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Photoredox-Enabled Synthesis of α-Alkylated Alkenylammonium Salts

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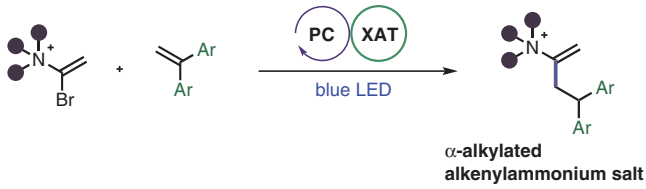

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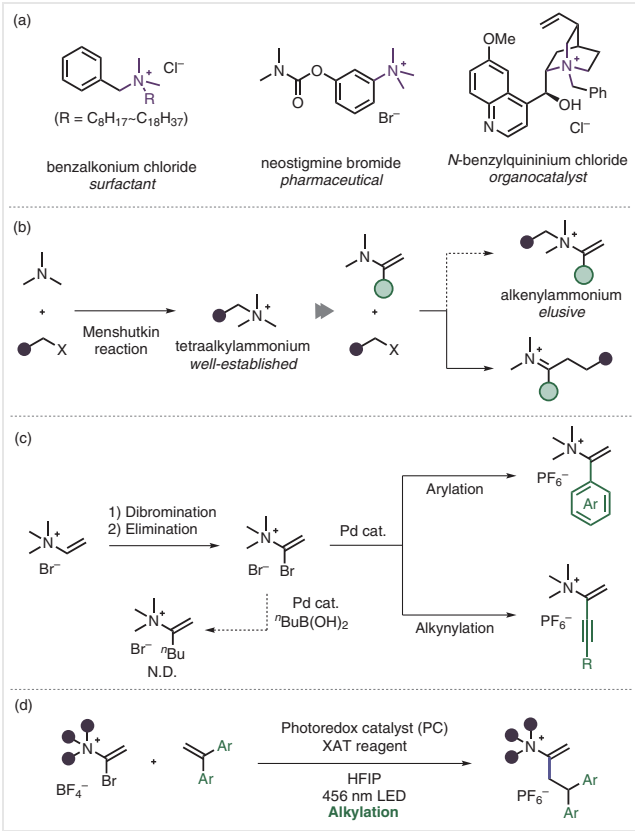
Abstract The development of novel synthetic methods for quaternary ammonium salts is highly demanded since the current synthesis heavily relies on the conventional Menshutkin reaction. Herein, we report photoredox-catalyzed alkylation of α-brominated alkenylammonium salts. Mechanistically, the generation of a highly reactive α-ammoniovinyl radical is the key to our method. This reaction enables the synthesis of various unprecedented α-alkylated alkenylammonium salts.

Key words alkenylammonium salts, photoredox catalyst, alkylation, halogen-atom transfer, quaternary ammonium salts

Quaternary ammonium salts are important chemical compounds, which are widely used as surfactants, pharmaceuticals, and organocatalysts (Scheme 1a).[1] In most cases, these compounds are synthesized through the Menshutkin reaction: quaternarization of tertiary amines.[2] Although this reaction is a practical method for the synthesis of tetraalkylammonium salts, it is difficult to synthesize alkenylammonium salts. This is because the alkylation of the corresponding tertiary enamines is known to proceed on the carbon atom, not on the nitrogen atom (Scheme 1b).[3] While the synthesis of trimethylvinylammonium salt, the simplest alkenylammonium salt, was attained by Kleine in 1904,[4] a versatile synthetic method for α-substituted alkenylammonium salts has not been developed. Because of the lack of reliable synthetic methods, the chemistry of alkenylammonium salts is behind compared to that of alkylammonium salts. Recently, we developed Suzuki–Miyaura or Sonogashira coupling of α-brominated alkenylammonium salts, which leads to structurally new α-arylated or α-alkynylated alkenylammonium salts (Scheme 1c).[5] However, the synthesis of α-alkylated alkenylammonium salts proved to be difficult under these Pd-catalyzed conditions.

Herein, we report the photoredox-catalyzed[6] synthesis of α-alkylated alkenylammonium salts from α-brominated alkenylammonium salts and 1,1-diarylethylenes (Scheme 1d). The halogen-atom transfer (XAT)[7] mediated generation



Scheme 1 (a) Examples of functional quaternary ammonium salts. (b) Synthesis of quaternary ammonium salts using the Menshutkin reaction. (c) Previous work. (d) This work.

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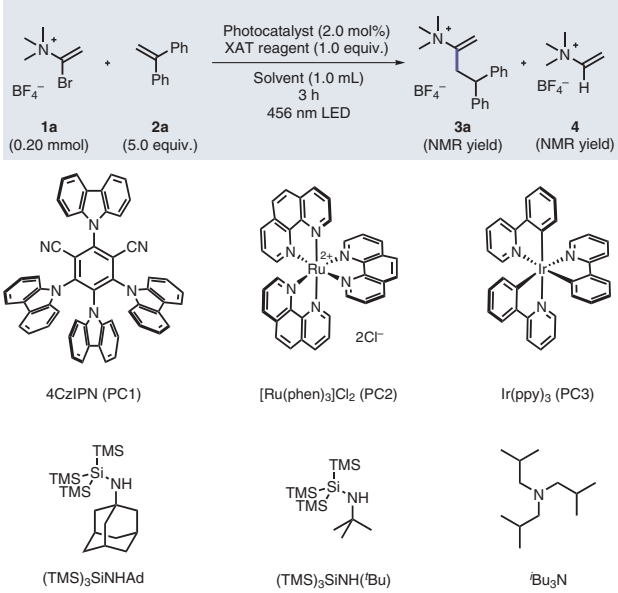
of highly reactive α-ammoniovinyl radical enables this process.

