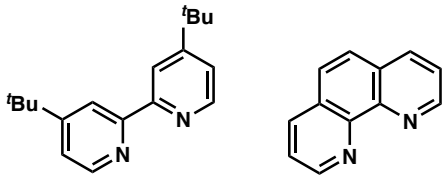
Our reaction development began with enol triflate **297**, prepared in one step from 4-*tert*-butylcyclohexanone, with the goal of identifying general conditions that could provide the alkenyl iodide, bromide, or chloride simply by changing the halide salt. We first explored reaction conditions similar to the asymmetric reductive cross-coupling reaction of alkenyl bromides that our lab previously developed where we first observed halide exchange side-products.[24] When **297** was subjected to $Ni(cod)_2$, **L4**, and NaI (1.5 equiv) in NMP, we obtained 51% yield of our desired alkenyl iodide **298a** (Table 5.1, entry 1), but poor recovery of starting material. A short solvent screen of DMA, THF and MeCN suggested promising reactivity across a range of solvents (Table 5.1, entries 2-4). Surprisingly, **298a** was formed in better yield (85% yield) in NMP without the addition of **L4** (Table 5.1, entry 5). However, poor conversion to alkenyl iodide **298a** was observed

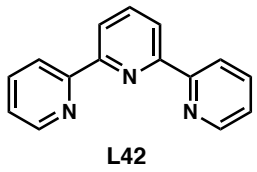
in solvents such as THF and MeCN without the chiral bis(oxazoline) ligand (Table 5.1, entries 7-8).

In an effort to optimize the reaction towards less polar solvents and away from costly chiral ligands, several achiral ligands were evaluated in THF (Table 5.2). While ligands such as **L41** provided comparable yield in THF (52% yield, Table 5.2, entry 4) to the reaction in DMA in the absence of ligand (63% yield, Table 5.2, entry 1), the reaction conversion was poor in THF. Other achiral ligands, such as substituted **L40** and **L42**, provided the desired product in low yield (Table 5.2, entries 3 and 5).

Table 5.2. *Evaluation of ligand effects on reaction.*





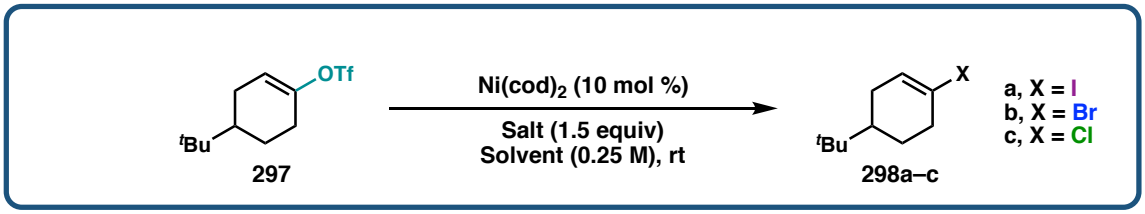


Entry	Solvent	Ligand	Yield 298a (%)	SM 297 (%)
1	DMA	—	63	0
2	THF	—	9	80
3	THF	L40	18	54
4	THF	L41	52	39
5	THF	L42	0	94

With these results in hand, we turned towards investigation of a mixed solvent system with DMA and THF (Table 5.3). While the yield of **298a** in DMA without an exogenous ligand was moderate, conversion of the starting enol triflate **297** to decomposition products prohibited further improvement in DMA (Table 5.1, entry 6). Interestingly, the addition of small quantities of THF to DMA significantly improved the

conversion of starting enol triflate **297** and yield of **298a** over either of the single solvent systems (Table 5.3, entries 1 and 8). Evaluation of several different ratios of DMA in THF revealed optimal yield and conversion occurs in approximately 20-30% DMA/THF, giving alkenyl iodide **298a** in 71% yield and some recovered starting material (Table 5.3, entries 3-4). While higher yield was observed at 40% DMA/THF, the high conversion of starting material to decomposition products discouraged further optimization in the mixed solvent system (Table 5.3, entry 5).

Table 5.3. *Evaluation of solvent and halide source.*



with NaI:

Entry	Solvent	Yield 298a (%)	SM 297 (%)
1	THF	5	91
2	10% DMA/THF	49	28
3	20% DMA/THF	71	26
4	30% DMA/THF	71	11
5	40% DMA/THF	78	4
6	50% DMA/THF	62	0
7	80% DMA/THF	54	5
8	DMA	55	0

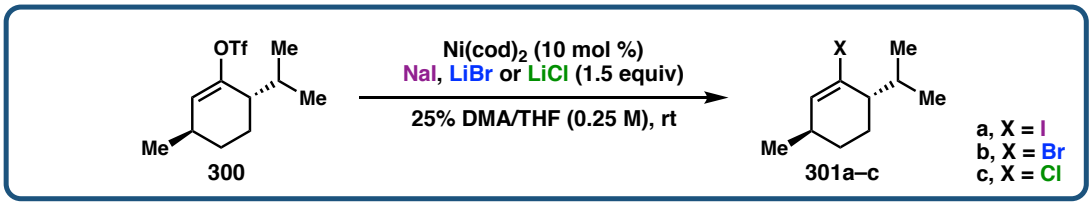
with 25% DMA/THF:

Entry	Salt	Yield 298 (%)	SM 297 (%)
9	LiI	47	0
10	LiBr	77	0
11	LiCl	83	0
12	NaI	82	9
13	NaBr	46	58
14	NaCl	0	96
15	KI	3	92
16	KBr	0	100
17	KCl	0	100

Next, we investigated halide salts for the iodination, bromination and chlorination reactions. Potassium salts provided poor results for all halides (Table 5.3, entries 15-17), while sodium salts provided poor yields for bromination and chlorination (Table 5.3, entries 12-14). Lithium salts worked well for the bromination and chlorination reaction

(Table 5.3, entries 10 and 11), while the sodium salt was optimal for the iodination (Table 5.3, entry 12).

Table 5.4. *Optimization of Ni-catalyzed exchange reaction conditions.*[a]



Entry	Deviation	Yield 301a (%)[b]	Yield 301b (%)[b]	Yield 301c (%)[b]	Entry	Deviation	Yield 301a (%)[b]	Yield 301b (%)[b]	Yield 301c (%)[b]
1	none	74	74	74	7	DMF	34	74	70
2	dtbbpy (0.2 equiv)	14	10	4	8	MeCN	4	52	7
3	TMEDA (0.2 equiv)	0	0	0	9	10% DMA/THF	68	68	77
4	dppf (0.2 equiv)	0	0	0	10	$^{n}Bu_4NX$ salt	71	84	80
5	DMA	72	75	70	11	5 mol % $Ni(cod)_2$	68	83	77
6	THF	35	75	61	12	10 mol % $Ni(cod)_2$	70	55	67

[a] Reactions conducted on 0.1 mmol scale under an inert atmosphere. [b] Determined by ^1H NMR vs 1,2,4,5-tetrachloronitrobenzene as an internal standard.

After initial reaction exploration, we found that evaluation of enol triflate **300**, prepared in one step from menthone, corroborated the results of extensive optimization efforts. Ultimately, we discovered that addition of the alkenyl triflate to a mixture of 10 mol % $Ni(cod)_2$ and 1.5 equiv of halide salt (either NaI, LiBr, or LiCl) in 1:3 DMA/THF at 23 °C provided the respective alkenyl halides in good yields (Table 5.4, entry 1). Ancillary ligands such as dtbbpy, TMEDA, and dppf inhibited the reaction, resulting in lower yields of alkenyl halide (Table 5.4, entries 2-4).

The alkenyl iodide formation proved most sensitive to the solvent: for example, while the bromination and chlorination work comparably well in both THF and DMA, the yield of the alkenyl iodide is significantly better in DMA than THF (Table 5.4, entries 5 and 6). Due to improved physical properties of the reaction mixture and work-up, a 1:3

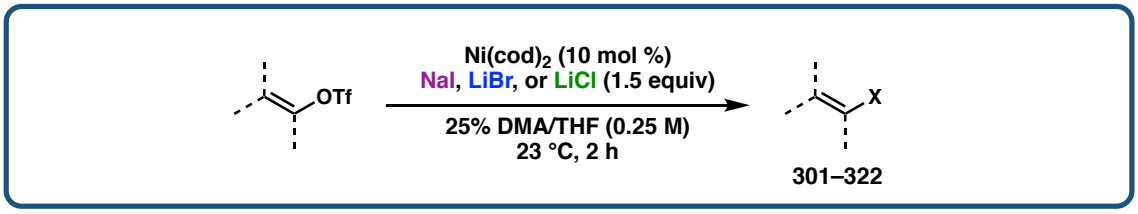
mixture of DMA and THF was selected as the optimal solvent system. Under these conditions, use of tetrabutylammonium salts provided all three halogenation products in comparably excellent yields (entry 10). At higher Ni loading, the yields of **301a–c** decreased due to increased homodimerization of the alkene (entry 12).

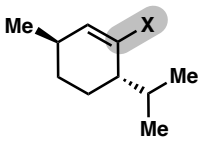
5.3 SUBSTRATE SCOPE

Having identified optimal reaction conditions, the substrate scope of the Ni-catalyzed halogenation reaction was investigated (Table 5.5). The halide exchange was found to be compatible with a variety of common functional groups, including amines (**303**), carbamates (**304**, **312**), pyridines (**317**), alkenes (**309**, **311**), esters (**316**), ketals (**305**, **320**), and enones (**310**). Dienyl bromides and chlorides could also be prepared in good yields; the yields of the corresponding iodides were typically lower (**309, 320**). Chemoselective halogenation of the alkenyl triflate was observed in preference to aryl triflates (**317**, **321**), aryl chlorides (**308**, **318**), and aryl boronates (**319**); however, competitive halide exchange was observed in the presence of aryl bromides and iodides.

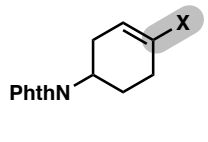
Although the Ni-catalyzed halogenation exhibits good functional group tolerance, the iodination, bromination, and chlorination did not perform equally well on all substrates. With the exception of the 1-arylvinyl triflates, the formation of the alkenyl chlorides proceeded with the most consistently high yields across different substrate classes. For example, 1-arylvinyl triflates (**316**–**319**, Table 5.5) provided the corresponding bromides and iodides in good yields; however, in the presence of chloride salts, elimination of the triflate to give the aryl acetylenes outcompeted chlorination.[32] For the non-styrenyl triflates, the yield of alkenyl iodide was most substrate-dependent. For example, cyclopentenyl triflates (**321**, **322**) were poor substrates for alkenyl iodide

***Table 5.5**. Alkenyl triflate substrate scope.*[a]

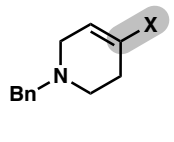




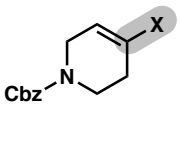
301a (I): 73%[b]
301b (Br): 80%
301c (Cl): 72%



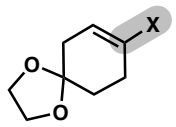
302a (I): 50%
302b (Br): 71%
302c (Cl): 92%



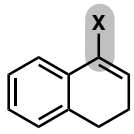
303a (I): 69%
303b (Br): 79%
303c (Cl): 80%



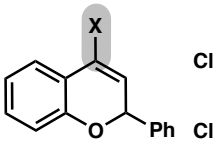
304a (I): 60%
304b (Br): 91%
304c (Cl): 86%



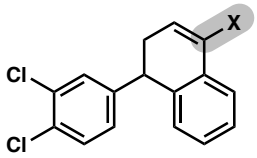
305a (I): 55%[c]
305b (Br): 73%
305c (Cl): 83%



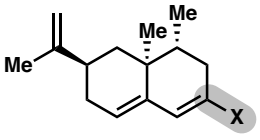
306a (I): 49%
306b (Br): 77%
306c (Cl): 80%



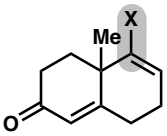
307a (I): 35%[d,e]
307b (Br): 75%
307c (Cl): 66%



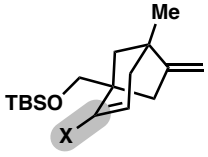
308a (I): 52%
308b (Br): 78%
308c (Cl): 75%



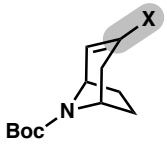
309a (I): 54%[c]
309b (Br): 82%
309c (Cl): 85%



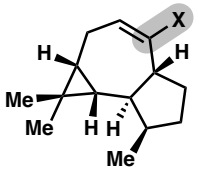
310a (I): 53%[c]
310b (Br): 78%
310c (Cl): 90%



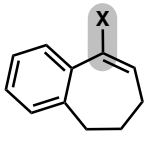
311a (I): 83%
311b (Br): 78%[d]
311c (Cl): 82%[d]



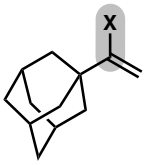
312a (I): 53%[c]
312b (Br): 65%
312c (Cl): 84%



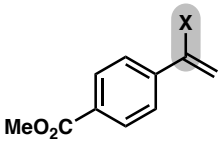
313a (I): 75%
313b (Br): 88%
313c (Cl): 88%



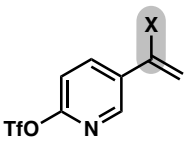
314a (I): 80%
314b (Br): 73%
314c (Cl): 71%



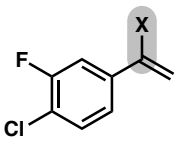
315a (I): 84%
315b (Br): 78%
315c (Cl): 78%



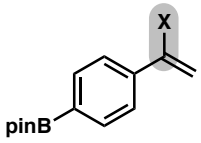
316a (I): 64%
316b (Br): 90%



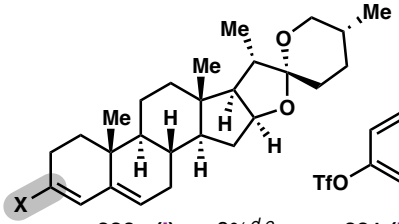
317a (I): 54%
317b (Br): 80%



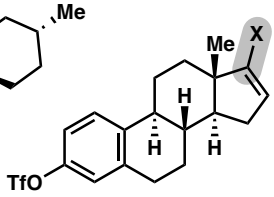
318a (I): 69%
318b (Br): 73%



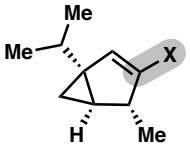
319a (I): 68%
319b (Br): 64%



320a (I): 9%[d,e]
320b (Br): 75%
320c (Cl): 97%



321 (I): 5%[d,e]
321b (Br): 59%
321c (Cl): 83%



322a (I): 3%[d,e]
322b (Br): 38%[f]
322c (Cl): 78%

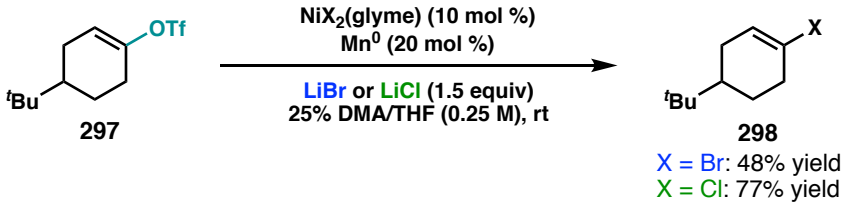
[a] Isolated yields, reactions conducted on 0.3 mmol scale under an N_2 atmosphere. [b] 0.5 mmol scale. [c] Enol nonaflate used. [d] 0.1 mmol scale. [e] Determined by ^{1}H NMR vs 1,2,4,5-tetrachloronitrobenzene as an internal standard. [f] 5 mol % $Ni(cod)_2$.

