

Site-Selective, Catalyst-Controlled Alkene Aziridination

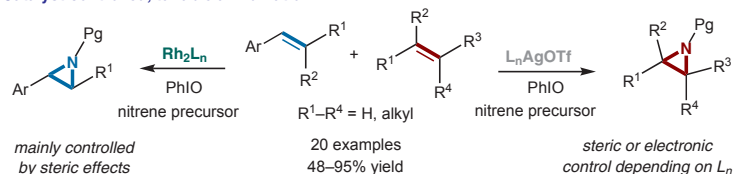
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Catalyst-controlled, tunable aziridination



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Abstract Transition-metal-catalyzed nitrene transfer is a convenient method to introduce nitrogen into simple substrates through either alkene aziridination or C–H bond amination. Silver complexes have an unusual capability to accommodate a broad range of N-donor ligands and coordination geometries in catalysts competent for nitrene transfer. This behavior has resulted in the ability to achieve tunable chemoselectivity between aziridination and C–H bond amidation, as well as tunable site-selective functionalization between two different C–H bonds. In this paper, efforts to engage the diversity of silver and rhodium catalysts to accomplish selective and tunable aziridination of mixtures of alkenes are discussed. It was found that the selectivity of dinuclear Rh catalysts is dictated largely by steric effects, while the identity of the ligand on silver can be tuned to influence whether the steric or electronic features in the competing alkenes is the primary factor controlling which precursor is preferentially aziridinated.

Key words nitrene transfer, silver, alkene, aziridine, site-selective

Transition-metal-catalyzed nitrene transfer represents a powerful strategy to introduce nitrogen into simple building blocks through the aziridination of an unsaturated C=C bond. Several transition metals have been employed for this purpose, including Rh,¹ Fe,² Cu,³ Ru,⁴ Co,⁵ and Ag.⁶ Aziridines resulting from the addition of metallonitrenes to alkenes are particularly useful intermediates, as the strained ring can be opened with a wide variety of nucleophiles, often in a regio- and stereocontrolled manner.⁷ Despite the diversity of catalysts known for alkene aziridination, the vast majority of these reports focus on substrates containing only a single site of unsaturation. The rare examples of selective aziridinations in precursors that contain multiple sites of unsaturation typically utilize large differences between the electronic features of the two alkenes to bias reactivity for the more electron-rich alkene.^{8–12}

Our group has had an ongoing interest in identifying opportunities to harness several unusual features of silver-catalyzed nitrene transfer to achieve tunable, chemo-, site- and stereoselective amination reactions.^{13–15} Most notably, we found that Ag(I) complexes competent for nitrene trans-

fer are able to accommodate a diverse range of coordination geometries. In our previous work, we demonstrated that altering the steric environment around Ag, by either changing the Ag:ligand ratio or the ligand identity, influences whether the catalyst prefers to engage in an aziridination or C–H bond insertion pathway.^{13,14} More recently, we have shown that controlling the coordination geometry of the putative silver nitrene can promote non-covalent interactions between the substrate and the catalyst.^{15a} In this manner, the site-selectivity of C–H bond amination can be tuned through the identity of the ligand to favor nitrene insertion into a variety of benzylic, allylic, and propargylic C–H bonds over tertiary alkyl C(sp³)–H bonds and vice versa.^{15f,g} We were curious if these similar design principles might be applied to tunable, catalyst-controlled intermolecular aziridinations of alkenes. While significantly more challenging, such preliminary studies would provide insight into the catalyst features that are necessary to achieve predictable, site-selective aziridination in substrates containing multiple C=C bonds. With this information in hand, the future development of a library of catalysts displaying predictable, tunable responses to the steric or electronic features of a given alkene could be envisaged, offering useful tools for the flexible late-stage introduction of nitrogen into complex molecules.

General Approach

Dinuclear Rh and Ag complexes were chosen for further study from an initial screening of common catalysts (Figure 1) for metal-catalyzed nitrene transfer,^{1–6} as they furnished good yields of the aziridines in most cases and provided opportunities for exploring the impact of ligand on selectivity. In addition to the nature of the catalyst and the substrate, the identity of the nitrene precursor is also an important factor in determining the selectivity of the amination event.^{15d} For the purposes of the studies described herein, we opted to utilize sulfamate-based nitrene precursors, particularly 2,2,2-trifluoro-1-(trifluoromethyl)ethylsulfamate (HfsNH₂) for Ag-based catalysts and 2,6-difluorophenylsulfamate (DfsNH₂) for Rh-based catalysts. These nitrogen sources are easily accessible, highly reactive and

in the case of cyclohexene **2e**, where both Rh₂esp₂ and Ag catalysts promoted competing allylic C–H amination.^{15d} Increasing the steric bulk of the rhodium catalyst by replacing Rh₂esp₂ with Rh₂TPA₄ (TPA = triphenylacetate) further improved the preference for the aziridination of styrene over aliphatic alkenes (>19:1), albeit in lower yields and decreased reactivity. The use of more electron-withdrawing ligands on Rh had little impact on the selectivity. These results indicate that: 1) for similar substitution patterns, a styrene is more reactive than a monoalkyl-substituted alkene, and 2) steric effects can be used to primarily drive which alkene undergoes aziridination using dinuclear Rh catalysts.

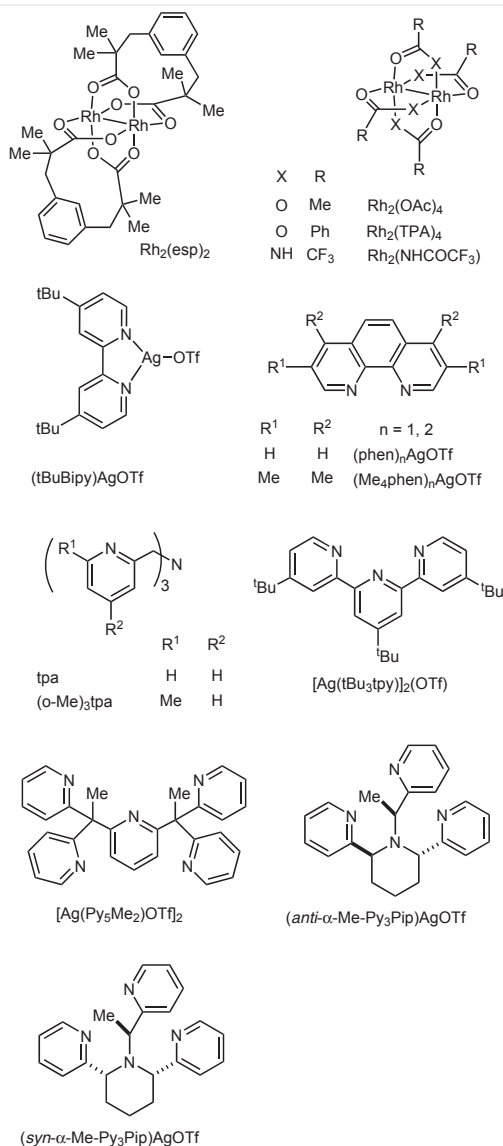
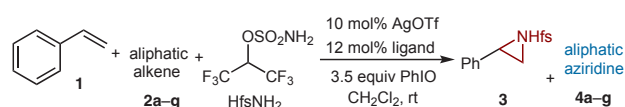