The reaction conditions for the synthesis of α-alkylated alkenylammonium salts were initially screened with α-brominated alkenylammonium salt **1a** and 1,1-diphenylethylene (**2a**) (Table 1). The use of $(TMS)_3SiNHAd$, which is reported by MacMillan and co-workers as a broadly useful XAT reagent,[8] with 4CzIPN (PC1) in MeOH under 456 nm LED irradiation gave α-alkylated alkenylammonium salt **3a** in 54% yield along with 32% of reduced byproduct **4** (entry 1). Byproduct **4** would be generated through hydrogen atom transfer[9] between α-ammoniovinyl radical and MeOH or $(TMS)_3SiNHAd$. A survey of photoredox catalysts revealed that $[Ru(phen)_3]Cl_2$ (PC2) and $Ir(ppy)_3$ (PC3) were not effective, and the conversion of **2a** decreased (entries 2 and 3). In this transformation, dramatic solvent effects were observed. With aprotic polar solvents, such as MeCN, acetone, and THF, the yield and selectivity of **3a** were not satisfactory (entries 4–6), though the exact reason for this is unclear. In addition, ^{t}BuOH was also not an appropriate solvent; on the other hand, the generation of byproduct **4** was almost suppressed by using HFIP as a solvent (entries 7 and 8). By increasing the amount of $(TMS)_3SiNHAd$ and prolonging the reaction time, the yield of **3a** improved to 45% still suppressing the generation of **4** (entries 9 and 10). Another XAT reagent, $(TMS)_3SiNH(^tBu)$, afforded product **3a** in 92% yield while triisobutylamine, which has been used for the generation of C(sp^2) radical,[10] failed to provide **3a** (entries 11 and 12). Finally, the conditions using 6.0 mol% of PC1 gave the best result where 93% of **3a** was obtained with good reproducibility (entry 13). Furthermore, the use of 5.0 equivalents of **2a** proved essential for achieving a high yield (entry 13 vs entries 14 and 15).

A proposed mechanism for this alkylation reaction of α-brominated alkenylammonium salts is described in Scheme 2a. Upon irradiation with blue light, the photoredox catalyst is converted into the long-lived triplet excited state PC*.[6f] Since the excited-state photocatalyst has high oxidation ability, single-electron oxidation of $(TMS)_3SiNH(^tBu)$ proceeds smoothly, and subsequent deprotonation gives *N*-centered radical **A**. Then, the electron-rich α-amino silicon-centered radical **B** is generated through the radical aza-Brook rearrangement of radical **A**.[8] As radical **B** possesses strong halogen abstraction ability, bromine atom transfer from **1a** to radical **B** furnishes the highly reactive α-ammoniovinyl radical **D**, and the reaction of radical **D** with **2a** gives radical intermediate **E**. The resulting radical **E** is reduced to anion intermediate **F** by $PC^{\bullet-}$,[6g] and protonation of **F** gives alkylated product **3a**. In the radical addition step (the reaction of radical **D** with **2a**), when MeOH is used as a solvent, the highly reactive α-ammoniovinyl radical **D** would abstract hydrogen atom from an α-C–H bond of MeOH, which competes with radical addition to **2a**. In contrast, the α-C–H bond of HFIP is less reactive for hydrogen atom abstraction than that of MeOH because of the polar and electrostatic influence of fluorine substituents.[11] The undesired reduction pathway, therefore, is suppressed by using HFIP as the solvent. To confirm the generation of anion intermediate **F**, this reaction was performed in HFIP/D_2O (Scheme 2b). As a result, deuterated product **3a-D**

Table 1 Investigation of the reaction conditions



Entry	Photo-catalyst	XAT reagent	Solvent	Yield (%) of **3a**[a]	Yield (%) of **4**[a]
1	PC1	$(TMS)_3SiNHAd$	MeOH	54	32
2	PC2	$(TMS)_3SiNHAd$	MeOH	12	15
3	PC3	$(TMS)_3SiNHAd$	MeOH	9	25
4	PC1	$(TMS)_3SiNHAd$	MeCN	12	40
5	PC1	$(TMS)_3SiNHAd$	acetone	35	29
6	PC1	$(TMS)_3SiNHAd$	THF	45	48
7	PC1	$(TMS)_3SiNHAd$	^{t}BuOH	43	13
8	PC1	$(TMS)_3SiNHAd$	HFIP	13	3
9[b,c,d]	PC1	$(TMS)_3SiNHAd$	HFIP	40	0
10[b,c,e]	PC1	$(TMS)_3SiNHAd$	HFIP	45	0
11[b,c,e]	PC1	$(TMS)_3SiNH(^tBu)$	HFIP	92	0
12[b,c,e]	PC1	$^iBu_3N$	HFIP	0	0
13[b,c,e,f]	**PC1**	**$(TMS)_3SiNH(^tBu)$**	**HFIP**	**93**	**0**
14[b,c,e,f,g]	PC1	$(TMS)_3SiNH(^tBu)$	HFIP	24	8
15[b,c,e,f,h]	PC1	$(TMS)_3SiNH(^tBu)$	HFIP	44	7