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 enol triflate was poor yielding; however, use of the corresponding enol nonaflate resulted in significantly higher yields of the iodide (**305a**, **309a**, **310a**, **312a**). The iodination of **300** could be conducted on gram scale to give alkenyl iodide **301a** in 72% yield.

5.4 APPLICATION OF NICKEL (II) CATALYSTS

Due to the relative bench stability and cost effectiveness of Ni(II) precatalysts compared to $Ni(cod)_2$, we investigated the use of Ni(II) salts with *in situ* reduction by Mn^0 or Zn^0 in the presence and absence of 1,5-cyclooctadiene (cod). Initial attempts to use NiX_2(glyme) and Mn^0 in the bromination and chlorination of **297** proved inferior to the corresponding $Ni(cod)_2$ conditions (Scheme 5.5). Unfortunately, the heterogeneous nature of these conditions rendered these transformations sensitive to reaction set up and stirring. Further optimization of Ni(II) precatalysts would prove more fruitful, but were discovered after extensive development of the Ni(0) precatalyst transformation.

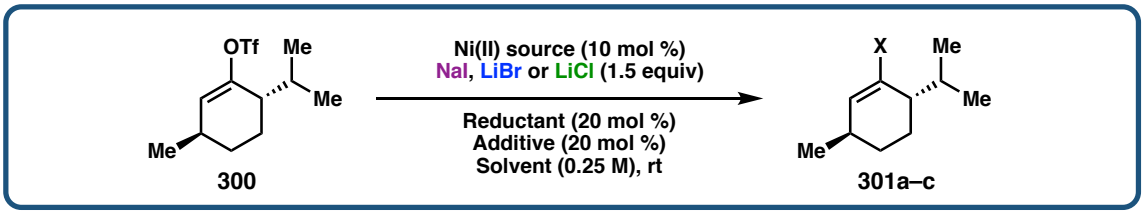
Scheme 5.5. *Initial attempts at use of Ni(II) precatalysts.*



We next turned our attention to the use of NiX_2 catalysts, as there is no commercially available NiX_2(glyme) iodide equivalent. Recognizing the potential utility of 1,5-cyclooctadiene (cod) as a ligand in the transformation, both Mn^0 and Zn^0 were

screened as reductants in the presence and absence of exogenous cod (Table 5.6). While moderate reactivity was observed for the bromination and chlorination reactions with NiX_2 salts (Table 5.6, entries 2-3), inconsistent results across all three halogenation reactions were discouraging for further optimization efforts (entries 1-4). Other Ni(II) catalysts, such as $Ni(acac)_2$ and $Ni(OTf)_2$, did not display any reactivity (entries 6 and 8). Finally, the use of NiX_2(glyme) with Zn^0 and exogenous cod gave bromide **301b** and chloride **301c** in excellent 87% yields (Table 5.6, entry 9). Gratifyingly, $Ni(OAc)_2$•$4H_2O$ provided similar yields for the bromination and chlorination, and a promising 33% yield of iodide **301a** (Table 5.6, entry 10).

Table 5.6. *Initial exploration of Ni(II) precatalyst conditions.*

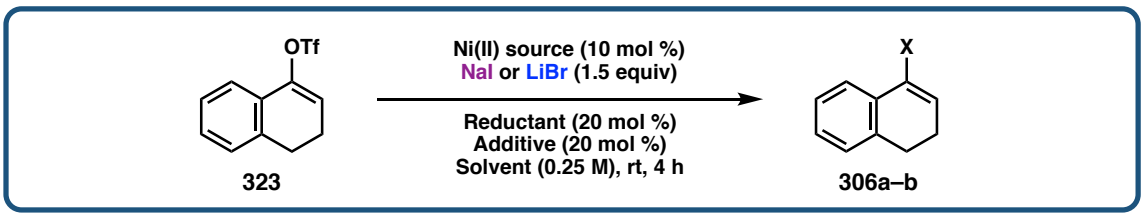


Entry	Ni source	reductant	additive	solvent	Yield 301a (%)	Yield 301b (%)	Yield 301c (%)
1	NiX_2	Mn^0	none	DMA/THF	0	0	0
2	NiX_2	Mn^0	COD	DMA/THF	4	41	63
3	NiX_2	Zn^0	none	DMA/THF	4	37	57
4	NiX_2	Zn^0	COD	DMA/THF	25	86	0
5	NiX_2	Zn^0	COD	DMA	62	83	0
6	$Ni(acac)_2$	Zn^0	none	DMA/THF	0	0	0
7	$Ni(acac)_2$	DIBAL	none	DMA/THF	3	5	0
8	$Ni(OTf)_2$	Zn^0	none	DMA/THF	0	0	0
9	NiX_2(dme)	Zn^0	COD	DMA/THF	—	87	87
10	$Ni(OAc)_2$•$4H_2O$	Zn^0	COD	DMA/THF	33	95	94

After observing promising reactivity with $Ni(OAc)_2$•$4H_2O$, we screened a number of Ni(II) catalysts with Zn^0 as a reductant, with cod, and in exclusively DMA, for the

iodination and bromination reaction (Table 5.7, entries 2-4). Unfortunately, the iodination under these conditions gave only trace amount of product. However, after evaluation of a number of additives, we discovered the addition of 20 mol % DMAP, as well as extending the reaction time, increased the yield of the iodination to 95% (Table 5.7, entry 6)

Table 5.7. *Optimization of Ni(II) precatalyst conditions.*

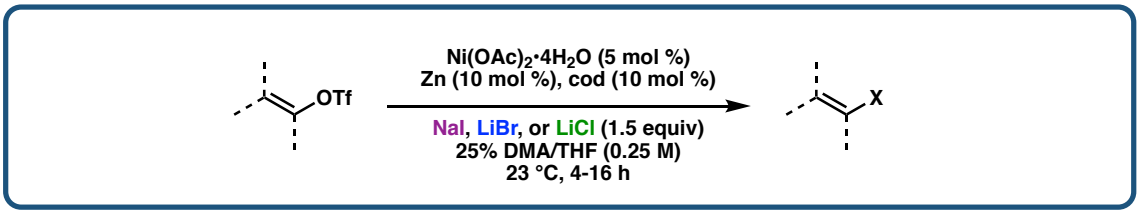


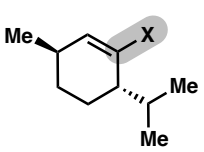
Entry	Ni source	reductant	additive	solvent	Yield 306a (%)	Yield 306b (%)
1	$Ni(acac)_2$	Zn^0	COD	DMA/THF	4	91
2	$Ni(acac)_2$	Zn^0	COD	DMA	4	97
3	$Ni(OTf)_2$	Zn^0	COD	DMA	5	0
4	$Ni(OAc)_2{\cdot}4H_2O$	Zn^0	COD	DMA	0	39
5	$Ni(OAc)_2{\cdot}4H_2O$	Zn^0	COD	DMA/THF	33	95
6	$Ni(OAc)_2{\cdot}4H_2O$	Zn^0	COD + DMAP	DMA/THF	95*	95

*reaction run 24 h

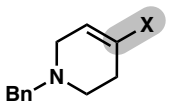
With optimized Ni(II) reaction conditions in hand, we explored the substrate scope under these conditions. Gratifyingly, the yields of the iodination, bromination, and chlorination of several substrates increased significantly over their corresponding Ni(0) results (Table 5.8). While $Ni(OAc)_2{\cdot}4H_2O$ is an inexpensive catalyst, we were pleased to see the yields of our halogenation reaction remained high even at lower Ni loading (5 mol %). Notably, substrates such as ketal **305** and tropinone-derivative **312** improved remarkably under these new reaction conditions.

***Table 5.8**. Substrate scope under Ni(II) precatalyst conditions.*[a]

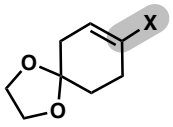




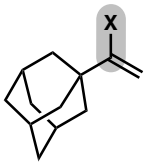
301a (I): 98%[b]
301b (Br): 78%
301c (Cl): 73%



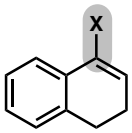
303a (I): 95%[b]
303b (Br): 92%
303c (Cl): 90%



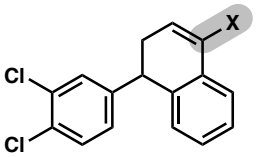
305a (I): 81%[b]
305b (Br): 94%
305c (Cl): 88%



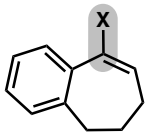
315a (I): 82%[b]
315b (Br): 90%
315c (Cl): 86%



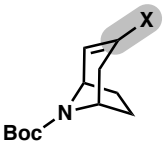
306a (I): 95%[b]
306b (Br): 96%
306c (Cl): 93%



308a (I): 80%[b]
308b (Br): 94%
308c (Cl): 87%



314a (I): 95%[b]
314b (Br): 94%
314c (Cl): 91%



312a (I): 55%[b]
312b (Br): 98%
312c (Cl): 98%

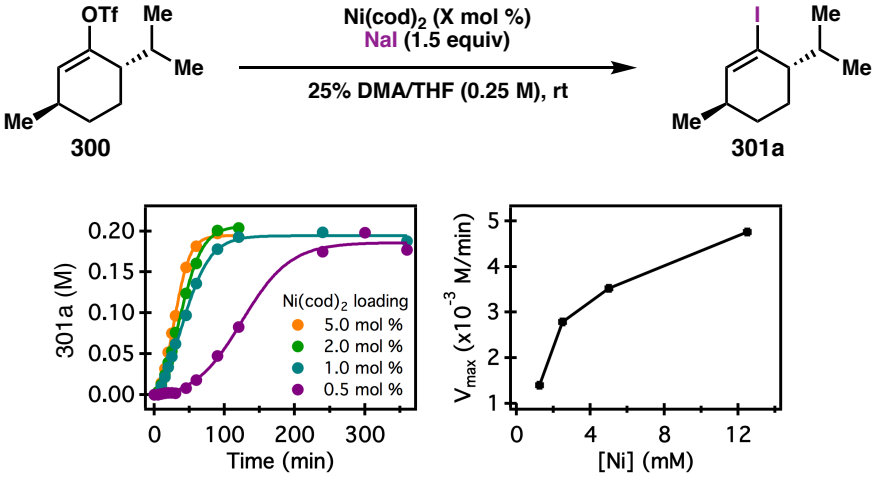
[a] Isolated yields, reactions conducted on 0.3 mmol scale under an N_2 atmosphere. [b] $Ni(OAc)_2 \cdot 4H_2O$ (10 mol %), Zn^0 (20 mol %), cod (20 mol %), DMAP (20 mol %). Determined by ^1H NMR vs 1,2,4,5-tetrachloronitrobenzene as an internal standard.

5.5 MECHANISTIC INVESTIGATIONS

To better understand the Ni-catalyzed halogenation of enol triflates, and the iodination in particular, a series of mechanistic experiments were performed on our initial Ni(0) system. The iodination of **300** exhibits an induction period at low $Ni(cod)_2$ loadings (e.g. 0.5 mol %, 1 mol %) (Figure 5.1). Addition of exogenous 1,5-cyclooctadiene (cod) inhibits the rate of the reaction, which suggests ligand dissociation could be the source of the induction period. Plotting V_{max} vs. [Ni] revealed that the reaction has a positive-order dependence on [Ni] that negatively deviates from first order at higher [Ni], suggesting the formation of dimeric (or higher order) off-cycle species at higher [Ni].[33] No change in the rate of iodination of **300** is observed when the amount of NaI is increased beyond 1 equiv. Although 10 mol % $Ni(cod)_2$ was used in Table 5.5 because it proved most robust

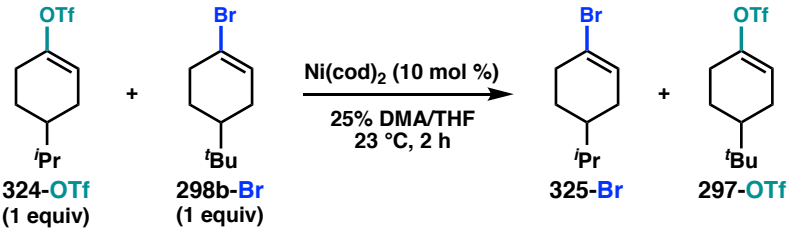
over a broad range of substrates, for highly reactive substrates, lower catalyst loadings can be beneficial to reduce formation of homodimers.

Figure 5.1. *Kinetic analysis.*



A crossover experiment was designed to evaluate the reversibility of alkenyl halide formation: treatment of a 1:1 mixture of **324** and **298b** with $Ni(cod)_2$ (10 mol %) in 1:3 DMA/THF at 23 °C resulted in complete recovery of **297** and **298b**, without detection of crossover products **297** or **325** (Scheme 5.6). Addition of 0.1 or 1.0 equiv LiBr resulted in conversion of **324** to **325** in 10% and 90% yield, respectively;[34] no **297** was detected at any point in either reaction. Monitoring the reaction by ^1H NMR confirms that no oxidative addition of **324** occurs in the absence of halide salt. Upon addition of a metal halide salt, conversion of **300** to the alkenyl halide (**301a–c**) was observed concomitantly with the formation of a Ni(I)–X species. The same Ni(I)–X species were detected upon mixing **301a–c** and $Ni(cod)_2$ (5 mol %).[35,36]

***Scheme 5.6**. Crossover experiment.*[a]



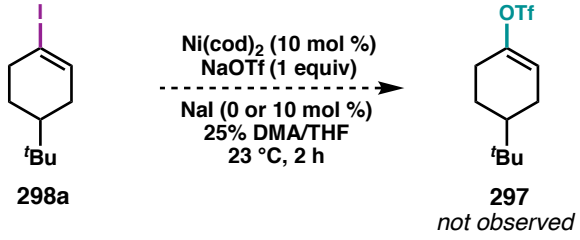
324-OTf (1 equiv) + **298b-Br** (1 equiv) → **325-Br** + **297-OTf**

	324-OTf (%)[b]	298b-Br (%)[b]	325-Br (%)[b]	297-OTf (%)[b]
no change	100	100	0	0
w/ LiBr (0.1 equiv)	90	100	10	0
w/ LiBr (1.0 equiv)	0	100	90	0

[a] Reactions conducted on 0.2 mmol scale under an inert atmosphere. [b] Determined by GC analysis vs undecane as an internal standard.