Table 1 Trends in the Aziridination of Styrene versus Aliphatic Alkenes^a



Aliphatic alkene	Rh ₂ (esp) ₂ ^b	^t BuBipy	^t Butpy	tpa	Py ₅ Me ₂
 2a	99% 6:1 ^c	92% >19:1	98% >19:1	99% >19:1	98% >19:1
 2b	99% 13:1	99% >19:1	99% >19:1	99% >19:1	89% >19:1
 2c	88% 13.5:1	93% >19:1	99% 13:1	88% 10:1	73% 12:1
 2d	84% 7.6:1	98% 7:1	99% 7:1	89% 6:1	85% >19:1
 2e	92% 13:1 ^d	98% 5:1	99% 2.1:1	77% 3.1:1	85% >19:1
 2f	80% 4.4:1	89% 1.6:1	99% 1:1.3	99% 2.4:1	85% 2.5:1
 2g	96% 9:1	99%, 1:1 99%, 1:3 ^f 99%, 1:2 ^h 99%, 1:3 ⁱ	99%, 1:3.5 ^e 99%, 1:5 ^g	46% 1:2.5	86% >19:1

^a The yield percentage of the products and the ratios of aziridinated styrene/aliphatic aziridine (**3/4**) obtained for the ligands used (top row) are entered in the table.

^b Reaction conditions: 2.5 mol% Rh₂(esp)₂, DfsNH₂, 1.2 equiv PhI(OAc)₂, 0.8 M CH₂Cl₂, 2.4 equiv MgO, 4 h, r.t.

^c Similar results were observed using Rh₂(OAc)₄ and Rh₂(tfacam)₄.

^d Aziridination:C-H insertion: 3.4:1.

^e Ratio of AgOTf/terpy = 1:1.2

^f Ratio of AgOTf/phen = 1:1.

^g Ratio of AgOTf/terpy = 1:3

^h Ratio of AgOTf/Me₄phen = 1:1.2

ⁱ Ratio of AqOTf/bathophen = 1:1.2

The reactivity of styrene (**1**) was first compared to a series of alkyl-substituted alkenes (Table 1). In all cases, Rh₂esp₂ (esp = $\alpha,\alpha,\alpha',\alpha'$ -tetramethyl-1,3-benzenedipropionic acid) preferred to aziridinate styrene over mono-, di-, tri- and tetraalkyl-substituted alkenes **2a–g** with selectivities ranging from 4.4:1 with **2f** to 13.5:1 using **2c**. It should be mentioned that issues with chemoselectivity were noted

Our previous investigations of chemoselective, silver-catalyzed nitrene transfer showed that intramolecular aziridination is preferred over C–H amination when bidentate nitrogen ligands, such as 2,2'-bipyridines (bipy) and 1,10-phenanthrolines (phen), are used in a ~1:1 ligand:AgOTf loading; increasing the ligand:AgOTf diverted the re-

activity to favor the allylic C–H amination.¹³ In these studies, we wanted to achieve both good chemoselectivity for intermolecular aziridination, as well as preferentially select for reaction of one alkene over other in a tunable fashion. The use of a (^tBuBipy)AgOTf (Table 1, column 2) catalyst favored the reaction of styrene **1** over mono-, di-, and trisubstituted alkenes, in a manner similar to that observed for Rh₂esp₂. However, in contrast to Rh₂esp₂, the preference for **1** using (^tBuBipy)AgOTf steadily decreased as the alkyl-substituted alkene became more electron-rich, culminating in a 1:1 **3**/**4g** ratio using **2g** as the substrate. These results suggest that steric considerations are not the only driving force for the selectivity exhibited by (^tBuBipy)AgOTf. Interestingly, Ag catalysts supported by ligands with phenanthroline backbones (phen, Me₄phen, bathophen) inverted the site-selectivity, favoring **4g**/**3** in up to a 3:1 ratio. The trend with the dimeric [(^tBu₃tpy)Ag]₂(OTf)₂ catalyst was similar to that observed for (^tBuBipy)AgOTf, displaying a decreased preference for the aziridination of **1** as the competing aliphatic alkene becomes more electron-rich. Aziridination of **2g** was preferred over **1** in a 5:1 **4g**/**3** ratio, suggesting that [(^tBu₃tpy)Ag]₂(OTf)₂ is more sensitive to electronic effects and/or less influenced by steric effects, as compared to the other catalysts in Table 1.

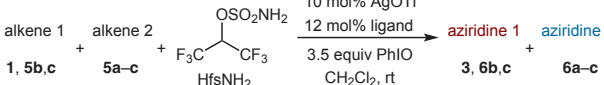
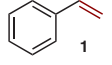
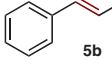
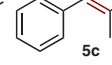
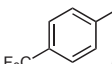
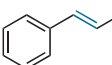
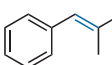
A catalyst supported by tris(2-pyridylmethyl)amine (tpa), (tpa)AgOTf, displayed similar behavior to (^tBuBipy)AgOTf and [(^tBu₃tpy)Ag]₂(OTf)₂, although the yield of **4g** was significantly lower, perhaps indicating some level of sensitivity to steric effects. Interestingly, dimeric complex [(Py₅Me₂)Ag]₂(OTf)₂^{15e} favored styrene aziridination in all cases, giving comparable yields and better selectivity than Rh₂esp₂ in several instances. Presumably, this is due to the increased steric bulk of the dimeric Ag complex, which mimics that of the more expensive Rh complex.

To summarize the insight gleaned from the results in Table 1, [(Py₅Me₂)Ag]₂(OTf)₂ behaves similarly to Rh₂esp₂ for the selective aziridination of styrene over aliphatic alkenes. While tunability was not general, it was a curious observation that we were able to alter the selectivity for aziridination between styrene and an electron-rich, tetra-substituted alkene using silver catalysts supported by bipy-, phen- or tpy-based ligands.

Styrene versus Substituted Styrenes in Intermolecular Aziridination

Competition experiments between **1** and **5a–c** (Table 2) were used to assess how the different catalysts responded to steric and electronic effects in substituted styrenes. Rh₂esp₂-catalyzed competition between **1** and **5a** gave poor selectivity, even though **5a** is significantly less electron-rich than **1**. The preference for aziridination of styrene to yield **3** increased in competitions with more substituted styrenes **5b** and **5c** to 7:1 and 20:1, respectively. These results again support the hypothesis that steric effects primarily dictate the selectivity observed with dinuclear Rh catalysts.