[a] ^{1}H NMR yield using $C_2H_2Cl_4$ as the internal standard.
[b] Reaction time of 16 h.
[c] Using 1.5 mL of HFIP.
[d] Using 2.0 equivalents of XAT reagent.
[e] Using 2.5 equivalents of XAT reagent.
[f] Using 6.0 mol% of PC1.
[g] Using 1.0 equivalents of **2a**.
[h] Using 3.0 equivalents of **2a**.

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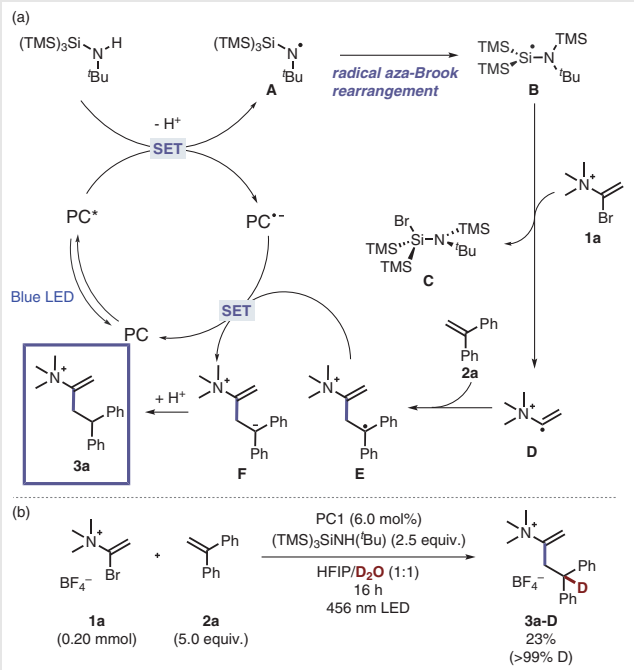
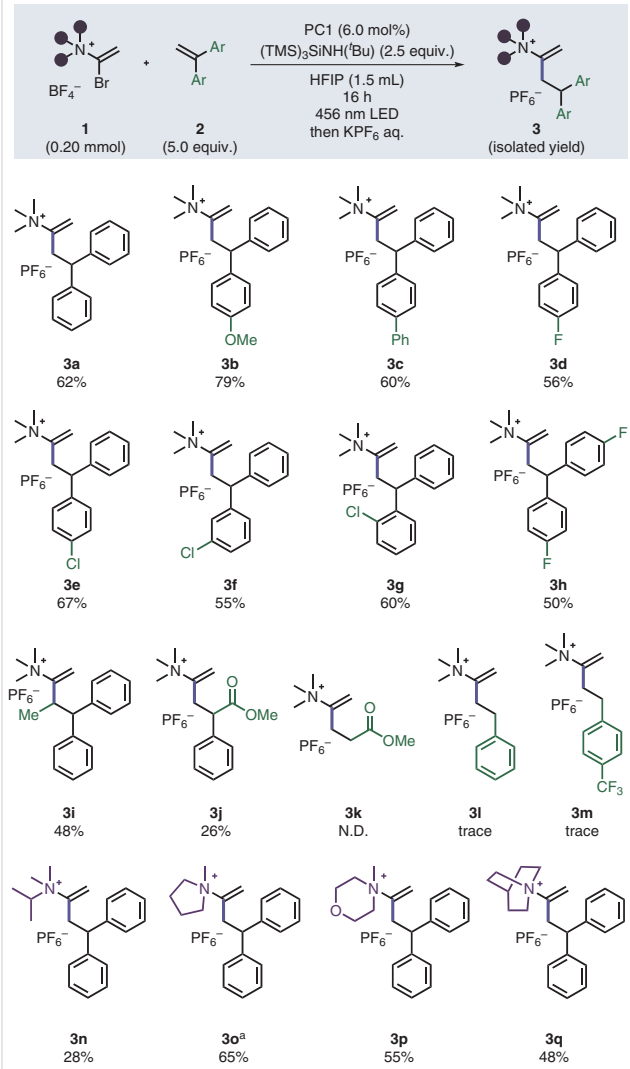
was obtained in 23% (^{1}H NMR yield), along with 40% recovery of **1a**. The result indicates that PC$^{\bullet-}$ reduces radical **E** to anion intermediate **F**, which is then quenched with D_2O.



Scheme 2 (a) Proposed mechanism. (b) Anion intermediate trapping experiment.