Similarly, subjection of alkenyl iodide **298a** to $Ni(cod)_2$ (10 mol %) and metal triflate salts (e.g. NaOTf) did not result in enol triflate formation (Scheme 5.7). 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 irreversible consumption of the enol triflate 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.[26] For example, an 85:15 mixture of **298b:298a** is obtained after 2 hours for both the Ni-catalyzed reactions of **298b** with LiI, or **298a** with LiBr.

***Scheme 5.7**. Attempts to observe halide-triflate exchange.*



298a → **297** *not observed*

5.6 CONCLUSION

In conclusion, two methods for a mild, Ni-catalyzed halogenation of alkenyl triflates have been developed. By modifying the halide salt, we observe that alkenyl iodides, bromides, or chlorides can be obtained using simple, commercially available catalysts, in a homogeneous or heterogeneous reaction. This reaction proceeds at room temperature and exhibits good functional group tolerance.

5.7 EXPERIMENTAL SECTION

5.7.1 *Materials and Methods*

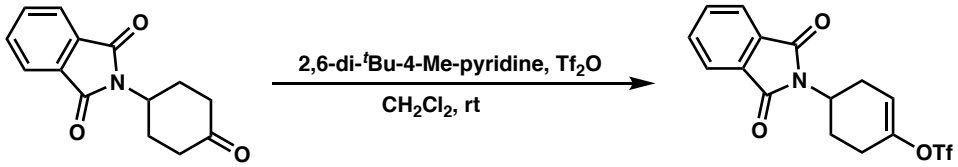
Unless otherwise stated, reactions were performed under a N_2 atmosphere using freshly dried solvents. Tetrahydrofuran (THF) and methylene chloride (CH_2Cl_2) were dried by passing through activated alumina columns. Diisopropylamine (*i*-Pr_2NH) was distilled over calcium hydride prior to use. Anhydrous 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.[1] 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, $\delta = 7.26$), $CDCl_3$ (^{13}C, $\delta = 77.0$), CD_3CN (^1H, $\delta = 1.94$), CD_3CN (^{13}C, $\delta = 1.32$), and C_6F_6 (^{19}F, $\delta = -161.64$). 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 *Substrate Preparation*

5.7.2.1 Enol Triflates

4-(1,3-dioxoisoindolin-2-yl)cyclohex-1-en-1-yl trifluoromethanesulfonate (326)



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) sequentially. The reaction was stirred at room temperature overnight, then diluted with hexanes and filtered over a plug of Celite. The Celite was washed 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 **326** 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).

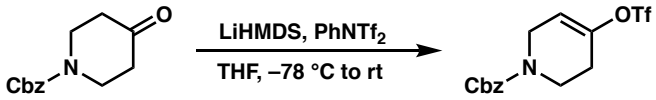
^{13}C NMR (101 MHz, $CDCl_3$): δ 168.2, 148.2, 134.3, 131.9, 123.4, 118.6 (q, $J_{C\text{-}F}$ = 320.2 Hz), 116.9, 45.6, 27.7, 26.7, 26.1.

^{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 (327)



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 **327** as a colorless oil.

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).

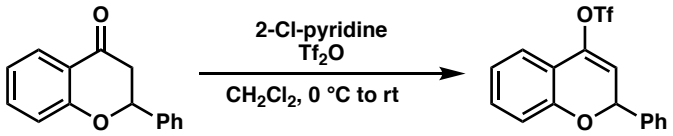
^{13}C NMR (101 MHz, d_3-MeCN, 65 °C): δ 156.2, 148.4, 138.5, 129.7, 129.2, 129.0, 117.4, 68.3, 43.1, 41.9, 29.0.

^{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 (328)



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 **328** as a pale solid.

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).

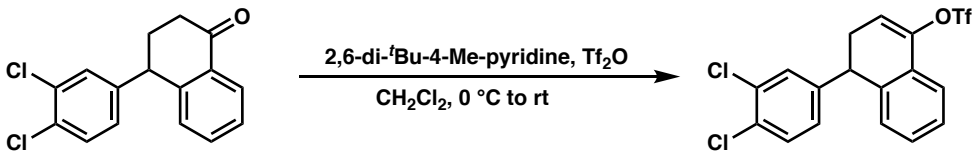
^{13}C NMR (101 MHz, $CDCl_3$): δ 153.9, 143.2, 138.8, 131.9, 129.2, 129.0, 127.1, 121.70, 121.67, 118.5 (q, J_{C-F} = 320.5 Hz), 116.6, 116.4, 113.1, 77.4.

^{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 (329)



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 **329** as a colorless oil.

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).

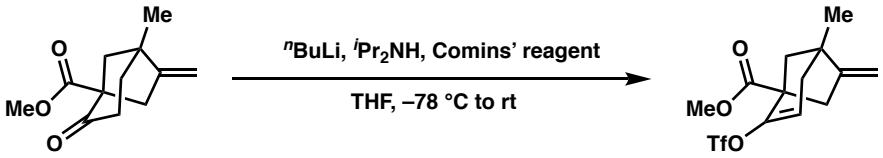
^{13}C NMR (101 MHz, $CDCl_3$): δ 146.2, 143.2, 137.4, 132.8, 131.2, 130.8, 130.3, 130.0, 128.7, 128.4, 127.9, 127.7, 121.9, 118.7 (q, $J_{C\text{-}F}$ = 320.4 Hz), 116.0, 42.4, 30.8.

^{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)bicyclo[3.2.1] oct-2-ene-1-carboxylate (330)



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 Comins' 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 **330** as a clear oil.

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).

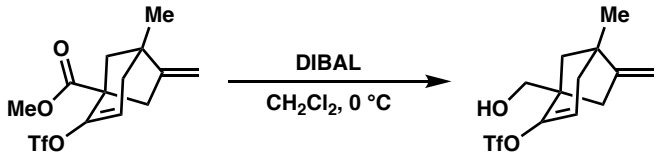
^{13}C NMR (101 MHz, $CDCl_3$): δ 171.1, 155.2, 149.6, 120.0 (q, $J_{C\text{-}F}$ = 319.9 Hz), 116.5, 107.7, 52.8, 52.6, 48.2, 44.7, 42.9, 41.9, 23.9.

^{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 (331)



To a flame dried, N_2 filled round bottom flask was added **330** (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 **331** as a clear oil.

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).

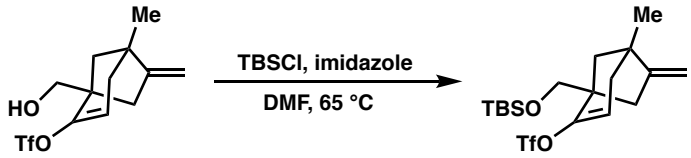
^{13}C NMR (101 MHz, $CDCl_3$): δ 156.6, 153.1, 118.7 (q, J_{C-F} = 319.8 Hz), 117.2, 107.1, 64.5, 48.4, 47.4, 44.3, 43.1, 42.3, 24.4.

^{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 (332)



To a round bottom flask was added **331** (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 **332** 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).

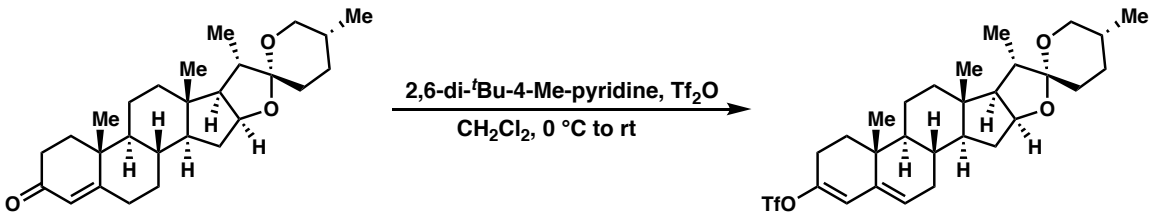
^{13}C NMR (101 MHz, $CDCl_3$): δ 157.3, 153.6, 120.1 (q, J_{C-F} = 319.3 Hz), 116.3, 106.7, 64.0, 48.4, 47.6, 43.8, 43.0, 42.4, 26.0, 24.5, 18.5, -5.5.

^{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 (333)



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-octadecahydrospiro[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 **333** 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).

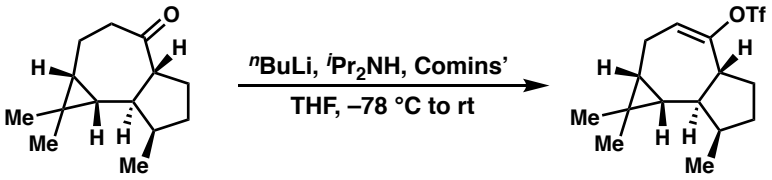
^{13}C NMR (101 MHz, $CDCl_3$): δ 147.1, 138.2, 128.1, 120.6, 118.7 (q, $J_{C\text{-}F}$ = 319.9 Hz), 109.5, 80.9, 67.0, 62.2, 56.6, 47.8, 41.8, 40.5, 39.8, 35.0, 33.9, 32.2, 31.9, 31.5, 31.3, 30.4, 28.9, 25.7, 21.2, 18.8, 17.3, 16.5, 14.7.

^{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 (334)



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 **334** as a colorless oil which solidified in the freezer.

$\mathbf{R}_f$ = 0.49 (silica, hexanes, $KMnO_4$).

$[\boldsymbol{a}]_D^{25}$ = –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).

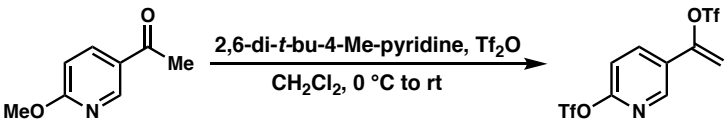
^{13}C NMR (101 MHz, $CDCl_3$): δ 154.6, 120.1, 118.7 (q, J_{C-F} = 319.9 Hz), 48.0, 43.1, 34.4, 32.0, 29.8, 28.5, 25.7, 25.6, 20.3, 18.7, 18.0, 15.3.

^{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 (335)

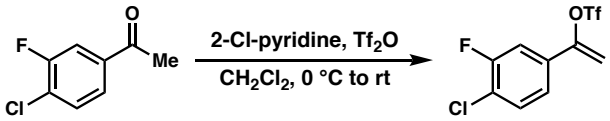


To a round bottom flask was added 1-(6-methoxypyridin-3-yl)ethan-1-one (756 mg, 5.0 mmol, 1.0 equiv), 2,6-di-tert-butyl-4-methylpyridine (2.26 g, 11 mmol, 2.2 equiv), and CH_2Cl_2 (15 mL). The reaction was cooled to 0 °C before trifluoromethanesulfonic anhydride (2.0 mL, 12.0 mmol, 2.4 equiv) was added. 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 **335** 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 (336)



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 **336** as a light yellow oil.

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).

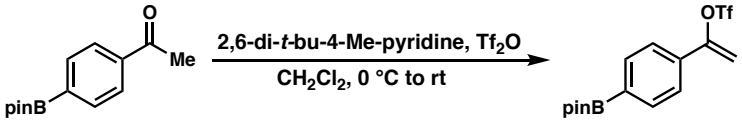
^{13}C NMR (101 MHz, $CDCl_3$): 158.3 (d, $J_{C\text{-}F}$ = 250.3 Hz), 151.3 (d, $J_{C\text{-}F}$ = 2.7 Hz), 132.6 (d, $J_{C\text{-}F}$ = 7.2 Hz), 131.4, 123.5 (d, $J_{C\text{-}F}$ = 17.7 Hz), 121.8 (d, $J_{C\text{-}F}$ = 3.9 Hz), 118.6 (q, $J_{C\text{-}F}$ = 320.3 Hz), 113.8 (d, $J_{C\text{-}F}$ = 23.7 Hz), 106.0.

^{19}F NMR (282 MHz, $CDCl_3$): δ -73.5, -113.2 (dd, $J_{F\text{-}H}$ = 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 (337)



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 **337** 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).

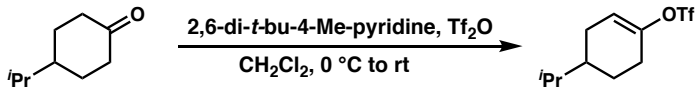
^{13}C NMR (101 MHz, $CDCl_3$): δ 153.6, 135.3, 134.4, 124.5, 118.6 (q, $J_{C\text{-}F}$ = 320.2 Hz), 105.1, 84.3, 25.0. *(Note: carbon bonded to boron not observed.)*

^{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 (324)



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-ditertbutyl-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 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, hexanes) to yield 2.3 g (68% yield) of **324** 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.

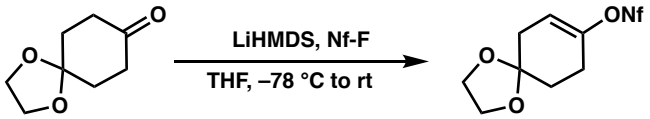
^{19}F NMR (282 MHz, $CDCl_3$): δ -73.9.

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.

5.7.2.2 Enol Nonaflates

1,4-dioxaspiro[4.5]dec-7-en-8-yl 1,1,2,2,3,3,4,4,4-nonafluorobutane-1-sulfonate (338)



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 (**338**) as a colorless oil.

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).

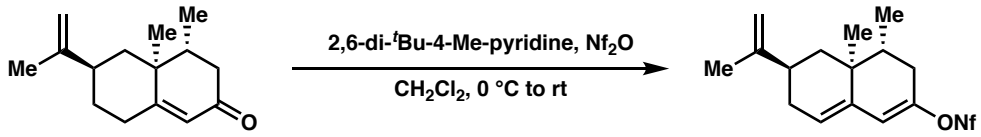
^{13}C NMR (101 MHz, $CDCl_3$): δ 148.4, 116.1, 106.3, 64.8, 34.3, 31.2, 26.6. (*Note: nonaflate carbons omitted due to low intensity resulting from C-F splitting*)

^{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 (339)



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 (**339**) as a colorless oil.

R*f* = 0.22 (silica, hexanes, UV).

$[\boldsymbol{\alpha}]_{\boldsymbol{D}}^{\mathbf{25}}$ = –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).