Table 2 Trends in the Competitive Aziridination of Styrenes^a

alkene 1 1 , 5b,c	alkene 2 5a–c		aziridine 1 3 , 6b,c	aziridine 2 6a–c
Alkene 2	Catalyst			
	Rh ₂ (esp) ₂	99%, 1.5:1		
	^t BuBipy	99%, 2.8:1		
	^t Bu ₃ tpy	99%, 1.6:1	not determined	not determined
	tpa	99%, 2.5:1		
	Py ₅ Me ₂	94%, 2.8:1		
	Rh ₂ (esp) ₂	86%, 7:1		59%, 1:4
	^t BuBipy	99%, 2:1		89%, 1:2.5
	^t Bu ₃ tpy	99%, 1:2 ^b	–	99%, 1.3:1
	tpa	99%, 1.3:1		99%, 1:1.1
	Py ₅ Me ₂	74%, 2:1 ^c		53%, 1:6
	Rh ₂ (esp) ₂	94%, 20:1	59%, 4:1	
	^t BuBip	99%, 5.5:1	89%, 2.5:1	
	^t Bu ₃ tpy	84%, 1:1 ^b	99%, 1:1.3	–
	tpa	99%, 1.9:1	99%, 1.1:1	
	Py ₅ Me ₂	80%, 20:1	53%, 6:1	

^a The ratios given refer to aziridine 1 (**3**, **6b,c**)/aziridine 2 (**6a–c**).

^b Ratio of AgOTf/ligand = 1:1.25.

^c Ratio of AgOTf/ligand = 1:3.

Silver catalysts preferred to aziridinate **1** over the electron-poor **5a** in comparable or better selectivities as compared to Rh₂esp₂. The ^tBuBipy, tpa, and Py₅Me₂ ligands showed a similar response to the electronics of **5a**, while a ^tBu₃tpy ligand was less sensitive, giving a 1.6:1 ratio of **3**/**6a**. When **1** was compared to substituted styrenes **5b,c**, a trend similar to that of Rh₂esp₂ was noted with (^tBuBipy)AgOTf, as the preference for reaction of **3** over **5b** and **5c** increased from 2:1 to 5.5:1, respectively. In contrast, [(^tBu₃tpy)Ag]₂(OTf)₂ displayed a slight preference for the aziridination of β-methylstyrene **5b** over **1**; no selectivity was noted for competitive reaction of **1** versus **5c**, despite increased steric congestion. Finally, the bulky [(Py₅Me₂)Ag]₂(OTf)₂ complex showed excellent selectivity for the reaction of **1** over **5c**, again displaying behavior similar to that of Rh₂esp₂.

To summarize the results in Table 2, steric effects are again the primary determining factor in controlling the selectivity for Rh₂esp₂-catalyzed aziridination. This is also true to a lesser extent with the majority of our silver catalysts; the notable exception is [(^tBu₃tpy)Ag]₂(OTf)₂, which again appears to be less sensitive to steric bulk and more responsive to electron-rich alkenes. Amongst the four Ag catalysts, [(Py₅Me₂)Ag]₂(OTf)₂ again behaves similarly to Rh₂esp₂ in its preference for aziridination of the least hindered alkene.

Substituted Styrenes versus Aliphatic Alkenes in Intermolecular Aziridination

Reactivities of a series of increasingly substituted styrenes **1** and **5b,c** were compared to electron-rich alkenes **2f,g** (Table 3). In competitive reactions of **1** with **2f,g**,

Rh_2esp_2 responded primarily to steric effects, producing **3** selectively over **4f,g** in ratios of 4.4:1 and 9:1, respectively. Di- and trisubstituted styrenes **5b,c** displayed much lower preferences for aziridination, even favoring reaction of **2g** over **5c** by a ratio of 2:1, albeit in low yield. Tunable chemoselectivity was achievable using different ligands with Ag-OTf . For example, $[(\text{Bu}_3\text{tpy})\text{Ag}]_2(\text{OTf})_2$ favored aziridination of both **2f,g** over **1**; most of the remaining silver catalysts preferred reaction of **1**. More useful tunability was noted in competition reactions of **5b** and **2g**, with $[(\text{Bu}_3\text{tpy})\text{Ag}]_2(\text{OTf})_2$ furnishing **4g** as the major product and $[(\text{Py}_5\text{Me}_2)\text{Ag}]_2(\text{OTf})_2$ delivering **6b** as the preferred aziridine. No useful tunability could be achieved to favor aziridination of **5c** over any of the aliphatic alkenes.

Table 3 Trends in the Competitive Aziridination of Styrenes versus Aliphatic Alkenes^a

alkene 1 1, 5b, c	alkene 2 2g, h	$\text{F}_3\text{C}-\text{CH}(\text{OSO}_2\text{NH}_2)-\text{CF}_3$ HfsNH ₂	10 mol% AgOTf 12 mol% ligand 3.5 equiv PhIO CH ₂ Cl ₂ , rt	aziridine 1 3, 6b, c	aziridine 2 4f, g
Catalyst					
2f	$\text{Rh}_2(\text{esp})_2$	80%, 4.4:1	73%, 1:2	70%, 1:2.7	
	tBuBipy	89%, 1.6:1	95%, 1.8:1	99%, 1:3.2	
	tBu ₃ tpy	99%, 1:1.3	87%, 1.5:1	99%, 1:2.1	
	tpa	99%, 2.4:1	99%, 1:1.2	99%, 1:1.2	
	Py ₅ Me ₂	86%, 2.5:1	86%, 1:1	66%, 1:8	
2g	$\text{Rh}_2(\text{esp})_2$	96%, 9:1	55%, 1.1:1	36%, 1:2	
	tBuBipy	99%, 1:1	99%, 1:2.5	99%, 1:5.6	
	tBu ₃ tpy	99%, 1:3.5	99%, 1:4.8	99%, 1:3.4	
	tpa	46%, 1:2.5	94%, 1:3.8	94%, 1:3.9	
	Py ₅ Me ₂	86%, 19:1	52%, 3.8:1	30%, 1:2.1	

^a The ratios given refer to aziridine 1 (**3, 6b, c**)/aziridine 2 (**4f, g**).

Competition between Substituted Aliphatic Alkenes in Intermolecular Aziridination

Finally, we compared alkyl-substituted alkenes of varying substitution patterns under the conditions of competitive aziridination (Table 4). Trends in reactivity discerned from these experiments include preference for the aziridination of the *cis*-**2d** over *trans*-**2c** with all but the $[(\text{Py}_5\text{Me}_2)\text{Ag}]_2(\text{OTf})_2$ catalyst, albeit in modest selectivity. All catalysts favored aziridination of the more electron-rich **2f** over either of the disubstituted alkenes **2c,d**, with *cis*-**2d** competing more effectively for aziridination than *trans*-**2c**. Interestingly, the addition of another Me group to the alkene of **2g** again showed the sensitivity of both Rh_2esp_2 and $[(\text{Py}_5\text{Me}_2)\text{Ag}]_2(\text{OTf})_2$ to steric effects, as aziridination of the less-substituted alkene either dominated or the preference for reaction of **2g** was lower than for the remaining complexes. In the case of Ag complexes $[(\text{Bu}_3\text{tpy})\text{Ag}]_2(\text{OTf})_2$, $(\text{tBuBipy})\text{AgOTf}$, and $(\text{tpa})\text{AgOTf}$, reaction of the more electron-rich **2g** was preferred over **2c,d**

and **2f** in all cases, providing tunable aziridination for a tri- versus a tetraalkylsubstituted alkene.