With the optimal reaction conditions in hand, we investigated the substrate scope of the synthesis of α-alkylated alkenylammonium salts (Scheme 3). For ease of isolation, the product α-alkylated alkenylammonium salts were collected as the PF_6 salts. In addition to 1,1-diphenylethylene (**2a**), 1,1-diarylethylenes having various substituents, such as a methoxy, phenyl, fluoro, or chloro group, at the *para* position were applicable for this transformation, and the corresponding products **3b**–**3e** were obtained in moderate to good yields (56–79%). Both *meta*- and *ortho*-chlorinated olefins (**2f** and **2g**) were smoothly converted into α-alkylated alkenylammonium salts (**3f** and **3g**). Not only unsymmetrical olefins, but also a symmetrical olefin provided the alkylated product **3h** in 50% yield. Notably, trisubstituted olefin and methyl atropate were compatible with our procedure (**3i** and **3j**), while methyl acrylate and styrene derivatives did not give the corresponding products (**3k**–**3m**). Next, we explored alternative α-brominated alkenylammonium salts in conjunction with 1,1-diphenylethylene (**2a**) as a model olefin. The reaction of the bulkier isopropyldimethylammonium salt gave **3n** in 28% yield. Heterocyclic ammonium salts were also tolerated by this reaction, and **3o**–**3q** were obtained in 48–65% yield.

Considering that there had been no prior examples for the preparation of α-alkylated alkenylammonium salts, we then demonstrated synthetic applications using **3a**. First, a



Scheme 3 Scope of the reaction (N.D. = not detected). [a] hexafluorophosphate salt **1c** was used as the starting material.

scale-up synthesis was accomplished, where 59% of **3a** was obtained on a 2.0-mmol scale (Scheme 4a). Then, derivatizations of obtained **3a** were conducted (Scheme 4b). Hydrogenation of **3a** using Pd/C gave **5** in 24% yield, which is a methylated analogue of plant biostimulant **6** discovered by our group.[12,13] Moreover, selective *N*-demethylation of **3a** occurred in the presence of DABCO, and the corresponding enamine reacted with benzaldehyde to give the condensation product **7** in 79% yield. This result highlights the utility of α-alkylated alkenylammonium salts as a new stable precursor of enamines.

In summary, we have developed a new synthetic method for α-alkylated alkenylammonium salts. Our photocatalytic conditions enable access to various α-alkylated alkenylammonium salts from α-brominated alkenylammonium salts and 1,1-diarylethylenes under mild conditions. Addi-

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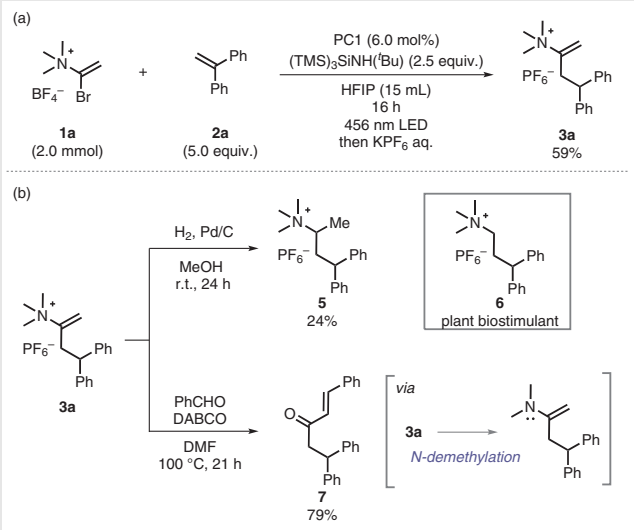

Scheme 4 (a) Scale-up experiment. (b) Transformations of α-alkylated alkenylammonium salt **3a**.

tionally, the scale-up synthesis and derivatizations of product **3a** further enhance the synthetic potential of our method. Further investigation of the physical properties and bioactivity of the obtained products is ongoing in our lab.

General experimental details are given in the Supporting Information.

α-Alkylated Alkenylammonium Salt 3a; Typical Procedure

A dried reaction tube with a stirring bar was charged with 1-bromo-*N*,*N*,*N*-trimethylethenammonium tetrafluoroborate (**1a**, 50 mg, 0.20 mmol, 1.0 equiv.), 4CzIPN (9.6 mg, 0.012 mmol, 6.0 mol%), and $(TMS)_3SiNHAd(^tBu)$ (160 mg, 0.50 mmol, 2.5 equiv.). The tube was filled with nitrogen by employing the usual Schlenk technique (evacuate–refill cycle). HFIP (1.5 mL) and 1,1-diphenylethylene (**2a**, 180 mg, 1.0 mmol, 5.0 equiv.) were added to the tube and the mixture was stirred under blue light irradiation with a cooling fan (a 40 W Kessil PR160 blue LED was placed 1 cm below the reaction vial) for 16 h. The crude mixture was concentrated in vacuo and purified by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH = 80:20) to provide the product. To exchange the counter anion, the obtained product was dissolved in CH_2Cl_2 and washed with saturated aqueous KPF_6 solution three times. The organic layer was dried with Na_2SO_4, filtered, and concentrated in vacuo. The crude product was recrystallized (CH_2Cl_2/Et_2O) to give **3a** (52.1 mg) as a white solid, which contained 0.25 mg of acetone, 0.28 mg of MeOH, and 0.94 mg of CH_2Cl_2. The yield of **3a** was calculated as 62%. Note: the ratio of **3a**, acetone, MeOH, and CH_2Cl_2 was determined by ^{1}H NMR since acetone, MeOH, and CH_2Cl_2 were not completely removed after drying in vacuo for 24 h.