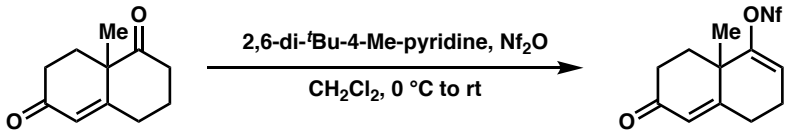
^{13}C NMR (101 MHz, $CDCl_3$): δ 149.6, 147.1, 138.5, 128.2, 120.5, 109.3, 39.7, 39.3, 37.1, 35.9, 34.3, 31.4, 30.3, 20.8, 17.3, 14.5. (*Note: nonaflate carbons omitted due to low intensity resulting from C-F splitting*)

^{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-nonafluorobutane-1-sulfonate (340)



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 (**340**) as a white solid.

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).

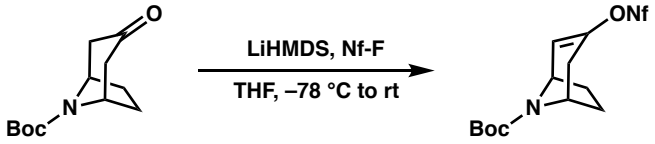
^{13}C NMR (101 MHz, $CDCl_3$): δ 213.0, 148.2, 136.4, 127.4, 119.4, 44.7, 35.2, 28.9, 25.1, 24.9, 22.7. (*Note: nonaflate carbons omitted due to low intensity resulting from C-F splitting*)

^{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 (341)



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 (**341**) as an off white solid.

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.

5.7.3 Ni-Catalyzed Halogenation

5.7.3.1 General Procedures for Ni-Catalyzed Halogenation

General Procedure 1: Enol Triflate Halogenation on 0.1 mmol Scale

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.

General Procedure 2: 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 3: 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 4: 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,

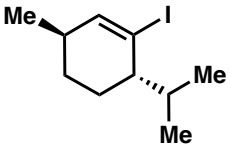
resulting in a clear yellow solution. Enol nonaflate (0.3 mmol, 1 equiv) was added in one portion, turning the reaction dark red (NaI) or aqua blue (LiBr or LiCl) over several minutes. The vial was sealed with Teflon cap and brought out of the glovebox. The reaction was allowed to stir on the bench (480 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.

General Procedure 5: Enol Triflate Halogenation on 0.1 mmol Scale with $Ni(OAc)_2$•$4H_2O$

A 1-dram vial was equipped with a stir bar and brought into a N_2-filled glovebox. The vial was charged with Zn^0 (0.01 mmol), $Ni(OAc)_2$•$4H_2O$ (0.005 mmol), 1,5-cyclooctadiene (cod) (0.01 mmol), anhydrous DMA (0.1 mL) and THF (0.3 mL). The reactions were stirred for 20 min at room temperature, then enol triflate (0.1 mmol, 1 equiv) was added. The vial was brought out of the glovebox to stir on the bench (480 rpm) for four to 24 hours at room temperature. Reactions were quenched by eluting through a small plug of silica gel (5 cm) in a large glass pipette with 40% Et_2O/pentane (10 mL collected). The crude reaction mixtures were concentrated under reduced pressure and analyzed by NMR with an internal standard (1,2,4,5-tetrachloronitrobenzene).

5.7.3.2 Characterization of Reaction Products

(3*R*,6*S*)-1-iodo-6-isopropyl-3-methylcyclohex-1-ene (301a)



Prepared from (3*R*,6*S*)-6-isopropyl-3-methylcyclohex-1-en-1-yl trifluoromethanesulfonate (143.2 mg, 0.3 mmol) and sodium iodide (112.5 mg, 0.75 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **301a** (96 mg, 73% yield) as a colorless oil.

$\mathbf{R}_f$ = 0.79 (silica, pentane, $KMnO_4$).

$\mathbf{[\alpha]_D^{25}}$ = –47° (c = 0.5, $CHCl_3$).

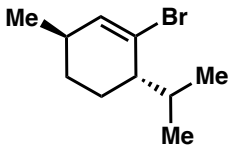
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.36 (d, *J* = 1.2 Hz, 1H), 2.35 – 2.14 (m, 3H), 1.89 – 1.79 (m, 1H), 1.68 (dddd, *J* = 13.3, 5.9, 4.5, 3.0 Hz, 1H), 1.54 – 1.42 (m, 1H), 1.18 (tdd, *J* = 13.1, 10.2, 3.1 Hz, 1H), 0.97 (d, *J* = 7.0 Hz, 3H), 0.94 (d, *J* = 6.8 Hz, 3H), 0.72 (d, *J* = 6.7 Hz, 3H).

^{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.

(3*R*,6*S*)-1-bromo-6-isopropyl-3-methylcyclohex-1-ene (301b)



Prepared from (3*R*,6*S*)-6-isopropyl-3-methylcyclohex-1-en-1-yl trifluoromethanesulfonate (85.9 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **301b** (52 mg, 80% yield) as a colorless oil.

$\mathbf{R}_f$ = 0.77 (silica, hexanes, $KMnO_4$).

$\mathbf{[\alpha]_D^{25}}$ = –26° (c = 1.0, $CHCl_3$).

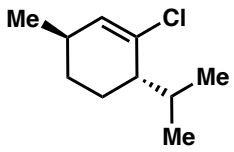
^{1}H NMR (400 MHz, $CDCl_3$): δ 5.99 (td, *J* = 2.0, 1.0 Hz, 1H), 2.39 (ddt, *J* = 13.7, 6.8, 3.4 Hz, 1H), 2.32 (ddtd, *J* = 9.8, 5.8, 3.8, 1.8 Hz, 1H), 2.24 – 2.12 (m, 1H), 1.85 – 1.71 (m, 2H), 1.51 – 1.39 (m, 1H), 1.14 (tdd, *J* = 12.4, 10.1, 2.6 Hz, 1H), 0.98 (d, *J* = 7.1 Hz, 3H), 0.93 (d, *J* = 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 (301c)



Prepared from (3*R*,6*S*)-6-isopropyl-3-methylcyclohex-1-en-1-yl trifluoromethanesulfonate (85.9 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **301c** (37 mg, 72% yield) as a colorless oil.

R_f = 0.87 (silica, hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = –11° (c = 0.5, $CHCl_3$).

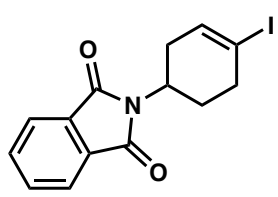
^{1}H NMR (400 MHz, $CDCl_3$): δ 5.73 (td, *J* = 2.0, 1.0 Hz, 1H), 2.37 (m, 1H), 2.27 (ddtd, *J* = 9.7, 5.7, 3.8, 1.9 Hz, 1H), 2.23 – 2.14 (m, 1H), 1.84 – 1.71 (m, 2H), 1.48 – 1.35 (m, 1H), 1.16 – 1.04 (m, 1H), 0.98 (d, *J* = 7.0 Hz, 3H), 0.93 (d, *J* = 7.0 Hz, 3H), 0.76 (d, *J* = 6.8 Hz, 3H).

^{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 (302a)



Prepared from 4-(1,3-dioxoisoindolin-2-yl)cyclohex-1-en-1-yl trifluoromethanesulfonate (113 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10 to 25% Et_2O/hexanes) to yield **302a** (53 mg, 50% yield) as a white solid.

R_f = 0.40 (silica, 30% Et_2O/hexanes, $KMnO_4$).

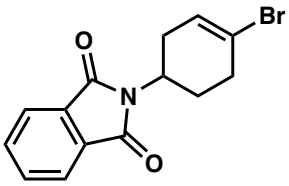
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.81 (tt, *J* = 5.1, 2.4 Hz, 2H), 7.76 – 7.66 (m, 2H), 6.29 (dq, *J* = 5.7, 1.9 Hz, 1H), 4.44 (dqd, *J* = 11.5, 5.5, 3.1 Hz, 1H), 3.06 – 2.92 (m, 1H), 2.82 – 2.61 (m, 3H), 2.19 (dtd, *J* = 16.8, 5.7, 5.0, 3.0 Hz, 1H), 1.78 – 1.66 (m, 1H).

^{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 (302b)



Prepared from 4-(1,3-dioxoisoindolin-2-yl)cyclohex-1-en-1-yl trifluoromethanesulfonate (113 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10 to 25% Et_2O/hexanes) to yield **302b** (65 mg, 71% yield) as a white solid.

$\mathbf{R}_f$ = 0.36 (silica, 30% Et_2O/hexanes, $KMnO_4$).

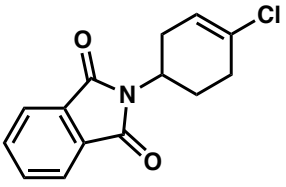
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.86 – 7.78 (m, 2H), 7.75 – 7.67 (m, 2H), 6.01 (dtd, *J* = 5.9, 2.3, 0.9 Hz, 1H), 4.42 (dddd, *J* = 12.6, 11.1, 5.5, 3.2 Hz, 1H), 3.01 – 2.89 (m, 1H), 2.79 – 2.63 (m, 2H), 2.63 – 2.51 (m, 1H), 2.25 – 2.14 (m, 1H), 1.88 – 1.76 (m, 1H).

^{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 (302c)



Prepared from 4-(1,3-dioxoisoindolin-2-yl)cyclohex-1-en-1-yl trifluoromethanesulfonate (113 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10 to 25% Et_2O/hexanes) to yield **302c** (72 mg, 92% yield) as a white solid.

$\mathbf{R}_f$ = 0.36 (silica, 30% Et_2O/hexanes, $KMnO_4$).

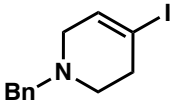
^{1}H NMR (500 MHz, $CDCl_3$): δ 7.85 – 7.79 (m, 2H), 7.74 – 7.68 (m, 2H), 5.80 (dtt, *J* = 5.9, 2.4, 0.7 Hz, 1H), 4.46 – 4.36 (m, 1H), 2.97 (dddt, *J* = 16.6, 11.0, 4.4, 2.3 Hz, 1H), 2.72 (tdd, *J* = 12.5, 11.8, 5.8 Hz, 1H), 2.66 – 2.55 (m, 1H), 2.49 – 2.40 (m, 1H), 2.27 – 2.18 (m, 1H), 1.90 – 1.82 (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 (303a)



Prepared from 1-benzyl-1,2,3,6-tetrahydropyridin-4-yl trifluoromethanesulfonate (96 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield **303a** (62 mg, 69% yield) as a light yellow oil.

$\mathbf{R}_f$ = 0.31 (silica, 10% Et_2O/hexanes, $KMnO_4$).

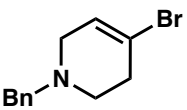
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35 – 7.22 (m, 5H), 6.26 (td, *J* = 3.5, 1.7 Hz, 1H), 3.56 (s, 2H), 3.04 – 3.00 (m, 2H), 2.61 (m, 4H).

^{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 (303b)



Prepared from 1-benzyl-1,2,3,6-tetrahydropyridin-4-yl trifluoromethanesulfonate (96 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 5% to 10 Et_2O/hexanes) to yield **303b** (60 mg, 79% yield) as a light yellow oil.

$\mathbf{R}_f$ = 0.60 (silica, 20% Et_2O/hexanes, $KMnO_4$).

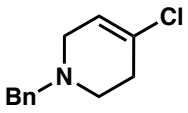
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37 – 7.24 (m, 5H), 5.99 (tt, *J* = 3.5, 1.6 Hz, 1H), 3.59 (s, 2H), 3.01 (dt, *J* = 3.7, 2.8 Hz, 2H), 2.66 (td, *J* = 5.7, 0.6 Hz, 2H), 2.58 – 2.52 (m, 2H).

^{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 (303c)



Prepared from 1-benzyl-1,2,3,6-tetrahydropyridin-4-yl trifluoromethanesulfonate (96 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 5 to 10% Et_2O/hexanes) to yield **303c** (50 mg, 80% yield) as a light yellow oil.

R_f = 0.56 (silica, 20% Et_2O/hexanes, $KMnO_4$).

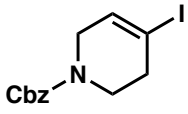
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.36 – 7.25 (m, 5H), 5.76 (tt, *J* = 3.5, 1.6 Hz, 1H), 3.60 (s, 2H), 3.03 (dt, *J* = 3.6, 2.8 Hz, 2H), 2.67 (t, *J* = 5.7 Hz, 2H), 2.43 (ttd, *J* = 5.7, 2.8, 1.5 Hz, 2H).

^{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 (304a)



Prepared from benzyl 4-(((trifluoromethyl)sulfonyl)oxy)-3,6-dihydropyridine-1(2*H*)-carboxylate (110 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield **304a** (61 mg, 60% yield) as a colorless oil.

R_f = 0.25 (silica, 10% EtOAc/hexanes, $KMnO_4$).

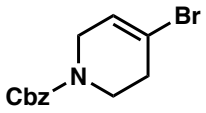
^{1}H NMR (400 MHz, d_3-MeCN, 65 °C): δ 7.61 – 7.11 (m, 5H), 6.38 – 6.30 (m, 1H), 5.13 (s, 2H), 3.97 (q, *J* = 3.0 Hz, 2H), 3.58 (t, *J* = 5.7 Hz, 2H), 2.69 – 2.49 (m, 2H).

^{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 (304b)



Prepared from benzyl 4-(((trifluoromethyl)sulfonyl)oxy)-3,6-dihydropyridine-1(2*H*)-carboxylate (110 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield **304b** (81 mg, 91% yield) as a colorless oil.

R_f = 0.36 (silica, 30% EtOAc/hexanes, $KMnO_4$).

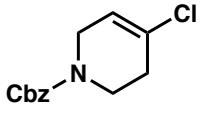
^{1}H NMR (400 MHz, d_3-MeCN, 65 °C): δ 7.38 (m, 4H), 7.33 (m, 1H), 6.06 (tt, *J* = 3.4, 1.7 Hz, 1H), 5.14 (s, 2H), 3.96 (q, *J* = 3.0 Hz, 2H), 3.63 (t, *J* = 5.8 Hz, 2H), 2.53 (ttd, *J* = 5.6, 2.7, 1.6 Hz, 2H).

^{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 (304c)



Prepared from benzyl 4-(((trifluoromethyl)sulfonyl)oxy)-3,6-dihydropyridine-1(2*H*)-carboxylate (110 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield **304c** (65 mg, 86% yield) as a colorless oil.

R_f = 0.36 (silica, 30% EtOAc/hexanes, $KMnO_4$).

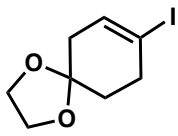
^{1}H NMR (400 MHz, d_3-MeCN, 65 °C): δ 7.41 – 7.36 (m, 4H), 7.36 – 7.31 (m, 1H), 5.84 (tt, *J* = 3.4, 1.6 Hz, 1H), 5.14 (s, 2H), 3.99 (q, *J* = 2.9 Hz, 2H), 3.64 (t, *J* = 5.8 Hz, 2H), 2.41 (ttd, *J* = 5.7, 2.7, 1.5 Hz, 2H).