Table 4 Competitive Aziridination of Alkyl-Substituted Alkenes^a

alkene 1 2c, d, f	alkene 2 2c, d, g	$\text{F}_3\text{C}-\text{CH}(\text{OSO}_2\text{NH}_2)-\text{CF}_3$ HfsNH ₂	10 mol% AgOTf 12 mol% ligand 3.5 equiv PhIO CH ₂ Cl ₂ , rt	aziridine 1 4c, d, f	aziridine 2 4c, d, g
Alkene 2	Catalyst				
2c	$\text{Rh}_2(\text{esp})_2$	90%, 3:1	66%, 4.7:1		
	tBuBipy	39%, 3:1	76%, >19:1		
	Bu ₃ tpy	74%, 3:1	99%, >19:1		
	tpa	8%, 2:1	78%, 18:1		
	Py ₅ Me ₂	14%, 1:1.8	68%, 11:1		
2d	$\text{Rh}_2(\text{esp})_2$	90%, 1:3	88%, >19:1		
	tBuBipy	39%, 1:3	77%, 3:1		
	Bu ₃ tpy	74%, 1:3	99%, >19:1		
	tpa	8%, 1:2	99%, 5.7:1		
	Py ₅ Me ₂	14%, 1.8:1	80%, 3.8:1		
2g	$\text{Rh}_2(\text{esp})_2$	41%, 1:1.2	39%, 3.5:1	69%, 2.8:1	
	tBuBipy	94%, 1:>19	94%, 1:6.6	99%, 1:1.9	
	Bu ₃ tpy	<99%, 1:>19	99%, 1:>19	99%, 1:3.5	
	tpa	99%, 1:>19	88%, 1:>19	97%, 1:2.5	
	Py ₅ Me ₂	21%, 1:2.4	27%, 1:1.7	71%, 3.8:1	

^a The ratios given refer to aziridine 1 (**4c, d, f**)/aziridine 2 (**4c, d, g**).

General Trends in Competitive Intermolecular Aziridination Catalyzed by Rh_2esp_2 and Ag-Based Complexes

The data in Tables 1–4 were helpful in revealing trends in catalyst-controlled aziridination using complexes based on Rh and Ag. The selectivity using Rh_2esp_2 responded mainly to steric effects. In comparing the aziridination of styrene versus a series of increasingly substituted aliphatic alkenes (Table 1), the selectivity for reaction of styrene generally increased as the competing aliphatic alkene became more sterically congested. However, since styrene aziridination was still preferred over monoalkylsubstituted alkenes, non-covalent interactions between the aryl group and the catalyst may also drive selectivity. Comparing the reactivity of styrene with more heavily substituted styrenes or alkyl-substituted alkenes (Tables 2 and 3) again suggested steric effects primarily determines the selectivity; even a competition between styrene and the electronically deactivated *p*-trifluoromethylstyrene gave only a 1.5:1 selectivity. Finally, the response of Rh_2esp_2 in competitions between alkyl-substituted alkenes (Table 4) was more nuanced, in that a more electron-rich alkene could trump reaction of a less substituted, less electron-rich alkenes; however, the yields in general were much lower.

Of the silver catalysts explored in Table 1, a bulky dimeric complex $[(\text{Py}_5\text{Me}_2)\text{Ag}]_2(\text{OTf})_2$ behaved most similarly to Rh_2esp_2 in reactions of styrene versus increasingly substituted aliphatic alkenes, typically in >12:1 selectivity with good yields. The same general behaviors were observed in Tables 2–4 with $[(\text{Py}_5\text{Me}_2)\text{Ag}]_2(\text{OTf})_2$, as compared to

Rh₂esp₂, and represents a less expensive alternative to dinuclear Rh catalysts for selective intermolecular aziridination in some cases.

The silver catalyst (^tBubipy)AgOTf, [(^tBu₃tpy)Ag]₂(OTf)₂, and (tpa)AgOTf complexes preferred aziridination of styrene when the competing aliphatic alkenes were mono- and dialkyl-substituted (Tables 1 and 2); however, as the competing alkyl-substituted alkenes became increasingly electron-rich, steric considerations were overridden and aziridination of the more hindered precursor could be favored. This effect was most pronounced with [(^tBu₃tpy)Ag]₂(OTf)₂, which appeared to be the catalyst either most sensitive to electronic effects and/or the least sensitive to steric considerations.

The response of Rh₂esp₂ and various silver complexes to competitive intermolecular aziridination were examined with simple aryl- and alkyl-substituted alkenes. Bulky Rh catalysts behaved similarly to a recently reported Ag complex, [(Py₅Me₂)Ag]₂(OTf)₂, while changing the nature of the ligand on Ag enabled moderate tunability to be achieved between pairs of alkenes in certain cases. These preliminary studies provide a foundation for further catalyst optimization in situations where mixtures of alkenes are present, or more than one alkene group is present in the precursor. In addition, the mild reaction conditions render them ideal for potential applications to the late-stage amination of complex molecules.

All glassware was either oven-dried overnight at 130 °C or flame-dried under a stream of dry N₂ prior to use. Unless otherwise specified, reagents were used as obtained from the vendor without further purification. CH₂Cl₂ was dried over CaH₂ and freshly distilled prior to use. Air- and moisture-sensitive reactions were performed using standard Schlenk techniques under an atmosphere of N₂. Analytical TLC was performed utilizing pre-coated silica gel 60 F254 plates containing a fluorescent indicator, while preparative chromatography was performed using SilicaFlash P60 silica gel (230–400 mesh). Unless otherwise stated, mobile phases for column chromatography were mixtures of hexanes/EtOAc. Columns were typically run using a gradient method, beginning with 100% hexanes and gradually increasing the polarity with EtOAc. Various stains were used to visualize reaction products, including KMnO₄, ceric ammonium molybdate (CAM stain), and UV-light.

¹H NMR, ¹³C NMR, and ¹⁹F NMR spectra were obtained using Bruker Avance-400 or Avance-500 spectrometer. For ¹H NMR, chemical shifts are reported relative to residual protiated solvent peaks (7.26, and 7.15 ppm for CDCl₃ and C₆D₆, respectively). ¹³C NMR spectra were recorded at 125 MHz on the same instruments noted above for recording ¹H NMR spectra. Chemical shifts were reported relative to residual protiated solvent peaks (77.2 for CDCl₃ and 128.0 for C₆D₆). ¹⁹F NMR spectra were recorded at 377 MHz and referenced to their respective ¹H NMR spectra. Accurate mass measurements were acquired at the University of Wisconsin, Madison using a Micromass LCT (electrospray ionization, time-of-flight analyzer or electron impact methods).