Mp 190 °C (dec).

^{1}H NMR (500 MHz, CD_3CN): δ = 3.16–3.18 (m, 11 H), 4.36 (t, *J* = 8.0 Hz, 1 H), 5.26 (brs, 1 H), 5.59 (d, *J* = 5.5 Hz, 1 H), 7.23 (t, *J* = 7.5 Hz, 2 H), 7.33 (t, *J* = 7.5 Hz, 4 H), 7.37 (d, *J* = 7.5 Hz, 4 H).

^{13}C NMR (126 MHz, CD_3CN): δ = 33.8, 49.6, 54.9, 111.8, 127.7, 128.6, 129.7, 144.1, 152.1.

^{19}F NMR (471 MHz, CD_3CN): δ = –71.4 (d, *J* = 705 Hz).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{19}H_{24}N$: 266.1909 $[M]^+$; found: 266.1919.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9644.

3b

Synthesized according to the typical procedure from **1a** (51 mg, 0.20 mmol) using 1-(4-methoxyphenyl)-1-phenylethene (**2b**, 220 mg, 1.0 mmol) and $(TMS)_3SiNH(^tBu)$ (160 mg, 0.50 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 80:20) and recrystallization (CH_2Cl_2/Et_2O) afforded **3b** (69.9 mg) as a pale yellow solid, which contained 0.27 mg of Et_2O. The yield of **3b** was calculated as 79%. Note: the ratio of **3b** and Et_2O was determined by ^{1}H NMR since Et_2O was not completely removed after drying in vacuo for 24 h.

Mp 119 °C (dec).

^{1}H NMR (500 MHz, CD_3CN): δ = 3.13 (d, *J* = 8.0 Hz, 2 H), 3.16 (s, 9 H), 3.74 (s, 3 H), 4.30 (t, *J* = 8.0 Hz, 1 H), 5.25 (brs, 1 H), 5.59 (d, *J* = 4.0 Hz, 1 H), 6.87 (d, *J* = 9.0 Hz, 2 H), 7.22 (t, *J* = 7.0 Hz, 1 H), 7.27 (d, *J* = 8.5 Hz, 2 H), 7.31–7.36 (m, 4 H).

^{13}C NMR (126 MHz, CD_3CN): δ = 34.0, 48.9, 54.9, 55.8, 111.7, 114.9, 127.6, 128.5, 129.6, 129.7, 136.0, 144.5, 152.2, 159.4.

^{19}F NMR (471 MHz, CD_3CN): δ = –71.4 (d, *J* = 707 Hz).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{20}H_{26}NO$: 296.2014 $[M]^+$; found: 296.2014.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9636.

3c

Synthesized according to the typical procedure from **1a** (50 mg, 0.20 mmol) using 4-(1-phenylethenyl)-1,1′-biphenyl (**2c**, 260 mg, 1.0 mmol) and $(TMS)_3SiNH(^tBu)$ (180 mg, 0.55 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 95:5 to 90:10) and recrystallization (CH_2Cl_2/Et_2O) afforded **3c** (62.8 mg) as a yellow solid, which contained 1.6 mg of Et_2O, 1.1 mg of acetone, and 0.33 mg of MeOH. The yield of **3c** was calculated as 60%. Note: the ratio of **3c**, Et_2O, acetone, and MeOH was determined by ^{1}H NMR since Et_2O, acetone, and MeOH were not completely removed after drying in vacuo for 24 h.

Mp 134 °C (dec).

^{1}H NMR (500 MHz, CD_3CN): δ = 3.19 (s, 9 H), 3.22 (d, *J* = 7.5 Hz, 2 H), 4.41 (t, *J* = 7.5 Hz, 1 H), 5.30 (brs, 1 H), 5.62 (d, *J* = 4.5 Hz, 1 H), 7.24 (t, *J* = 7.5 Hz, 1 H), 7.34–7.37 (m, 3 H), 7.40–7.47 (m, 6 H), 7.61 (d, *J* = 8.0 Hz, 4 H).

^{13}C NMR (126 MHz, CD_3CN): δ = 33.8, 49.3, 55.0, 111.8, 127.7, 127.8, 128.2, 128.4, 128.6, 129.1, 129.79, 129.83, 140.3, 141.1, 143.4, 144.0, 152.1.

^{19}F NMR (471 MHz, CD_3CN): δ = –71.4 (d, *J* = 707 Hz).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{25}H_{28}N$: 342.2222 $[M]^+$; found: 342.2205.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9637.

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3d

Synthesized according to the typical procedure from **1a** (51 mg, 0.20 mmol) using 1-(4-fluorophenyl)-1-phenylethene (**2d**, 210 mg, 1.0 mmol) and $(TMS)_3SiNH(^tBu)$ (190 mg, 0.58 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 80:20) and recrystallization (CH_2Cl_2/Et_2O) afforded **3d** (48.8 mg) as a pale yellow solid, which contained 0.24 mg of acetone and 0.85 mg of CH_2Cl_2. The yield of **3d** was calculated as 56%. Note: the ratio of **3d**, acetone, and CH_2Cl_2 was determined by ^1H NMR since acetone and CH_2Cl_2 were not completely removed after drying in vacuo for 24 h.