^{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 (305a)



Prepared from 1,4-dioxaspiro[4.5]dec-7-en-8-yl 1,1,2,2,3,3,4,4,4-nonafluorobutane-1-sulfonate (131.4 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 4. The crude residue was purified by column chromatography (silica, 0.5% triethylamine/10% EtOAc/pentane) to yield **305a** (44 mg, 55% yield) as a colorless oil.

R_f = 0.45 (silica, 10% EtOAc/hexanes, $KMnO_4$).

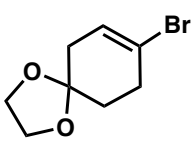
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.18 (tt, *J* = 3.9, 1.7 Hz, 1H), 3.97 (s, 4H), 2.70 (tq, *J* = 6.5, 2.2 Hz, 2H), 2.30 (dddd, *J* = 4.0, 3.3, 2.3, 1.2 Hz, 2H), 1.80 (tt, *J* = 6.5, 0.9 Hz, 2H).

^{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 (305b)



Prepared from 1,4-dioxaspiro[4.5]dec-7-en-8-yl trifluoromethane-sulfonate (86.5 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10% Et_2O/pentane) to yield **305b** (48 mg, 73% yield) as a colorless oil.

R_f = 0.41 (silica, 10% EtOAc/hexanes, $KMnO_4$).

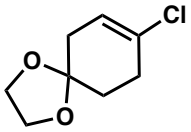
^{1}H NMR (400 MHz, $CDCl_3$): δ 5.90 (tt, *J* = 4.0, 1.6 Hz, 1H), 3.97 (s, 4H), 2.62 (ttd, *J* = 6.5, 2.4, 1.6 Hz, 2H), 2.29 (dtt, *J* = 4.1, 2.4, 0.9 Hz, 2H), 1.84 (tt, *J* = 6.6, 0.9 Hz, 2H).

^{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 (305c)



Prepared from 1,4-dioxaspiro[4.5]dec-7-en-8-yl trifluoromethanesulfonate (**1e**, 86.5 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10% Et_2O/pentane) to yield **305c** (44 mg, 83% yield) as a colorless oil.

$\mathbf{R}_f$ = 0.38 (silica, 10% EtOAc/hexanes, $KMnO_4$).

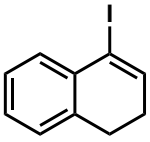
^{1}H NMR (400 MHz, $CDCl_3$): δ 5.69 (tt, *J* = 4.1, 1.6 Hz, 1H), 3.98 (s, 4H), 2.51 (tq, *J* = 6.5, 2.0 Hz, 2H), 2.36 – 2.29 (m, 2H), 1.91 – 1.81 (m, 2H).

^{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 (306a)



Prepared from 3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (93.5 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **306a** (38 mg, 49% yield) as a colorless oil.

$\mathbf{R}_f$ = 0.65 (silica, hexanes, UV).

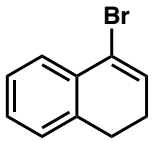
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43 (dd, *J* = 7.5, 1.3 Hz, 1H), 7.27 – 7.20 (m, 1H), 7.17 (td, *J* = 7.4, 1.4 Hz, 1H), 7.05 – 7.00 (m, 1H), 6.83 (t, *J* = 4.8 Hz, 1H), 2.85 (t, *J* = 8.0 Hz, 2H), 2.36 (ddd, *J* = 9.1, 7.4, 4.9 Hz, 2H).

^{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 (306b)



Prepared from 3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (93.5 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **306b** (48 mg, 77% yield) as a colorless oil.

R_f = 0.62 (silica, hexanes, UV).

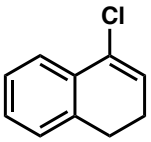
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.57 (dd, *J* = 7.5, 1.4 Hz, 1H), 7.26 (td, *J* = 7.6, 1.5 Hz, 1H), 7.21 (td, *J* = 7.4, 1.5 Hz, 1H), 7.11 (dq, *J* = 7.8, 1.2 Hz, 1H), 6.46 (t, *J* = 4.8 Hz, 1H), 2.85 (t, *J* = 8.1 Hz, 2H), 2.38 (ddd, *J* = 9.1, 7.4, 4.9 Hz, 2H).

^{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 (306c)



Prepared from 3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (93.5 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **306c** (39 mg, 80% yield) as a colorless oil.

R_f = 0.56 (silica, hexanes, $KMnO_4$).

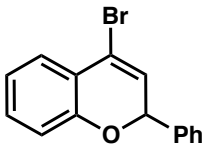
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.57 (dd, *J* = 7.5, 1.5 Hz, 1H), 7.28 – 7.23 (m, 1H), 7.21 (td, *J* = 7.4, 1.6 Hz, 1H), 7.16 – 7.11 (m, 1H), 6.18 (t, *J* = 4.8 Hz, 1H), 2.84 (t, *J* = 8.0 Hz, 2H), 2.40 (ddd, *J* = 9.1, 7.5, 4.8 Hz, 2H).

^{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 (307b)



Prepared from 2-phenyl-2*H*-chromen-4-yl trifluoromethanesulfonate (107 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10% PhMe/hexanes) to yield **307b** (65 mg, 75% yield) as a yellow oil. *Note: This compound decomposes readily at room temperature.*

R_f = 0.69 (silica, 10% Et_2O/hexanes, $KMnO_4$).

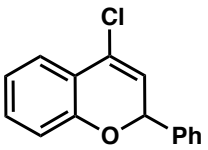
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.46 (ddd, *J* = 7.7, 2.6, 1.5 Hz, 3H), 7.43 – 7.33 (m, 3H), 7.23 – 7.17 (m, 1H), 6.97 (td, *J* = 7.6, 1.2 Hz, 1H), 6.81 (dd, *J* = 8.1, 1.2 Hz, 1H), 6.21 (d, *J* = 3.7 Hz, 1H), 5.91 (d, *J* = 3.7 Hz, 1H).

^{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 (307c)



Prepared from 2-phenyl-2*H*-chromen-4-yl trifluoromethanesulfonate (107 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10% PhMe/hexanes) to yield **307c** (48 mg, 66% yield) as a colorless oil. *Note: This compound decomposes readily at room temperature.*

R_f = 0.68 (silica, 10% Et_2O/hexanes, $KMnO_4$).

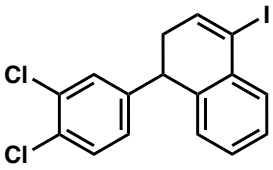
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.52 – 7.47 (m, 1H), 7.47 – 7.43 (m, 2H), 7.42 – 7.35 (m, 3H), 7.21 (ddd, *J* = 8.1, 7.4, 1.6 Hz, 1H), 6.98 (td, *J* = 7.6, 1.2 Hz, 1H), 6.84 (dd, *J* = 8.1, 1.1 Hz, 1H), 5.97 (s, 2H).

^{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 (308a)



Prepared from 4-(3,4-dichlorophenyl)-3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (127.0 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **308a** (63 mg, 52% yield) as a white solid.

R_f = 0.44 (silica, hexanes, UV).

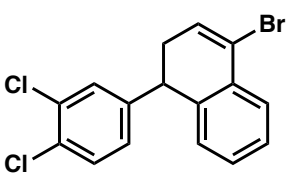
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.54 (dd, *J* = 7.8, 1.2 Hz, 1H), 7.37 (d, *J* = 8.3 Hz, 1H), 7.33 – 7.26 (m, 2H), 7.17 (td, *J* = 7.5, 1.3 Hz, 1H), 6.98 (ddd, *J* = 8.3, 2.2, 0.5 Hz, 1H), 6.77 – 6.72 (m, 2H), 4.16 – 4.09 (m, 1H), 2.70 (ddd, *J* = 16.8, 7.0, 4.9 Hz, 1H), 2.59 (ddd, *J* = 16.8, 8.9, 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 (308b)



Prepared from 4-(3,4-dichlorophenyl)-3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (127.0 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure

2. The crude residue was purified by column chromatography (silica, pentane) to yield **308b** (83 mg, 78% yield) as a white solid.

R_f = 0.35 (silica, hexanes, $KMnO_4$).

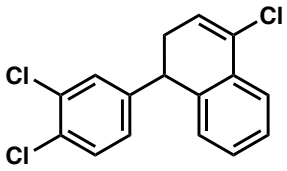
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.67 (dd, *J* = 7.7, 1.3 Hz, 1H), 7.37 (d, *J* = 8.3 Hz, 1H), 7.31 (tdd, *J* = 7.7, 1.3, 0.6 Hz, 1H), 7.28 (d, *J* = 2.1 Hz, 1H), 7.20 (td, *J* = 7.5, 1.3 Hz, 1H), 7.00 (ddd, *J* = 8.3, 2.2, 0.5 Hz, 1H), 6.81 (dt, *J* = 7.4, 1.2 Hz, 1H), 6.38 (t, *J* = 4.8 Hz, 1H), 4.18 – 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 (308c)



Prepared from 4-(3,4-dichlorophenyl)-3,4-dihydronaphthalen-1-yl trifluoromethanesulfonate (127.0 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **308c** (69 mg, 75% yield) as a white solid.

R_f = 0.55 (silica, hexanes, UV).

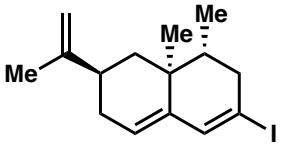
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.70 (dd, *J* = 7.7, 1.3 Hz, 1H), 7.38 (d, *J* = 8.3 Hz, 1H), 7.33 (tdd, *J* = 7.7, 1.4, 0.6 Hz, 1H), 7.30 – 7.28 (m, 1H), 7.22 (td, *J* = 7.5, 1.4 Hz, 1H), 7.01 (ddd, *J* = 8.3, 2.2, 0.5 Hz, 1H), 6.85 (dt, *J* = 7.6, 1.2 Hz, 1H), 6.13 (t, *J* = 4.8 Hz, 1H), 4.17 – 4.09 (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 (309a)



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 (150 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 4. The crude residue was purified by column chromatography (silica, pentane) to yield **309a** (54 mg, 54% yield) as a colorless oil.

R_f = 0.63 (silica, hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = –155° (c = 1.0, $CHCl_3$).

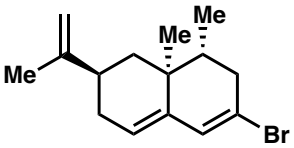
^{1}H NMR (500 MHz, $CDCl_3$): δ 6.58 (d, *J* = 2.4 Hz, 1H), 5.41 (dd, *J* = 5.4, 2.8 Hz, 1H), 4.80 – 4.70 (m, 2H), 2.54 (dd, *J* = 18.4, 5.2 Hz, 1H), 2.40 (dddd, *J* = 16.9, 8.5, 4.3, 2.4 Hz, 2H), 2.23 (dddd, *J* = 20.0, 6.8, 5.1, 2.3 Hz, 1H), 2.01 – 1.85 (m, 1H), 1.79 – 1.65 (m, 5H), 1.20 – 1.11 (m, 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 (309b)



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 (105.1 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **309b** (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.*

R_f = 0.57 (silica, hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = –172° (c = 1.0, $CHCl_3$).

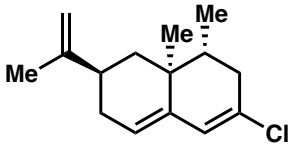
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.30 (d, *J* = 2.3 Hz, 1H), 5.45 (dd, *J* = 5.3, 2.8 Hz, 1H), 4.79 – 4.71 (m, 2H), 2.48 – 2.29 (m, 3H), 2.22 (dt, *J* = 18.6, 5.3 Hz, 1H), 1.99 – 1.87 (m, 1H), 1.75 (t, *J* = 1.1 Hz, 3H), 1.74 – 1.67 (m, 2H), 1.21 – 1.10 (m, 1H), 0.92 (d, *J* = 0.7 Hz, 3H), 0.90 (d, *J* = 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 (309c)



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 (105.1 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **309c** (60 mg, 85% yield) as a colorless oil. *Note: This compound decomposes readily at room temperature.*

R_f = 0.63 (silica, hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = –165° (c = 1.0, $CHCl_3$).

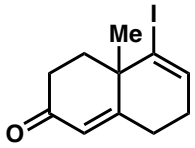
^{1}H NMR (500 MHz, $CDCl_3$): δ 6.09 (dt, *J* = 1.7, 0.9 Hz, 1H), 5.44 (ddd, *J* = 5.2, 2.1, 0.8 Hz, 1H), 4.75 (p, *J* = 1.1 Hz, 2H), 2.47 – 2.37 (m, 1H), 2.29 – 2.21 (m, 3H), 2.00 – 1.92 (m, 1H), 1.76 (t, *J* = 1.2 Hz, 3H), 1.75 – 1.71 (m, 1H), 1.71 (s, 1H), 1.17 (td, *J* = 12.7, 0.8 Hz, 1H), 0.93 – 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 (310a)



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 (138 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 4. The crude residue was purified by column chromatography (silica, 5-10% Et_2O/hexanes) to yield **310a** (46 mg, 53% yield) as a colorless oil.

R_f = 0.24 (silica, 10% Et_2O/hexanes, $KMnO_4$).

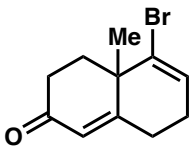
^{1}H NMR (500 MHz, $CDCl_3$): δ 6.68 (dt, *J* = 2.6, 0.8 Hz, 1H), 5.66 – 5.58 (m, 1H), 2.76 (ddd, *J* = 15.5, 7.3, 5.9 Hz, 1H), 2.72 (s, 2H), 2.63 – 2.53 (m, 1H), 2.49 – 2.40 (m, 1H), 2.36 (ddd, *J* = 15.5, 7.3, 6.7 Hz, 1H), 1.87 – 1.80 (m, 1H), 1.71 (dddd, *J* = 13.5, 11.5, 6.5, 0.8 Hz, 1H), 1.22 (d, *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 (310b)



Prepared from 8a-methyl-6-oxo-3,4,6,7,8,8a-hexahydronaphthalen-1-yl trifluoromethanesulfonate (93.1 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 5% Et_2O/hexanes) to yield **310b** (56 mg, 78% yield) as a colorless oil. *Note: This compound decomposes readily at room temperature.*

R_f = 0.24 (silica, 10% Et_2O/hexanes, $KMnO_4$).

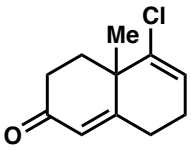
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.43 – 6.38 (m, 1H), 5.70 – 5.63 (m, 1H), 2.81 – 2.73 (m, 1H), 2.73 (s, 3H), 2.54 – 2.40 (m, 1H), 2.40 – 2.32 (m, 1H), 1.99 – 1.90 (m, 1H), 1.68 (dddd, *J* = 13.6, 12.2, 6.0, 0.7 Hz, 1H), 1.22 (d, *J* = 0.7 Hz, 3H).