Competitive Ag-Catalyzed Aziridination; General Procedure

A flame-dried reaction flask was charged with AgOTf (6.4 mg, 0.025 mmol, 0.1 equiv) and the appropriate ligand (0.03 mmol, 0.12 equiv). CH₂Cl₂ (4 mL) was added to the flask and the mixture was stirred vigorously for 20 min. The alkene (0.625 mmol each, 5 equiv total), nitrene precursor HfsNH₂ (0.25 mmol, 1 equiv) and 4Å molecular sieves (1 mmol substrate/g of sieves) were then added to the reaction flask. Iodosobenzene (193 mg, 0.88 mmol, 3.5 equiv) was added in one portion and the reaction mixture was allowed to stir at r.t. for 4 h. The reaction mixture was filtered through a glass frit and the filtrate concentrated under reduced pressure. Mesitylene (5 µL, 0.0359 mmol) was added as an internal standard and the crude mixture was diluted in deuterated solvent (CDCl₃ or C₆D₆, 0.6 mL). Due to the similar *R*_f values of the aziridine products, mixtures from the competition experiments were not purified; determination of the product ratios was carried out using quantitative ¹H NMR and an internal standard as described above.

For the purposes of isolation and characterization of all new compounds with Hfs protecting group as described below, the general procedure was followed utilizing a single alkene substrate. A commercially available and inexpensive *tert*-butylbipyridine ligand was employed, even though it might not be the optimal ligand for a given alkene substrate.

Compound 3

The product was purified by column chromatography using a 0 → 10% gradient of EtOAc in hexanes with 5% increments; yield: 48.8 mg (0.14 mmol, 54%); clear white oil; *R*_f = 0.37 (15% EtOAc/hexanes).

¹H NMR (400 MHz, CDCl₃): δ = 7.38 (dd, *J* = 5.0, 1.8 Hz, 3 H), 7.28 (dd, *J* = 6.9, 2.9 Hz, 2 H), 5.32 (sept, *J* = 5.5 Hz, 1 H), 3.91 (dd, *J* = 7.3, 4.8 Hz, 1 H), 3.10 (dd, *J* = 7.3, 0.9 Hz, 1 H), 2.67 (d, *J* = 4.8 Hz, 1 H).

¹³C NMR (125 MHz, CDCl₃): δ = 133.10, 129.16, 128.84, 126.48, 119.37 (q, *J* = 284.6 Hz), 73.80 (sept, *J* = 35.6 Hz), 43.61, 38.31.

¹⁹F NMR (377 MHz, CDCl₃): δ = −72.81 (t, *J* = 8.2 Hz, 3 F), −72.90 (t, *J* = 8.5 Hz, 3 F).

HRMS (ESI): *m/z* [M + NH₄]⁺ calcd for C₁₁H₉F₆NO₃S: 367.0546; found: 367.0545.

Compound 4a

The product was purified by column chromatography using 0 → 10% gradient of EtOAc in hexanes with 5% increments; yield: 49.1 mg (0.13 mmol, 50%); clear white oil; *R*_f = 0.67 (20% Et₂O/hexanes).

¹H NMR (500 MHz, CDCl₃): δ = 5.26 (sept, *J* = 5.6 Hz, 1 H), 2.92 (ddd, *J* = 12.1, 6.6, 5.1 Hz, 1 H), 2.74 (d, *J* = 7.0 Hz, 1 H), 2.32 (d, *J* = 4.9 Hz, 1 H), 1.62–1.56 (m, 2 H), 1.45 (dtd, *J* = 15.6, 7.7, 4.8 Hz, 2 H), 1.38–1.29 (m, 6 H), 0.89 (t, *J* = 6.9 Hz, 3 H).

¹³C NMR (126 MHz, CDCl₃): δ = 119.80 (q, *J* = 284.8 Hz), 73.48 (sept, *J* = 35.5 Hz), 43.40, 36.11, 31.54, 30.86, 28.69, 26.16, 22.47, 13.99.

¹⁹F NMR (377 MHz, CDCl₃): δ = −72.88 (s, 6 F).

HRMS (ESI): *m/z* [M + NH₄]⁺ calcd for C₁₁H₁₇F₆NO₃S: 375.1172; found: 375.1171.

Compound 4b

The product was purified by column chromatography using 5 → 15% gradient of Et₂O in pentanes with 5% increments; yield: 45.8 mg (0.13 mmol, 51%); clear white oil; *R*_f = 0.5 (20% Et₂O/hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 5.26 (sept, J = 5.6 Hz, 1 H), 2.75 (td, J = 7.2, 4.9 Hz, 1 H), 2.70 (d, J = 7.1 Hz, 1 H), 2.37 (d, J = 4.9 Hz, 1 H), 1.85–1.69 (m, 5 H), 1.34–1.08 (m, 6 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 120.97 (q, J = 284.8 Hz), 73.26 (sept, J = 35.4 Hz), 47.72, 38.89, 34.98, 29.73, 29.17, 25.92, 25.46, 25.28.

^{19}F NMR (377 MHz, CDCl_3): δ = –72.83 (q, J = 8.6, 7.5 Hz, 3 F), –72.94 (q, J = 9.8, 8.6 Hz, 3 F).

HRMS (ESI): m/z $[\text{M} + \text{NH}_4]^+$ calcd for $\text{C}_{11}\text{H}_{15}\text{F}_6\text{NO}_3\text{S}$: 373.1015; found: 373.1015.

Compound 4c

The product was purified by column chromatography using 5 $\rightarrow$ 15% gradient of Et_2O in pentanes with 5% increments; yield: 59.5 mg (0.19 mmol, 70%); clear white oil; R_f = 0.63 (20% Et_2O /hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 5.25 (sept, J = 5.6 Hz, 1 H), 2.79–2.71 (m, 2 H), 1.86 (ddq, J = 13.3, 8.8, 4.9 Hz, 2 H), 1.61–1.40 (m, 6 H), 0.98 (t, J = 7.2 Hz, 6 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 118.77 (q, J = 284.8 Hz), 73.30 (sept, J = 35.29 Hz), 51.03, 31.42, 20.06, 13.65.

^{19}F NMR (377 MHz, CDCl_3): δ = –72.55 (q, J = 9.3 Hz, 3 F), –72.96 (q, J = 9.4 Hz, 3 F).

HRMS (ESI): m/z $[\text{M} + \text{Na}]^+$ calcd for $\text{C}_{11}\text{H}_{17}\text{F}_6\text{NO}_3\text{SNa}$: 380.0726; found: 380.0721.

Compound 4d

The product was purified by column chromatography using 5 $\rightarrow$ 15% gradient of Et_2O in pentanes with 5% increments; yield: 45.1 mg (0.13 mmol, 50%); clear white oil; R_f = 0.65 (20% Et_2O /hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 5.25 (sept, J = 5.6 Hz, 1 H), 2.98–2.91 (m, 2 H), 1.59–1.44 (m, 8 H), 1.02–0.96 (m, 6 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 119.85 (q, J = 284.8 Hz), 73.25 (sept, J = 35.41 Hz), 48.11, 28.42, 20.21, 13.72.