Mp 152 °C (dec).

^1H NMR (500 MHz, CD_3CN): δ = 3.13–3.18 (m, 11 H), 4.37 (t, *J* = 8.0 Hz, 1 H), 5.25 (brs, 1 H), 5.60 (d, *J* = 5.0 Hz, 1 H), 7.07 (t, *J* = 8.5 Hz, 2 H), 7.23 (t, *J* = 6.5 Hz, 1 H), 7.32–7.39 (m, 6 H).

^{13}C NMR (126 MHz, CD_3CN): δ = 34.1, 48.9, 55.0, 112.0, 116.3 (d, *J* = 21.6 Hz), 127.9, 128.6, 129.8, 130.4 (d, *J* = 8.4 Hz), 140.2 (d, *J* = 3.6 Hz), 143.9, 152.0, 162.5 (d, *J* = 244 Hz).

^{19}F NMR (471 MHz, CD_3CN): δ = –71.4 (d, *J* = 707 Hz, 6 F), –116.2 (m, 1 F).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{19}H_{23}FN$: 284.1815 $[M]^+$; found: 284.1825.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9648.

3e

Synthesized according to the typical procedure from **1a** (51 mg, 0.20 mmol) using 1-(4-chlorophenyl)-1-phenylethene (**2e**, 220 mg, 1.0 mmol) and $(TMS)_3SiNH(^tBu)$ (210 mg, 0.67 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 80:20) and recrystallization (CH_2Cl_2/Et_2O) afforded **3e** (66.0 mg) as a yellow solid, which contained 3.7 mg of Et_2O and 2.8 mg of CH_2Cl_2. The yield of **3e** was calculated as 67%. Note: the ratio of **3e**, Et_2O, and CH_2Cl_2 was determined by ^1H NMR since Et_2O and CH_2Cl_2 were not completely removed after drying in vacuo for 24 h.

Mp 129.4–134.2 °C.

^1H NMR (500 MHz, CD_3CN): δ = 3.14–3.16 (m, 11 H), 4.36 (t, *J* = 8.0 Hz, 1 H), 5.24 (brs, 1 H), 5.60 (d, *J* = 4.5 Hz, 1 H), 7.22–7.26 (m, 1 H), 7.32–7.37 (m, 8 H).

^{13}C NMR (126 MHz, CD_3CN): δ = 33.8, 49.0, 55.0, 112.0, 128.0, 128.6, 129.7, 129.8, 130.3, 133.0, 143.0, 143.6, 151.9.

^{19}F NMR (471 MHz, CD_3CN): δ = –71.4 (d, *J* = 705 Hz).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{19}H_{23}ClN$: 300.1519 $[M]^+$; found: 300.1504.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9644.

3f

Synthesized according to the typical procedure from **1a** (50 mg, 0.20 mmol) using 1-(3-chlorophenyl)-1-phenylethene (**2f**, 220 mg, 1.0 mmol) and $(TMS)_3SiNH(^tBu)$ (160 mg, 0.52 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 90:10) and recrystallization (CH_2Cl_2/*n*-hexane) afforded **3f** (49.0 mg, 0.110 mmol, 55%) as a pale yellow solid.

Mp 144 °C (dec).

^1H NMR (500 MHz, CD_3CN): δ = 3.15–3.17 (m, 11 H), 4.37 (t, *J* = 8.0 Hz, 1 H), 5.24 (brs, 1 H), 5.60 (d, *J* = 5.0 Hz, 1 H), 7.23–7.26 (m, 2 H), 7.31–7.38 (m, 6 H), 7.43 (s, 1 H).

^{13}C NMR (126 MHz, CD_3CN): δ = 33.5, 49.2, 54.9, 111.9, 127.2, 127.8, 128.0, 128.5, 128.6, 129.8, 131.3, 134.9, 143.2, 146.5, 151.8.

^{19}F NMR (471 MHz, CD_3CN): δ = –71.4 (d, *J* = 707 Hz).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{19}H_{23}ClN$: 300.1519 $[M]^+$; found: 300.1516.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9639.

3g

Synthesized according to the typical procedure from **1a** (50 mg, 0.20 mmol) using 1-(2-chlorophenyl)-1-phenylethene (**2g**, 220 mg, 1.0 mmol) and $(TMS)_3SiNH(^tBu)$ (210 mg, 0.67 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 80:20) and recrystallization (CH_2Cl_2/Et_2O) afforded **3g** (54.5 mg, 0.122 mmol, 60%) as a pale yellow solid.

Mp 134 °C (dec).

^1H NMR (500 MHz, CD_3CN): δ = 3.15–3.18 (m, 11 H), 4.84 (t, *J* = 8.0 Hz, 1 H), 5.19 (brs, 1 H), 5.60 (d, *J* = 5.5 Hz, 1 H), 7.26 (t, *J* = 7.5 Hz, 2 H), 7.33–7.38 (m, 5 H), 7.43 (dd, *J* = 7.5, 1.5 Hz, 1 H), 7.50 (dd, *J* = 7.5, 1.5 Hz, 1 H).