^{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 (310c)



Prepared from 8a-methyl-6-oxo-3,4,6,7,8,8a-hexahydronaphthalen-1-yl trifluoromethanesulfonate (93.1 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 5% Et_2O/hexanes) to yield **310c** (53 mg, 90% yield) as a colorless oil. *Note: This compound decomposes readily at room temperature.*

R_f = 0.13 (silica, 10% EtOAc/hexanes, $KMnO_4$).

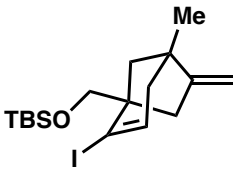
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.19 (dt, *J* = 2.4, 0.7 Hz, 1H), 5.68 – 5.63 (m, 1H), 2.77 (ddd, *J* = 15.4, 7.3, 5.9 Hz, 1H), 2.68 – 2.52 (m, 2H), 2.52 – 2.45 (m, 1H), 2.45 – 2.32 (m, 2H), 1.98 (dddd, *J* = 13.6, 5.7, 1.7, 0.6 Hz, 1H), 1.72 – 1.63 (m, 1H), 1.22 (d, *J* = 0.7 Hz, 3H).

^{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 (311a)**



Prepared from (1*r*,5*r*)-1-(((*tert*-butyldimethylsilyl)oxy)methyl)-5-methyl-6-methylenebicyclo[3.2.1]oct-2-en-2-yl trifluoromethanesulfonate (128 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **311a** (101 mg, 83% yield) as a colorless oil.

R_f = 0.60 (silica, hexanes, $KMnO_4$).

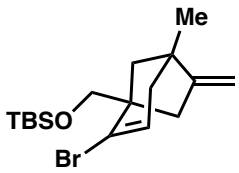
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.23 (dd, *J* = 4.8, 2.5 Hz, 1H), 4.90 (td, *J* = 1.8, 0.9 Hz, 1H), 4.88 (dd, *J* = 2.9, 1.9 Hz, 1H), 3.70 (d, *J* = 9.9 Hz, 1H), 3.49 (d, *J* = 9.9 Hz, 1H), 2.41 – 2.23 (m, 3H), 1.94 – 1.77 (m, 3H), 1.17 (s, 3H), 0.91 (s, 9H), 0.08 (s, 3H), 0.07 (s, 3H).

^{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 (311b)**



Prepared from (1*r*,5*r*)-1-(((*tert*-butyldimethylsilyl)oxy)methyl)-5-methyl-6-methylenebicyclo[3.2.1]oct-2-en-2-yl trifluoromethanesulfonate (36 mg, 0.1 mmol) and lithium bromide (13.0 mg, 0.15 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **311b** (28 mg, 78% yield) as a colorless oil.

R_f = 0.58 (silica, hexanes, $KMnO_4$).

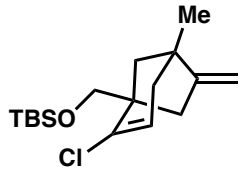
^{1}H NMR (500 MHz, $CDCl_3$): δ 5.86 (dd, *J* = 4.9, 2.5 Hz, 1H), 4.91 (t, *J* = 2.1 Hz, 1H), 4.89 – 4.86 (m, 1H), 3.82 (d, *J* = 9.9 Hz, 1H), 3.57 (d, *J* = 9.9 Hz, 1H), 2.50 – 2.43 (m, 1H), 2.42 – 2.36 (m, 1H), 2.24 (dd, *J* = 16.9, 2.5 Hz, 1H), 1.94 – 1.87 (m, 1H), 1.82 (d, *J* = 1.5 Hz, 2H), 1.19 (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 (311c)**



Prepared from (1*r*,5*r*)-1-(((*tert*-butyldimethylsilyl)oxy)methyl)-5-methyl-6-methylenebicyclo[3.2.1]oct-2-en-2-yl trifluoromethanesulfonate (36 mg, 0.1 mmol) and lithium chloride (6.4 mg, 0.15

mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **311c** (27 mg, 82% yield) as a colorless oil.

R_f = 0.56 (silica, hexanes, $KMnO_4$).

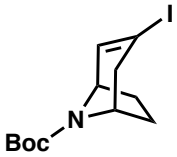
^{1}H NMR (400 MHz, $CDCl_3$): δ 5.61 (dd, *J* = 4.8, 2.5 Hz, 1H), 4.89 (ddd, *J* = 7.2, 2.7, 1.8 Hz, 2H), 3.88 (d, *J* = 9.9 Hz, 1H), 3.59 (d, *J* = 9.9 Hz, 1H), 2.54 – 2.38 (m, 2H), 2.26 (dd, *J* = 16.9, 2.6 Hz, 1H), 1.97 – 1.88 (m, 1H), 1.84 – 1.73 (m, 2H), 1.20 (s, 3H), 0.90 (s, 9H), 0.06 (s, 3H), 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 (312a)**



Prepared from *tert*-butyl (1*r*,5*s*)-3-(((perfluorobutyl)sulfonyl)oxy)-8-azabicyclo[3.2.1]oct-2-ene-8-carboxylate (152 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 4. The crude residue was purified by column chromatography (silica, 10% acetone/hexanes) to yield **312a** (53 mg, 53% yield) as a colorless oil.

R_f = 0.55 (silica, 30% Et_2O/hexanes, $KMnO_4$).

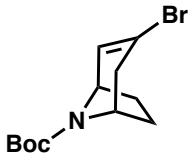
^{1}H NMR (400 MHz, d_3-MeCN, 65 °C): δ 6.70 – 6.65 (m, 1H), 4.23 (t, *J* = 5.6 Hz, 1H), 4.17 – 4.11 (m, 1H), 3.16 – 3.06 (m, 1H), 2.31 (dt, *J* = 17.5, 1.4 Hz, 1H), 2.26 – 2.12 (m, 1H), 1.98 – 1.81 (m, 2H), 1.76 (ddt, *J* = 15.6, 9.8, 3.8 Hz, 1H), 1.44 (d, *J* = 0.6 Hz, 9H).

^{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 (312b)**



Prepared from *tert*-butyl (1*r*,5*s*)-3-(((trifluoromethyl)sulfonyl)oxy)-8-azabicyclo[3.2.1]oct-2-ene-8-carboxylate (107 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10 to 20% Et_2O/hexanes) to yield **312b** (56 mg, 65% yield) as a colorless oil.

R_f = 0.55 (silica, 30% Et_2O/hexanes, $KMnO_4$).

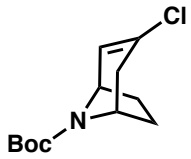
^{1}H NMR (400 MHz, d_3-MeCN, 65 °C): δ 6.38 (ddd, *J* = 5.5, 2.0, 1.4 Hz, 1H), 4.32 (td, *J* = 5.5, 1.2 Hz, 1H), 4.29 – 4.22 (m, 1H), 3.06 (ddt, *J* = 17.3, 4.3, 2.0 Hz, 1H), 2.26 – 2.13 (m, 2H), 1.99 – 1.85 (m, 2H), 1.74 (dddd, *J* = 12.9, 9.6, 6.7, 1.2 Hz, 1H), 1.45 (s, 9H).

^{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 (312c)**



Prepared from *tert*-butyl (1*r*,5*s*)-3-(((trifluoromethyl)sulfonyl)oxy)-8-azabicyclo[3.2.1]oct-2-ene-8-carboxylate (107 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10 to 20% Et_2O/hexanes) to yield **312c** (61 mg, 84% yield) as a colorless oil.

R_f = 0.55 (silica, 30% Et_2O/hexanes, $KMnO_4$).

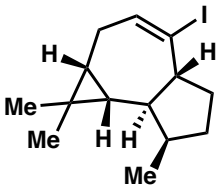
^{1}H NMR (400 MHz, d_3-MeCN, 65 °C): δ 6.16 (ddd, *J* = 5.6, 2.0, 1.3 Hz, 1H), 4.47 – 4.35 (m, 1H), 4.35 – 4.28 (m, 1H), 2.96 (ddt, *J* = 17.2, 3.9, 1.8 Hz, 1H), 2.26 – 2.14 (m, 1H), 2.09 (dt, *J* = 17.3, 1.4 Hz, 1H), 1.99 – 1.89 (m, 2H), 1.79 – 1.67 (m, 1H), 1.46 (s, 9H).

^{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.

(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 (313a)



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 (101.5 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **313a** (48 mg, 75% yield) as a colorless oil.

$\mathbf{R}_f$ = 0.72 (silica, hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = –184° (c = 1.0, $CHCl_3$).

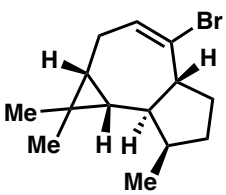
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.43 (ddd, *J* = 8.8, 3.6, 2.2 Hz, 1H), 2.77 (tdd, *J* = 11.3, 7.4, 3.3 Hz, 1H), 2.37 – 2.22 (m, 1H), 2.18 – 2.02 (m, 3H), 1.89 (dddd, *J* = 13.0, 9.8, 8.2, 3.1 Hz, 1H), 1.77 (td, *J* = 11.6, 8.4 Hz, 1H), 1.44 (dddd, *J* = 12.5, 11.4, 9.8, 8.8 Hz, 1H), 1.16 (dtd, *J* = 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 (313b)



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 (101.5 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **313b** (73 mg, 88% yield) as a colorless oil.

R_f = 0.68 (silica, hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = –152° (c = 1.0, $CHCl_3$).

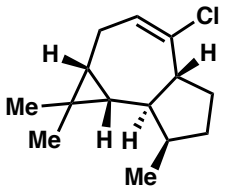
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.10 (ddd, *J* = 9.3, 3.3, 2.1 Hz, 1H), 2.77 (dddd, *J* = 18.2, 9.2, 3.7, 2.1 Hz, 1H), 2.29 – 2.10 (m, 3H), 2.04 – 1.85 (m, 2H), 1.76 (td, *J* = 11.7, 8.3 Hz, 1H), 1.46 (dddd, *J* = 12.6, 11.4, 9.8, 8.8 Hz, 1H), 1.18 (dtd, *J* = 13.1, 8.6, 4.3 Hz, 1H), 1.03 (d, *J* = 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 (313c)



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 (101.5 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **313c** (40 mg, 88% yield) as a colorless oil.

R_f = 0.78 (silica, hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = –174° (c = 1.0, $CHCl_3$).

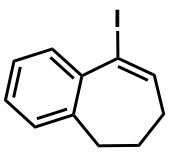
^{1}H NMR (400 MHz, $CDCl_3$): δ 5.84 (ddd, *J* = 9.3, 3.3, 2.1 Hz, 1H), 2.68 (dddd, *J* = 18.1, 9.2, 3.8, 2.1 Hz, 1H), 2.26 – 2.09 (m, 3H), 2.01 (ddt, *J* = 16.8, 10.4, 3.6 Hz, 1H), 1.90 (dddd, *J* = 13.1, 9.9, 8.2, 3.1 Hz, 1H), 1.75 (td, *J* = 11.7, 8.3 Hz, 1H), 1.44 (dddd, *J* = 12.6, 11.3, 9.8, 8.8 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 (314a)



Prepared from 6,7-dihydro-5*H*-benzo[7]annulen-9-yl trifluoromethanesulfonate (87.7 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, hexanes) to yield **314a** (65 mg, 80% yield) as a light yellow oil.

$\mathbf{R_f}$ = 0.66 (silica, hexanes, $KMnO_4$).

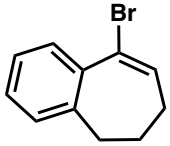
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.49 (dd, *J* = 7.7, 1.3 Hz, 1H), 7.31 – 7.25 (m, 1H), 7.18 (td, *J* = 7.4, 1.4 Hz, 1H), 7.12 (dd, *J* = 7.6, 1.4 Hz, 1H), 6.95 (t, *J* = 7.5 Hz, 1H), 2.66 (t, *J* = 7.0 Hz, 2H), 2.14 (p, *J* = 7.1 Hz, 2H), 1.83 (q, *J* = 7.3 Hz, 2H).

^{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 (314b)



Prepared from 6,7-dihydro-5*H*-benzo[7]annulen-9-yl trifluoromethanesulfonate (87.7 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, hexanes) to yield **314b** (49 mg, 73% yield) as a light yellow oil.

$\mathbf{R_f}$ = 0.51 (silica, hexanes, $KMnO_4$).

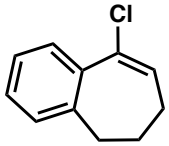
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.58 (dd, *J* = 7.7, 1.4 Hz, 1H), 7.30 (td, *J* = 7.5, 1.6 Hz, 1H), 7.25 – 7.15 (m, 2H), 6.64 (t, *J* = 7.4 Hz, 1H), 2.68 (t, *J* = 6.9 Hz, 2H), 2.14 (p, *J* = 7.1 Hz, 2H), 1.92 (q, *J* = 7.0 Hz, 2H).

^{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 (314c)



Prepared from 6,7-dihydro-5*H*-benzo[7]annulen-9-yl trifluoromethanesulfonate (87.7 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, hexanes) to yield **314c** (38 mg, 71% yield) as a light yellow oil.

R_f = 0.54 (silica, hexanes, $KMnO_4$).

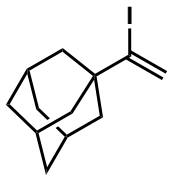
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.60 (dd, *J* = 7.6, 1.5 Hz, 1H), 7.30 (td, *J* = 7.5, 1.7 Hz, 1H), 7.27 – 7.22 (m, 1H), 7.20 (dd, *J* = 7.5, 1.6 Hz, 1H), 6.40 (t, *J* = 7.1 Hz, 1H), 2.69 (t, *J* = 6.7 Hz, 2H), 2.17 – 2.09 (m, 2H), 1.99 (qd, *J* = 7.1, 0.9 Hz, 2H).

^{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.

(3*r*,5*r*,7*r*)-1-(1-iodovinyl)adamantane (315a)



Prepared from 1-((3*r*,5*r*,7*r*)-adamantan-1-yl)vinyl trifluoromethanesulfonate (93.0 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **315a** (72 mg, 84% yield) as a colorless oil.

R_f = 0.74 (silica, hexanes, $KMnO_4$).

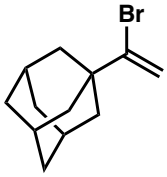
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.08 (d, *J* = 2.1 Hz, 1H), 5.80 (d, *J* = 2.1 Hz, 1H), 2.04 – 1.95 (m, 3H), 1.76 – 1.71 (m, 6H), 1.71 – 1.59 (m, 6H).