^{19}F NMR (377 MHz, CDCl_3): δ = –72.86 (s, 6 F).

HRMS (ESI): m/z $[\text{M} + \text{NH}_4]^+$ calcd for $\text{C}_{11}\text{H}_{17}\text{F}_6\text{NO}_3\text{S}$: 375.1172; found: 375.1174.

Compound 4f

The product was purified by column chromatography using 0 $\rightarrow$ 10% gradient of EtOAc in hexanes with 5% increments; yield: 43.1 mg (0.14 mmol, 52%); clear white oil; R_f = 0.43 (20% EtOAc /hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 5.23 (sept, J = 5.6 Hz, 1 H), 3.02 (q, J = 5.9 Hz, 1 H), 1.64 (s, 3 H), 1.34 (s, 3 H), 1.30 (d, J = 5.8 Hz, 3 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 119.93 (q, J = 282.7 Hz), 73.27 (sept, J = 35.2 Hz), 53.02, 51.12, 20.99, 20.06, 12.46.

^{19}F NMR (377 MHz, CDCl_3): δ = –72.53 (q, J = 9.4 Hz, 3 F), –72.99 (q, J = 9.1 Hz, 3 F).

HRMS (ESI): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_8\text{H}_{11}\text{F}_6\text{NO}_3\text{S}$: 316.0436; found: 316.0434.

Compound 4g

The product was purified by column chromatography using 5 $\rightarrow$ 15% gradient of Et_2O in pentanes with 5% increments; yield: 57.2 mg (0.18 mmol, 68%); clear white oil; R_f = 0.50 (20% Et_2O /hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 5.18 (sept, J = 5.6 Hz, 1 H), 1.50 (s, 12 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 120.03 (q, J = 286.8 Hz), 73.12 (pent, J = 35.1 Hz), 55.93, 19.89.

^{19}F NMR (377 MHz, CDCl_3): δ = –72.69 (s, 6 F).

HRMS (ESI): m/z $[\text{M} + \text{Na}]^+$ calcd for $\text{C}_9\text{H}_{13}\text{F}_6\text{NO}_3\text{SNa}$: 352.0413; found: 352.0411.

Compound 6a

The product was purified by column chromatography using 0 $\rightarrow$ 10% gradient of EtOAc in hexanes with 5% increments; yield: 74.1 mg (0.18 mmol, 69%); clear white oil; R_f = 0.43 (15% EtOAc /hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 7.65 (d, J = 8.1 Hz, 2 H), 7.41 (d, J = 8.1 Hz, 2 H), 5.33 (sept, J = 5.3 Hz, 1 H), 3.95 (dd, J = 7.3, 4.7 Hz, 1 H), 3.14 (d, J = 7.2 Hz, 1 H), 2.65 (d, J = 4.6 Hz, 1 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 137.26, 131.42 (q, J = 32.8 Hz), 126.92, 125.90 (q, J = 3.7 Hz), 123.82 (q, J = 273.7 Hz), 119.77 (q, J = 285.5 Hz), 73.99 (sept, J = 35.7 Hz), 42.69, 38.45.

^{19}F NMR (377 MHz, CDCl_3): δ = –62.91 (s, 3 F), –72.92 (t, J = 7.7 Hz, 3 F), –72.98 (t, J = 7.6 Hz, 3 F).

HRMS (ESI): m/z $[\text{M} + \text{NH}_4]^+$ calcd for $\text{C}_{12}\text{H}_8\text{F}_9\text{NO}_3\text{S}$: 435.0419; found: 435.0418.

Compound 6b

The product was purified by column chromatography using 0 $\rightarrow$ 10% gradient of EtOAc in hexanes with 5% increments; yield: 63.9 mg (0.18 mmol, 67%); clear white oil; R_f = 0.67 (20% EtOAc /hexanes).

^1H NMR (400 MHz, CDCl_3): δ = 7.36 (m, 3 H), 7.25 (dd, J = 5.1, 1.9 Hz, 2 H), 5.29 (sept, J = 5.2 Hz, 1 H), 3.81 (d, J = 4.7 Hz, 1 H), 3.12 (qd, J = 6.0, 4.7 Hz, 1 H), 1.75 (d, J = 6.0 Hz, 3 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 133.28, 129.02, 128.71, 126.63, 119.83 (q, J = 283.4 Hz), 73.56 (sept, J = 35.4 Hz), 51.92, 49.13, 13.75.

^{19}F NMR (377 MHz, CDCl_3): δ = –72.62 (q, J = 9.0 Hz, 3 F), –72.96 (q, J = 9.1 Hz, 3 F).

HRMS (ESI): m/z $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{12}\text{H}_{11}\text{F}_6\text{NO}_3\text{S}$: 364.0437; found: 364.0435.

Compound 6c

The product was purified by column chromatography using 0 $\rightarrow$ 10% gradient of EtOAc in hexanes with 5% increments; yield: 93.6 mg (0.24 mmol, 95%); clear white oil; R_f = 0.57 (15% EtOAc /hexanes).

^1H NMR (400 MHz, CDCl_3): δ = 7.39–7.32 (m, 3 H), 7.29 (dd, J = 7.7, 1.9 Hz, 2 H), 5.34 (sept, J = 5.6 Hz, 1 H), 4.08 (s, 1 H), 1.81 (s, 3 H), 1.15 (s, 3 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 132.39, 128.49, 128.35, 126.96, 119.88 (q, J = 283.7 Hz), 73.46 (sept, J = 35.4 Hz), 56.42, 55.21, 21.04, 20.23.

^{19}F NMR (377 MHz, CDCl_3): δ = –72.63 (q, J = 9.0 Hz, 3 F), –73.06 (q, J = 9.0 Hz, 3 F).

HRMS (ESI): m/z $[\text{M} + \text{Na}]^+$ calcd for $\text{C}_{13}\text{H}_{13}\text{F}_6\text{NO}_3\text{SNa}$: 400.0413; found: 400.0413.

Competitive Rh-Catalyzed Aziridination; General Procedure

A flame-dried reaction flask was charged with Rh_2esp_2 (3.8 mg, 0.005 mmol, 0.02 equiv) and CH_2Cl_2 (4 mL) and the mixture was stirred vigorously for 20 min. The alkene (0.625 mmol each, 5 equiv total), nitrone precursor DfsNH_2 (0.25 mmol, 1 equiv), MgO (24.2 mg, 0.6 mmol, 2.4 equiv) were added to the flask. (Diacetoxyiodo)benzene (96.6 mg, 0.3 mmol, 1.2 equiv) was added in one portion and the reaction mixture was allowed to stir at r.t. for 4 h. The mixture was fil-

tered through a glass frit and the filtrate concentrated under reduced pressure. Mesitylene (5 μ L, 0.0359 mmol) was added as internal standard and the crude mixture was diluted in deuterated solvent (CDCl_3 or C_6D_6 , 0.6 mL). Due to the similar R_f values of the aziridine products, the mixtures were not purified from the competition experiments; determination of the product ratios was carried out using quantitative ^1H NMR spectroscopy and an internal standard as described above.