^{13}C NMR (126 MHz, CD_3CN): δ = 33.8, 45.5, 55.0, 111.8, 128.0, 128.6, 129.1, 129.3, 129.4, 129.7, 130.8, 134.4, 140.8, 142.3, 151.8.

^{19}F NMR (471 MHz, CD_3CN): δ = –71.4 (d, *J* = 704 Hz).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{19}H_{23}ClN$: 300.1519 $[M]^+$; found: 300.1519.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9643.

3h

Synthesized according to the typical procedure from **1a** (50 mg, 0.20 mmol) using 1,1-bis(4-fluorophenyl)ethene (**2h**, 220 mg, 1.0 mmol) and $(TMS)_3SiNH(^tBu)$ (180 mg, 0.55 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 95:5 to 86:14) and recrystallization (CH_2Cl_2/Et_2O) afforded **3h** (46.0 mg) as a white solid, which contained 0.32 mg of Et_2O, 0.51 mg of acetone, and 0.35 mg of CH_2Cl_2. The yield of **3h** was calculated as 50%. Note: the ratio of **3h**, Et_2O, acetone, and CH_2Cl_2 was determined by ^1H NMR since Et_2O, acetone, and CH_2Cl_2 were not completely removed after drying in vacuo for 24 h.

Mp 150 °C (dec).

^1H NMR (500 MHz, CD_3CN): δ = 3.11 (d, *J* = 7.5 Hz, 2 H), 3.15 (s, 9 H), 4.38 (t, *J* = 8.0 Hz, 1 H), 5.24 (brs, 1 H), 5.61 (d, *J* = 4.5 Hz, 1 H), 7.06–7.11 (m, 4 H), 7.35–7.38 (m, 4 H).

^{13}C NMR (126 MHz, CD_3CN): δ = 34.2, 48.0, 54.9, 112.0, 116.3 (d, *J* = 21.6 Hz), 130.4 (d, *J* = 8.4 Hz), 139.9 (d, *J* = 3.6 Hz), 151.7, 162.5 (d, *J* = 244 Hz).

^{19}F NMR (471 MHz, CD_3CN): δ = –71.4 (d, *J* = 705 Hz, 6 F), –116.1 (m, 2 F).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{19}H_{22}F_2N$: 302.1720 $[M]^+$; found: 302.1721.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9637.

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3i

Synthesized according to the typical procedure from **1a** (50 mg, 0.20 mmol) using 1,1-diphenylpropene (**2i**, 190 mg, 1.0 mmol) and $(TMS)_3SiNH(^tBu)$ (170 mg, 0.54 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 80:20) and recrystallization (CH_2Cl_2/Et_2O) afforded **3i** (41.5 mg) as a pale yellow solid, which contained 0.75 mg of Et_2O. The yield of **3i** was calculated as 48%. Note: the ratio of **3i** and Et_2O was determined by ^1H NMR since Et_2O was not completely removed after drying in vacuo for 24 h.

Mp 134 °C (dec).

^1H NMR (500 MHz, CD_3CN): δ = 1.21 (d, *J* = 7.0 Hz, 3 H), 2.90 (s, 9 H), 3.36–3.40 (m, 1 H), 4.10 (d, *J* = 11.5 Hz, 1 H), 5.76–5.79 (m, 2 H), 7.16 (t, *J* = 7.5 Hz, 1 H), 7.22–7.31 (m, 5 H), 7.39 (t, *J* = 8.0 Hz, 2 H), 7.54 (d, *J* = 8.0 Hz, 2 H).

^{13}C NMR (126 MHz, CD_3CN): δ = 24.3, 38.7, 54.6, 59.6, 111.9, 127.77, 127.82, 129.3, 129.4, 129.7, 130.0, 143.0, 143.4, 158.0.

^{19}F NMR (471 MHz, CD_3CN): δ = –71.4 (d, *J* = 705 Hz).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{20}H_{26}N$: 280.2065 $[M]^+$; found: 280.2068.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9639.

3j

Synthesized according to the typical procedure from **1a** (50 mg, 0.20 mmol) using methyl atropate (**2j**, 98 mg, 0.60 mmol, 3.0 equiv.) and $(TMS)_3SiNH(^tBu)$ (170 mg, 0.54 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 25:75) and recrystallization (MeOH/Et_2O) afforded **3j** (20.8 mg, 0.0529 mmol, 26%) as a white solid.

Mp 169.1–169.9 °C.

^1H NMR (500 MHz, CD_3CN): δ = 2.76 (dd, *J* = 17.5, 6.0 Hz, 1 H), 3.15 (dd, *J* = 17.5, 9.5 Hz, 1 H), 3.21 (s, 9 H), 3.63 (s, 3 H), 4.06 (dd, *J* = 9.5, 6.0 Hz, 1 H), 5.33 (brs, 1 H), 5.64 (d, *J* = 5.0 Hz, 1 H), 7.33–7.41 (m, 5 H).

^{13}C NMR (126 MHz, CD_3CN): δ = 32.3, 50.0, 53.0, 54.9, 110.7, 128.8, 129.0, 129.9, 138.2, 151.7, 173.5.