^{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 (315b)



Prepared from 1-((3*r*,5*r*,7*r*)-adamantan-1-yl)vinyl trifluoromethanesulfonate (125 mg, 0.4 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **315b** (76 mg, 78% yield) as a colorless oil.

R_f = 0.81 (silica, hexanes, $KMnO_4$).

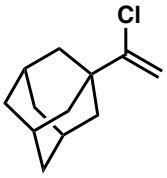
^{1}H NMR (400 MHz, $CDCl_3$): δ 5.56 (d, *J* = 2.0 Hz, 1H), 5.42 (d, *J* = 2.0 Hz, 1H), 2.03 (q, *J* = 3.2 Hz, 3H), 1.82 – 1.76 (m, 6H), 1.74 – 1.61 (m, 6H).

^{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 (315c)



Prepared from 1-((3*r*,5*r*,7*r*)-adamantan-1-yl)vinyl trifluoromethanesulfonate (93.0 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **315c** (46 mg, 77% yield) as a colorless oil.

R_f = 0.84 (silica, hexanes, $KMnO_4$).

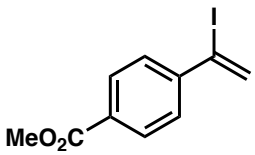
^{1}H NMR (400 MHz, $CDCl_3$): δ 5.13 (d, *J* = 1.5 Hz, 1H), 5.09 (d, *J* = 1.5 Hz, 1H), 2.04 (q, *J* = 3.2 Hz, 3H), 1.79 (d, *J* = 3.0 Hz, 6H), 1.76 – 1.62 (m, 6H).

^{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.

methyl 4-(1-iodovinyl)benzoate (316a)



Prepared from methyl 4-(1-(((trifluoromethyl)sulfonyl) oxy)vinyl)benzoate (93.1 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 5 to 20% Et_2O/hexanes) to yield **316a** (56 mg, 64% yield) as a white solid. *Note: This compound slowly oxidizes to the α-iodo acetophenone under ambient conditions.*

R_f = 0.25 (silica, 10% Et_2O/hexanes, UV).

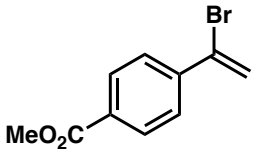
^{1}H NMR (500 MHz, $CDCl_3$): δ 7.99 – 7.95 (m, 2H), 7.59 – 7.54 (m, 2H), 6.56 (d, *J* = 1.9 Hz, 1H), 6.17 (d, *J* = 1.9 Hz, 1H), 3.92 (s, 3H).

^{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 (316b)



Prepared from methyl 4-(1-(((trifluoromethyl)sulfonyl) oxy)vinyl)benzoate (93.1 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 1 to 2% Et_2O/hexanes) to yield **316b** (69 mg, 90% yield) as a white solid. *Note: This compound slowly oxidizes to the α-bromo acetophenone under ambient conditions.*

R_f = 0.47 (silica, 10% EtOAc/hexanes, $KMnO_4$).

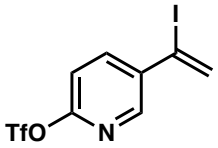
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.03 – 7.98 (m, 2H), 7.68 – 7.62 (m, 2H), 6.22 (d, *J* = 2.2 Hz, 1H), 5.88 (d, *J* = 2.2 Hz, 1H), 3.92 (s, 3H).

^{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 (317a)



Prepared from 1-(6-(((trifluoromethyl)sulfonyl)oxy)pyridin-3-yl)vinyl trifluoromethanesulfonate (120 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield **317a** (62 mg, 54% yield) as a colorless oil. *Note: This compound slowly oxidizes to the α-iodo acetophenone under ambient conditions.*

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).

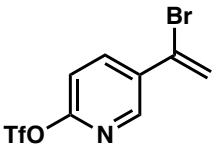
^{13}C NMR (101 MHz, $CDCl_3$): δ 155.6, 147.0, 141.0, 138.6, 130.9, 118.7 (q, $J_{C\text{-}F}$ = 320.6 Hz), 114.6, 99.3.

^{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 (317b)



Prepared from 1-(6-(((trifluoromethyl)sulfonyl)oxy)pyridin-3-yl)vinyl trifluoromethanesulfonate (120 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 10% Et_2O/hexanes) to yield **317b** (80 mg, 80% yield) as a colorless oil. *Note: This compound slowly oxidizes to the α-bromo acetophenone under ambient conditions.*

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).

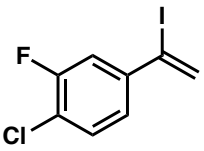
^{13}C NMR (126 MHz, $CDCl_3$): δ 155.8, 146.9, 140.1, 135.5, 124.9, 121.3, 118.7 (q, $J_{C\text{-}F}$ = 320.7 Hz), 114.7.

^{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 (318a)



Prepared from 1-(4-chloro-3-fluorophenyl)vinyl trifluoromethanesulfonate (91.4 mg, 0.3 mmol) and sodium iodide (67.5 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **318a** (58 mg, 69% yield) as a yellow oil. *Note: This compound slowly oxidizes to the α-iodo acetophenone derivative under ambient conditions.*

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).

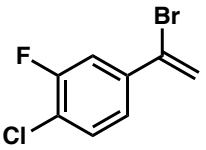
^{13}C NMR (101 MHz, $CDCl_3$): δ 157.5 (d, $J_{C\text{-}F}$ = 249.4 Hz), 142.3 (d, $J_{C\text{-}F}$ = 6.9 Hz), 130.3, 128.9, 124.4 (d, $J_{C\text{-}F}$ = 3.5 Hz), 121.6 (d, $J_{C\text{-}F}$ = 17.9 Hz), 116.5 (d, $J_{C\text{-}F}$ = 22.8 Hz), 104.0 (d, $J_{C\text{-}F}$ = 2.2 Hz).

^{19}F NMR (282 MHz, $CDCl_3$): δ -114.9 (dd, $J_{F\text{-}H}$ = 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 (318b)



Prepared from 1-(4-chloro-3-fluorophenyl)vinyl trifluoromethanesulfonate (91.4 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **318b** (52 mg, 73% yield) as a yellow oil. *Note: This compound slowly oxidizes to the α-bromo acetophenone derivative under ambient conditions.*

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).

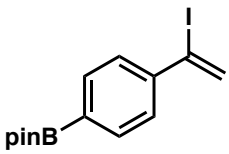
^{13}C NMR (126 MHz, $CDCl_3$): δ 157.6 (d, $J_{C\text{-}F}$ = 249.1 Hz), 139.0 (d, $J_{C\text{-}F}$ = 7.2 Hz), 130.3, 128.2 (d, $J_{C\text{-}F}$ = 2.3 Hz), 123.5 (d, $J_{C\text{-}F}$ = 3.8 Hz), 121.7 (d, $J_{C\text{-}F}$ = 18.0 Hz), 119.2, 115.7 (d, $J_{C\text{-}F}$ = 23.0 Hz).

^{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 (319a)



Prepared from 1-(4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)vinyl trifluoromethanesulfonate (113.5 mg, 0.3 mmol) and sodium iodide (68 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 0 to 5% Et_2O/hexanes) to yield **319a** (72 mg, 68% yield) as a light yellow oil.

R_f = 0.53 (silica, 10% EtOAc/hexanes, $KMnO_4$).

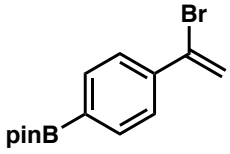
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.77 – 7.72 (m, 2H), 7.53 – 7.48 (m, 2H), 6.51 (d, J = 1.8 Hz, 1H), 6.11 (d, J = 1.7 Hz, 1H), 1.34 (s, 12H).

^{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 (319b)



Prepared from 1-(4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)vinyl trifluoromethanesulfonate (113.5 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General

Procedure 2. The crude residue was purified by column chromatography (silica, 0 to 5% Et_2O/hexanes) to yield **319b** (59 mg, 64% yield) as a light yellow oil which crystallized upon standing in the freezer.

R_f = 0.48 (silica, 10% Et_2O/hexanes, $KMnO_4$).

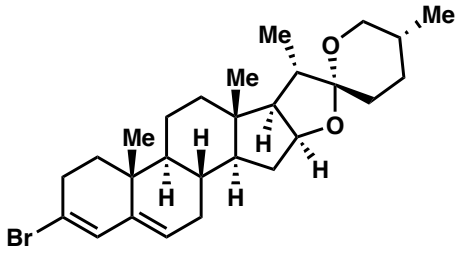
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.81 – 7.76 (m, 2H), 7.62 – 7.56 (m, 2H), 6.17 (d, *J* = 2.0 Hz, 1H), 5.81 (d, *J* = 2.0 Hz, 1H), 1.35 (s, 12H).

^{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.

(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[naphtho[2',1':4,5]indeno[2,1-*b*]furan-10,2'-pyran] (320b)



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[naphtho-[2',1':4,5]indeno[2,1-*b*]furan-10,2'-pyran]-4-yl trifluoromethanesulfonate (163.4 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 40% Et_2O/hexanes) to yield **320b** (107 mg, 75% yield) as a white solid.

R_f = 0.56 (silica, 10% Et_2O/hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = –176° (c = 1.0, $CHCl_3$).

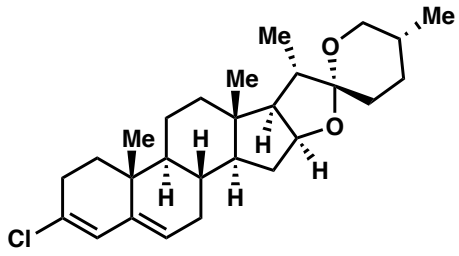
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.26 (d, *J* = 2.3 Hz, 1H), 5.39 (dd, *J* = 5.1, 2.9 Hz, 1H), 4.41 (ddd, *J* = 8.6, 7.5, 6.3 Hz, 1H), 3.47 (ddd, *J* = 10.9, 4.6, 2.0 Hz, 1H), 3.36 (t, *J* = 10.8 Hz, 1H), 2.67 – 2.53 (m, 1H), 2.46 (ddd, *J* = 18.4, 5.9, 1.6 Hz, 1H), 2.17 (dt, *J* = 18.7, 5.3 Hz, 1H), 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[naphtho[2',1':4,5]indeno[2,1-*b*]furan-10,2'-pyran] (320c)



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[naphtho[2',1':4,5]indeno[2,1-*b*]furan-10,2'-pyran]-4-yl trifluoromethanesulfonate (163.4 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 40% Et_2O/hexanes) to yield **320c** (125 mg, 97% yield) as a white solid.

R_f = 0.57 (silica, 10% EtOAc/hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = –183° (c = 1.0, $CHCl_3$).

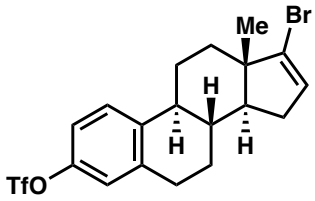
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.05 (d, *J* = 2.3 Hz, 1H), 5.38 (dd, *J* = 5.0, 2.9 Hz, 1H), 4.41 (ddd, *J* = 8.6, 7.6, 6.4 Hz, 1H), 3.47 (ddd, *J* = 10.9, 4.5, 2.0 Hz, 1H), 3.37 (t, *J* = 10.9 Hz, 1H), 2.50 (ddd, *J* = 17.8, 12.0, 5.8 Hz, 1H), 2.31 (ddd, *J* = 18.3, 5.9, 1.5 Hz, 1H), 2.19 (dt, *J* = 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 (321b)



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) (160.3 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 5% to 15% PhMe/hexanes) to yield **321b** (82 mg, 59% yield) as a colorless, tacky oil.

R_f = 0.38 (silica, 10% PhMe/hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = 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).

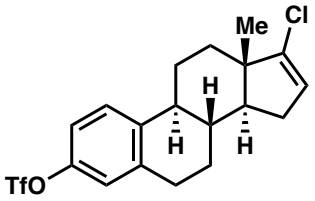
^{13}C NMR (101 MHz, $CDCl_3$): δ 147.7, 140.8, 139.5, 135.6, 129.1, 127.0, 121.3, 118.9 (q, $J_{C\text{-}F}$ = 320.7 Hz), 118.3, 54.9, 48.9, 44.4, 37.0, 34.6, 31.7, 29.5, 27.0, 26.2, 15.3.

^{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 (321c)



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) (160.3 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, 1.5% EtOAc/hexanes) to yield **321c** (109 mg, 83% yield) as a colorless, tacky oil.

R_f = 0.67 (silica, 10% EtOAc/hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = +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).

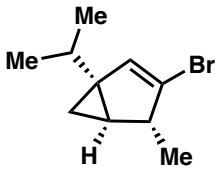
^{13}C NMR (101 MHz, $CDCl_3$): δ 147.7, 144.7, 140.9, 139.5, 127.0, 124.7, 121.3, 118.9 (q, $J_{C\text{-}F}$ = 320.7 Hz), 118.3, 55.1, 47.9, 44.5, 36.9, 33.8, 30.5, 29.5, 26.9, 26.1, 15.2.

^{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 (322b)



Prepared from (1*S*,4*R*,5*R*)-1-isopropyl-4-methylbicyclo[3.1.0]hex-2-en-3-yl trifluoromethanesulfonate (85.3 mg, 0.3 mmol) and lithium bromide (39.1 mg, 0.45 mmol) according to General Procedure 2 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 **322b** (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.

R_f = 0.88 (silica, hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = –13° (c = 0.5, $CHCl_3$).

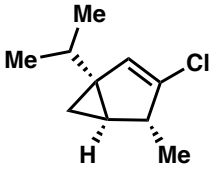
^{1}H NMR (500 MHz, $CDCl_3$): δ 5.93 (t, *J* = 1.3 Hz, 1H), 2.59 – 2.52 (m, 1H), 1.38 (p, *J* = 6.9 Hz, 1H), 1.15 – 1.11 (m, 4H), 0.99 (d, *J* = 6.8 Hz, 3H), 0.89 (d, *J* = 6.8 Hz, 3H), 0.81 – 0.78 (m, 1H), 0.28 (t, *J* = 4.2 Hz, 1H).

^{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 (322c)



Prepared from (1*S*,4*R*,5*R*)-1-isopropyl-4-methylbicyclo[3.1.0]hex-2-en-3-yl trifluoromethanesulfonate (85.3 mg, 0.3 mmol) and lithium chloride (19.1 mg, 0.45 mmol) according to General Procedure 2. The crude residue was purified by column chromatography (silica, pentane) to yield **322c** (40 mg, 78% yield) as a colorless oil.

R_f = 0.85 (silica, hexanes, $KMnO_4$).

$[\alpha]_D^{25}$ = +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).