For the purposes of isolation and characterization, the general procedure was followed utilizing a single alkene substrate, even though Rh_2esp_2 may not be the optimal catalyst for all substrates.

Compound 3 (Dfs protecting group)

The product was purified by column chromatography using 0 $\rightarrow$ 10% gradient of EtOAc in pentanes with 5% increments; yield: 56.8 mg (0.18 mmol, 67%); clear white oil; R_f = 0.41 (25% EtOAc/hexanes).

^1H NMR (400 MHz, CDCl_3): δ = 7.36 (m, 3 H), 7.30 (dt, J = 6.8, 2.5 Hz, 2 H), 7.23 (tt, J = 8.6, 5.9 Hz, 1 H), 7.00 (dd, J = 8.7, 7.5 Hz, 2 H), 3.95 (dd, J = 7.3, 4.7 Hz, 1 H), 3.16 (d, J = 7.2 Hz, 1 H), 2.68 (d, J = 4.7 Hz, 1 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 155.79 (dd, J = 254.9, 2.9 Hz), 133.88, 128.81, 128.67, 127.90 (t, J = 9.1 Hz), 126.91 (t, J = 15.6 Hz), 126.57, 112.59 (dd, J = 18.3, 4.0 Hz), 43.29, 38.24.

^{19}F NMR (377 MHz, CDCl_3): δ = -123.53 (s, 2 F).

HRMS (ESI): m/z [$\text{M} + \text{NH}_4$] $^+$ calcd for $\text{C}_{14}\text{H}_{11}\text{F}_2\text{NO}_3\text{S}$: 329.0766; found: 329.0764.

Compound 4a (Dfs protecting group)

The product was purified by column chromatography using 0 $\rightarrow$ 10% gradient of EtOAc in pentanes with 5% increments; yield: 40.5 mg (0.13 mmol, 52%); clear white oil; R_f = 0.50 (20% EtOAc/hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 7.24 (tt, J = 8.6, 5.9 Hz, 1 H), 7.02 (dd, J = 8.7, 7.5 Hz, 2 H), 2.97 (ddd, J = 12.1, 6.6, 5.1 Hz, 1 H), 2.81 (d, J = 7.0 Hz, 1 H), 2.35 (d, J = 4.9 Hz, 1 H), 1.62 (dddd, J = 20.2, 14.3, 7.7, 2.1 Hz, 2 H), 1.51–1.40 (m, 2 H), 1.38–1.23 (m, 6 H), 0.88 (t, J = 6.8 Hz, 3 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 155.85 (d, J = 254.5 Hz), 127.70 (t, J = 9.1 Hz), 126.94 (t, J = 15.5 Hz), 112.56 (dd, J = 18.3, 4.1 Hz), 42.97, 35.95, 31.57, 30.96, 28.74, 26.20, 22.50, 14.02.

^{19}F NMR (377 MHz, CDCl_3): δ = -123.69 (s, 2 F).

HRMS (ESI): m/z [$\text{M} + \text{Na}$] $^+$ calcd for $\text{C}_{14}\text{H}_{11}\text{F}_2\text{NO}_3\text{SNa}$: 342.0946; found: 342.0941.

Compound 4b (Dfs protecting group)

The product was purified by column chromatography using 0 $\rightarrow$ 10% gradient of EtOAc in pentanes with 5% increments; yield: 48.8 mg (0.15 mmol, 60%); clear white oil; R_f = 0.47 (20% EtOAc/hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 7.24 (tt, J = 8.6, 5.9 Hz, 1 H), 7.01 (dd, J = 8.7, 7.5 Hz, 2 H), 2.81 (td, J = 7.0, 4.6 Hz, 1 H), 2.78 (d, J = 7.0 Hz, 1 H), 2.42 (d, J = 4.5 Hz, 1 H), 1.91–1.63 (m, 5 H), 1.37–1.05 (m, 6 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 155.88 (dd, J = 254.5, 3.1 Hz), 127.68 (t, J = 9.1 Hz), 126.91 (t, J = 15.5 Hz), 112.55 (dd, J = 18.3, 4.1 Hz), 47.34, 38.98, 34.84, 29.86, 29.22, 26.00, 25.54, 25.35.

^{19}F NMR (377 MHz, CDCl_3): δ = -123.73 (s, 2 F).

HRMS (ESI): m/z [$\text{M} + \text{Na}$] $^+$ calcd for $\text{C}_{14}\text{H}_{17}\text{F}_2\text{NO}_3\text{SNa}$: 340.0789; found: 340.0783.

Compound 4c (Dfs protecting group)

The product was purified by column chromatography using 0 $\rightarrow$ 10% gradient of EtOAc in pentanes with 5% increments; yield: 39.4 mg (0.13 mmol, 48%); clear white oil; R_f = 0.63 (20% EtOAc/hexanes).

^1H NMR (400 MHz, CDCl_3): δ = 7.22 (tt, J = 8.6, 5.9 Hz, 1 H), 7.00 (dd, J = 8.7, 7.5 Hz, 2 H), 2.77 (p, J = 4.7 Hz, 2 H), 1.99–1.87 (m, 2 H), 1.66–1.40 (m, 6 H), 0.98 (t, J = 7.2 Hz, 6 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 156.02 (dd, J = 254.5, 3.1 Hz), 127.56 (t, J = 9.1 Hz), 127.07 (t, J = 15.5 Hz), 112.52 (dd, J = 18.3, 4.1 Hz), 50.64, 31.54, 20.18, 13.77.

^{19}F NMR (377 MHz, CDCl_3): δ = -123.27 (s, 2 F).

HRMS (ESI): m/z [$\text{M} + \text{Na}$] $^+$ calcd for $\text{C}_{14}\text{H}_{19}\text{F}_2\text{NO}_3\text{SNa}$: 342.0946; found: 342.0942.

Compound 4d (Dfs protecting group)

The product was purified by column chromatography using 0 $\rightarrow$ 10% gradient of EtOAc in pentanes with 5% increments; yield: 53.4 mg (0.17 mmol, 64%); clear white oil; R_f = 0.56 (20% EtOAc/hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 7.23 (tt, J = 8.5, 5.8 Hz, 1 H), 7.01 (dd, J = 8.7, 7.6 Hz, 2 H), 3.03 (dq, J = 5.3, 1.9 Hz, 2 H), 1.67–1.45 (m, 7 H), 1.03–0.96 (m, 6 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 155.89 (dd, J = 254.5, 3.2 Hz), 127.54 (t, J = 9.2 Hz), 126.86 (t, J = 15.6 Hz), 112.52 (dd, J = 18.3, 4.1 Hz), 47.61, 28.59, 20.29, 13.78.

^{19}F NMR (377 MHz, CDCl_3): δ = -123.60 (s, 2 F).

HRMS (ESI): m/z [$\text{M} + \text{Na}$] $^+$ calcd for $\text{C}_{14}\text{H}_{19}\text{F}_2\text{NO}_3\text{SNa}$: 342.0946; found: 342.0943.

Compound 4f (Dfs protecting group)

The product was purified by column chromatography using 0 $\rightarrow$ 10% gradient of EtOAc in pentanes with 5% increments; yield: 50.0 mg (0.18 mmol, 68%); clear white oil; R_f = 0.43 (20% EtOAc/hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 7.22 (tt, J = 8.5, 5.8 Hz, 1 H), 7.00 (dd, J = 8.7, 7.6 Hz, 2 H), 3.04 (q, J = 5.9 Hz, 1 H), 1.64 (s, 3 H), 1.34 (d, J = 5.9 Hz, 3 H), 1.30 (s, 3 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 155.98 (dd, J = 254.5, 3.2 Hz), 127.49 (t, J = 9.2 Hz), 127.12 (t, J = 15.4 Hz), 112.46 (dd, J = 18.5, 4.1 Hz), 52.27, 50.75, 20.96, 20.20, 12.67 (d, J = 1.4 Hz).

^{19}F NMR (377 MHz, CDCl_3): δ = -123.32 (s, 2 F).

HRMS (ESI): m/z [$\text{M} + \text{Na}$] $^+$ calcd for $\text{C}_{11}\text{H}_{13}\text{F}_2\text{NO}_3\text{SNa}$: 300.0476; found: 300.0472.

Compound 4g (Dfs protecting group)

The product was purified by column chromatography using 0 $\rightarrow$ 10% gradient of EtOAc in hexanes with 5% increments; yield: 46.8 mg (0.16 mmol, 60%); clear white oil; R_f = 0.45 (25% EtOAc/hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 7.21 (tt, J = 8.5, 5.8 Hz, 1 H), 6.99 (dd, J = 8.6, 7.5 Hz, 2 H), 1.49 (s, 12 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 156.08 (dd, J = 254.5, 3.5 Hz), 127.29 (t, J = 9.2 Hz), 127.16 (t, J = 15.3 Hz), 112.40 (dd, J = 18.5, 4.1 Hz), 55.18, 19.97.

^{19}F NMR (377 MHz, CDCl_3): δ = -123.25 (s, 2 F).

HRMS (ESI): m/z [$\text{M} + \text{Na}$] $^+$ calcd for $\text{C}_{12}\text{H}_{15}\text{F}_2\text{NO}_3\text{SNa}$: 314.0633; found: 314.0627.

Compound 6a (Dfs protecting group)

The product was purified by column chromatography using 0 → 10% gradient of EtOAc in hexanes with 5% increments; yield: 88.7 mg (0.23 mmol, 86%); clear white oil; R_f = 0.34 (15% EtOAc/hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 7.62 (d, J = 8.1 Hz, 2 H), 7.43 (d, J = 8.0 Hz, 2 H), 7.25 (tt, J = 8.5, 5.8 Hz, 1 H), 7.01 (dd, J = 8.8, 7.6 Hz, 2 H), 3.99 (dd, J = 7.3, 4.6 Hz, 1 H), 3.20 (d, J = 7.2 Hz, 1 H), 2.66 (d, J = 4.5 Hz, 1 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 155.71 (dd, J = 254.7, 2.8 Hz), 138.06 (d, J = 1.7 Hz), 130.97 (q, J = 32.6 Hz), 128.14 (t, J = 9.1 Hz), 126.97, 126.83 (t, J = 15.5 Hz), 125.68 (q, J = 3.8 Hz), 123.79 (q, J = 271.5 Hz), 112.66 (dd, J = 18.4, 3.9 Hz), 42.37, 38.35.

^{19}F NMR (377 MHz, CDCl_3): δ = -62.70 (s, 3 F), -123.66 (s, 2 F).

HRMS (ESI): m/z [$\text{M} + \text{Na}$] $^+$ calcd for $\text{C}_{15}\text{H}_{10}\text{F}_5\text{NO}_3\text{SNa}$: 402.0194; found: 402.0192.

Compound 6b (Dfs protecting group)

The product was purified by column chromatography using 0 → 10% gradient of EtOAc in hexanes with 5% increments; yield: 44.1 mg (0.14 mmol, 53%); clear white oil; R_f = 0.36 (15% EtOAc/hexanes).

^1H NMR (500 MHz, CDCl_3): δ = 7.38–7.32 (m, 3 H), 7.27 (dd, J = 7.3, 2.4 Hz, 2 H), 7.18 (tt, J = 8.5, 5.8 Hz, 1 H), 6.93 (dd, J = 8.7, 7.5 Hz, 2 H), 3.84 (d, J = 4.6 Hz, 1 H), 3.08 (qd, J = 6.0, 4.5 Hz, 1 H), 1.77 (d, J = 6.0 Hz, 3 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 155.79 (dd, J = 255.0, 3.0 Hz), 134.11, 128.67, 128.52, 127.66 (t, J = 9.1 Hz), 126.96 (t, J = 15.5 Hz), 126.72, 51.56, 48.87, 13.68.

^{19}F NMR (377 MHz, CDCl_3): δ = -122.98 (s, 2 F).

HRMS (ESI): m/z [$\text{M} + \text{Na}$] $^+$ calcd for $\text{C}_{15}\text{H}_{13}\text{F}_2\text{NO}_3\text{SNa}$: 348.0476; found: 348.0471.

Compound 6c (Dfs protecting group)

The product was purified by column chromatography using 0 → 10% gradient of EtOAc in hexanes with 5% increments; yield: 57.1 mg (0.17 mmol, 65%); yellow oil; R_f = 0.33 (15% EtOAc/hexanes).

^1H NMR (400 MHz, CDCl_3): δ = 7.33 (m, 5 H), 7.21 (tt, J = 8.1, 5.8 Hz, 1 H), 6.99 (dd, J = 8.6, 7.4 Hz, 2 H), 4.15 (s, 1 H), 1.83 (s, 3 H), 1.16 (s, 3 H).

^{13}C NMR (126 MHz, CDCl_3): δ = 155.88 (dd, J = 254.4, 3.2 Hz), 133.13, 128.32, 128.07, 127.55 (t, J = 9.1 Hz), 127.21, 127.07 (t, J = 15.7 Hz), 112.49 (dd, J = 18.3, 4.1 Hz), 55.92, 54.47, 20.96, 20.40.

^{19}F NMR (377 MHz, CDCl_3): δ = -123.28 (s, 2 F).

HRMS (ESI): m/z [$\text{M} + \text{Na}$] $^+$ calcd for $\text{C}_{16}\text{H}_{15}\text{F}_2\text{NO}_3\text{SNa}$: 362.0633; found: 362.0626.

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Supporting Information

Supporting information for this article is available online at <https://doi.org/10.1055/s-0037-1609858>.

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