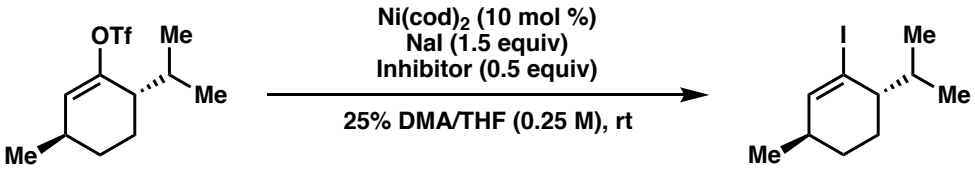
^{13}C NMR (101 MHz, $CDCl_3$): δ 134.6, 129.4, 46.8, 39.5, 31.1, 26.1, 21.6, 20.9, 20.8, 20.2.

FTIR (NaCl, thin film, cm^{-1}): 2956, 2924, 2854, 1458, 1364, 1057, 1026.

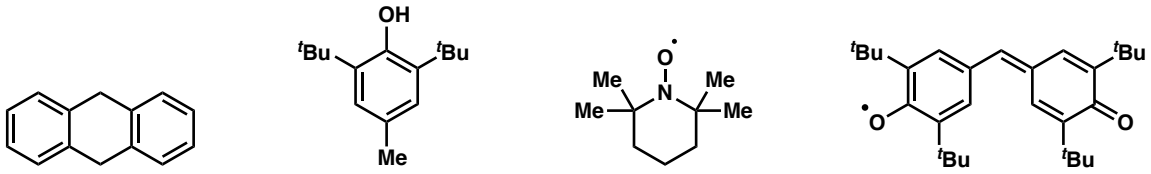
HRMS (EI, *m/z*): calc'd for $C_{10}H_{15}Cl$ $[M+\cdot]^+$: 170.0862; found: 170.0888.

5.7.4 Mechanistic Studies

5.7.4.1 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 **300** (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.



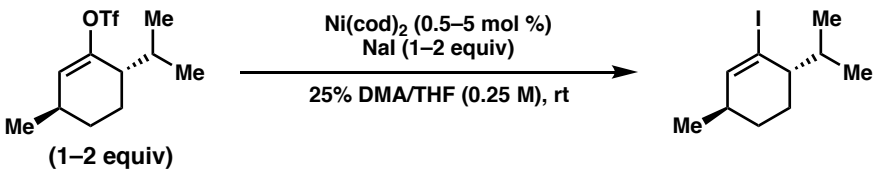
DHA
62% yield

BHT
67% yield

TEMPO
0% yield

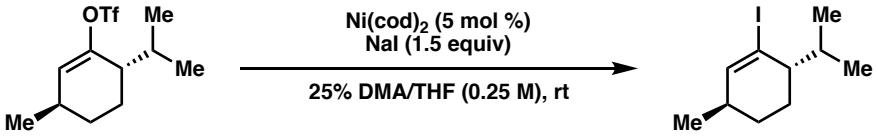
Galvinoxyl
5% yield

5.7.4.2 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. Enol triflate (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.

5.7.4.3 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.

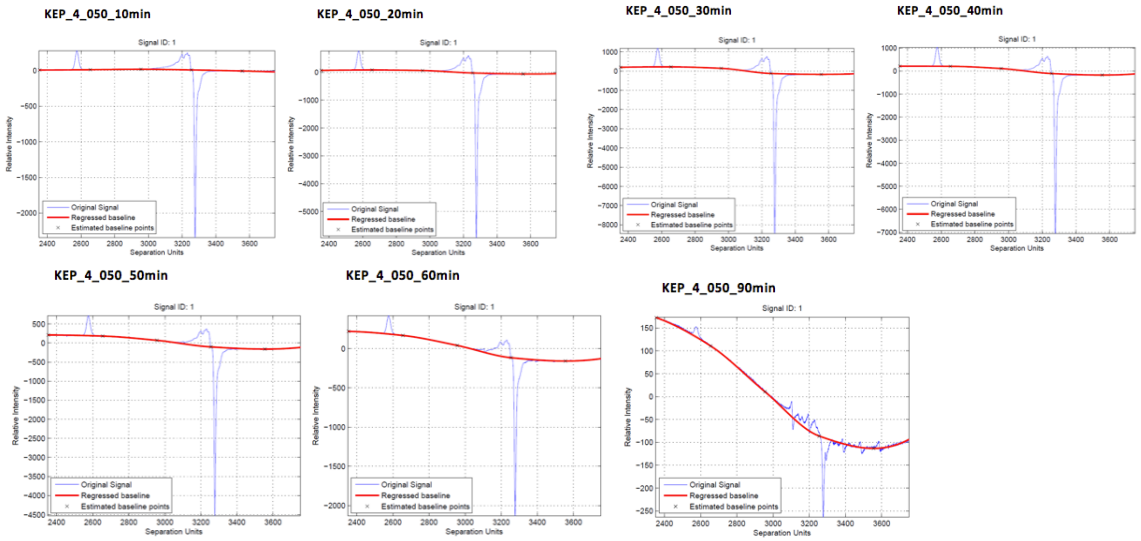


Figure S5.1: Baseline corrections of EPR spectra using MatLab.

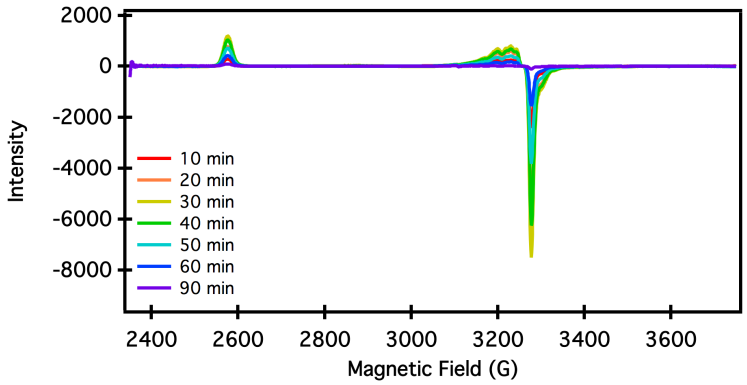


Figure S5.2: EPR spectra of the iodination of **300** at various time points.

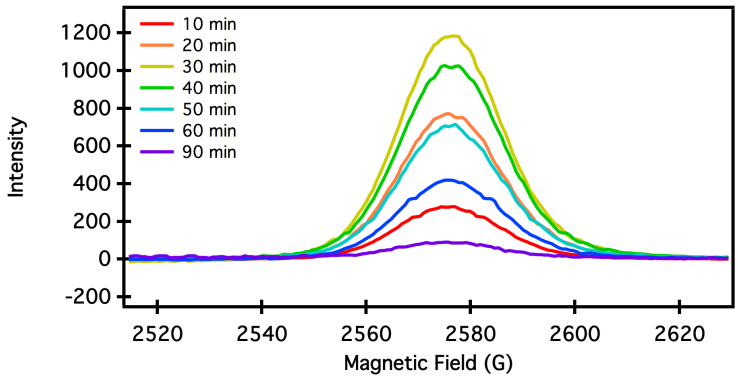


Figure S5.3: EPR spectra of the iodination of **300** at various time points (2520-2620 G region).

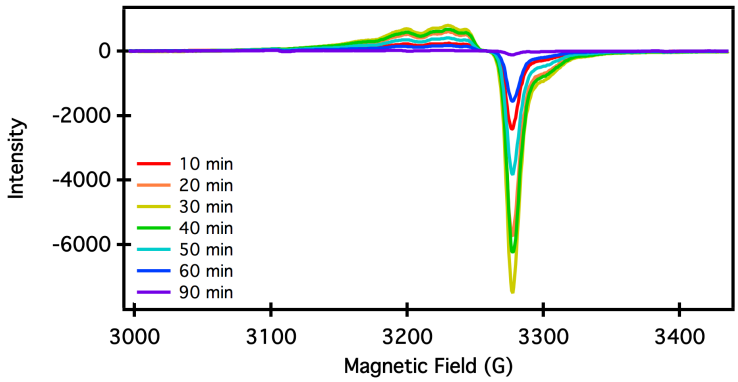


Figure S5.4: EPR spectra of the iodination of **300** at various time points (3000-3400 G region).

The spectra in **Figure S5.2** were processed by calculating the double integral. By comparison to the known concentration of $CuSO_4$ in **Figure S5.5**, 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).

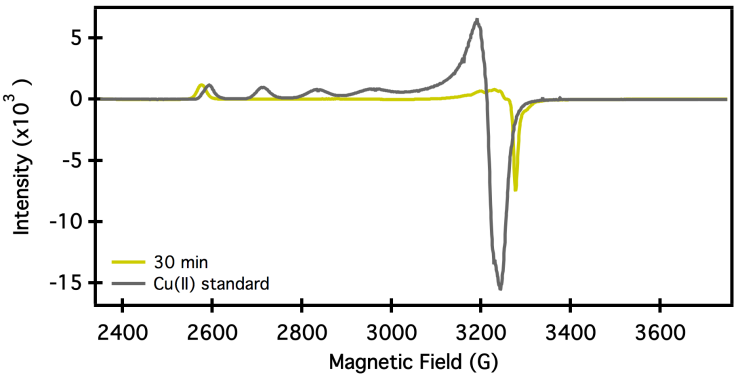


Figure S5.5: EPR spectra of the iodination of **300** at 30 minutes compared to 12.5 mM $CuSO_4$.

The halogenation of **300** 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.

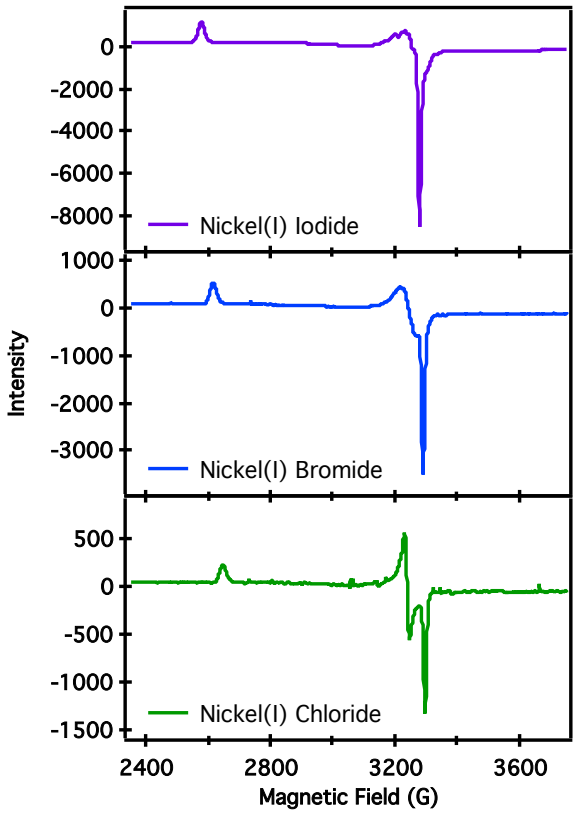
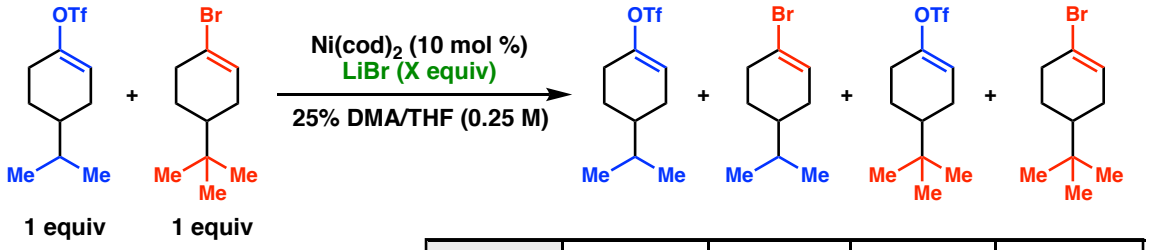


Figure S5.6: EPR spectra of the iodination, bromination, and chlorination of **300** at 30 minutes.

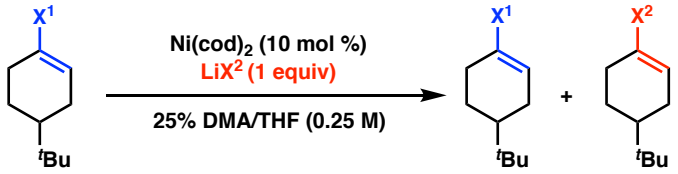
5.7.4.4 Crossover Experiments



0 equiv LiBr	100% recovered	0%	0%	100% recovered
0.1 equiv LiBr	90% recovered	10%	0%	100% recovered
1.0 equiv LiBr	0% recovered	90%	0%	100% recovered

A 2-dram vial equipped with a stir bar was brought into a N_2-filled glovebox. The vial was charged with LiBr (X 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 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.

5.7.4.5 Halide Competition



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 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.

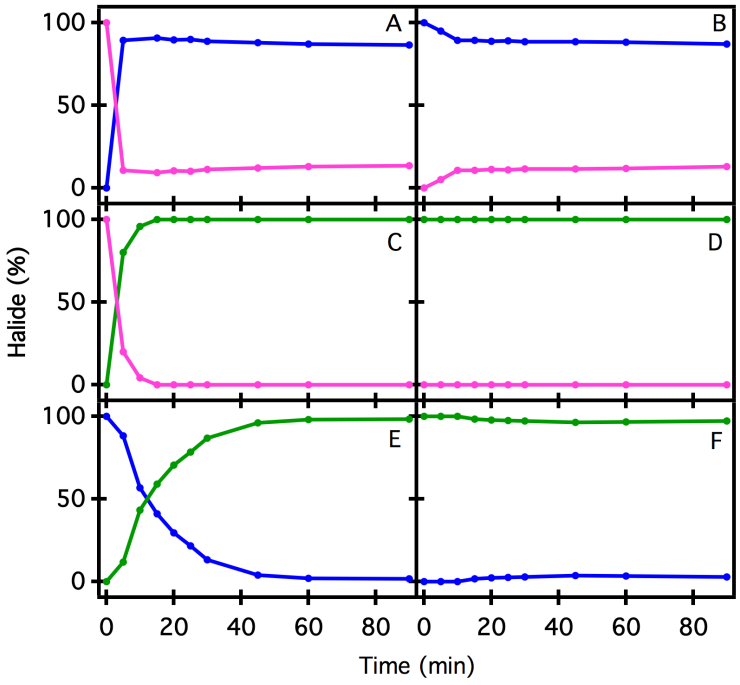


Figure S5.7: Ratios in terms of percentages for halide cross-over experiments: **A)** alkenyl iodide + LiBr, **B)** alkenyl bromide + LiI, **C)** alkenyl iodide + LiCl, **D)** alkenyl chloride + LiI, **E)** alkenyl bromide + LiCl, and **F)** alkenyl chloride + LiBr.

5.7.4.6 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. Enol triflate **300** (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.

5.8 NOTES AND REFERENCES

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