^{19}F NMR (471 MHz, CD_3CN): δ = –71.4 (d, *J* = 707 Hz).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{15}H_{22}NO_2$: 248.1651 $[M]^+$; found: 248.1652.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9636.

3n

Synthesized according to the typical procedure from 1-bromo-*N*-(2-propyl)-*N*,*N*-dimethylethenammonium tetrafluoroborate (**1b**, 56 mg, 0.20 mmol) using 1,1-diphenylethylene (**2a**, 180 mg, 1.0 mmol) and $(TMS)_3SiNH(^tBu)$ (170 mg, 0.52 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 95:5) and recrystallization (CH_2Cl_2/Et_2O) afforded **3n** (24.8 mg, 0.0566 mmol, 28%) as a white solid.

Mp 137 °C (dec).

^1H NMR (500 MHz, CD_3CN): δ = 1.17 (d, *J* = 6.5 Hz, 6 H), 2.99 (s, 6 H), 3.13 (d, *J* = 7.5 Hz, 2 H), 3.95–4.00 (m, 1 H), 4.39 (t, *J* = 7.5 Hz, 1 H), 5.44 (brs, 1 H), 5.55 (d, *J* = 5.0 Hz, 1 H), 7.22 (t, *J* = 7.5 Hz, 2 H), 7.33 (t, *J* = 7.5 Hz, 4 H), 7.39 (d, *J* = 7.5 Hz, 4 H).

^{13}C NMR (126 MHz, CD_3CN): δ = 16.3, 34.0, 48.1, 49.6, 65.7, 113.4, 127.8, 128.5, 129.7, 144.2, 150.9.

^{19}F NMR (471 MHz, CD_3CN): δ = –71.4 (d, *J* = 705 Hz).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{21}H_{28}N$: 294.2222 $[M]^+$; found: 294.2231.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9639.

3o

Synthesized according to the typical procedure from *N*-(1-bromoethenyl)-*N*-methylpyrrolidinium hexafluorophosphate (**1c**, 68 mg, 0.20 mmol) using 1,1-diphenylethylene (**2a**, 180 mg, 0.98 mmol) and $(TMS)_3SiNH(^tBu)$ (160 mg, 0.51 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 80:20) and recrystallization (CH_2Cl_2/Et_2O) afforded **3o** (56.9 mg, 0.130 mmol, 65%) as a pale yellow solid.

Mp 148 °C (dec).

^1H NMR (500 MHz, CD_2Cl_2): δ = 2.21–2.28 (m, 4 H), 3.08 (s, 3 H), 3.16 (d, *J* = 7.5 Hz, 2 H), 3.53–3.58 (m, 2 H), 3.68–3.72 (m, 2 H), 4.27 (t, *J* = 7.5 Hz, 1 H), 5.35 (brs, 1 H), 5.55 (d, *J* = 5.0 Hz, 1 H), 7.24 (t, *J* = 7.0 Hz, 2 H), 7.30–7.36 (m, 8 H).

^{13}C NMR (126 MHz, CD_2Cl_2): δ = 20.9, 35.4, 49.8, 50.9, 64.5, 112.7, 127.6, 127.9, 129.4, 142.6, 150.6.

^{19}F NMR (471 MHz, CD_2Cl_2): δ = –73.0 (d, *J* = 711 Hz).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{21}H_{26}N$: 292.2065 $[M]^+$; found: 292.2074.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9642.

3p

Synthesized according to the typical procedure from *N*-(1-bromoethenyl)-*N*-methylmorpholinium tetrafluoroborate (**1d**, 59 mg, 0.20 mmol) using 1,1-diphenylethylene (**2a**, 180 mg, 1.0 mmol) and $(TMS)_3SiNH(^tBu)$ (160 mg, 0.51 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 80:20) and recrystallization (CH_2Cl_2/Et_2O) afforded **3p** (49.8 mg, 0.110 mmol, 55%) as a pale yellow solid.

Mp 160 °C (dec).

^1H NMR (500 MHz, CD_3CN): δ = 3.10 (d, *J* = 7.5 Hz, 2 H), 3.12 (s, 3 H), 3.48–3.53 (m, 2 H), 3.71–3.76 (m, 2 H), 3.79–3.82 (m, 2 H), 3.89–3.92 (m, 2 H), 4.40 (t, *J* = 7.5 Hz, 1 H), 5.51 (brs, 1 H), 5.60 (d, *J* = 5.0 Hz, 1 H), 7.23 (t, *J* = 7.5 Hz, 2 H), 7.33 (t, *J* = 7.5 Hz, 4 H), 7.39 (d, *J* = 7.5 Hz, 4 H).

^{13}C NMR (126 MHz, CD_3CN): δ = 33.8, 49.4, 53.4, 60.7, 62.1, 114.8, 127.8, 128.5, 129.8, 144.0, 148.8.

^{19}F NMR (471 MHz, CD_3CN): δ = –71.4 (d, *J* = 705 Hz).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{21}H_{26}NO$: 308.2014 $[M]^+$; found: 308.2007.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9640.

3q

Synthesized according to the typical procedure from *N*-(1-bromoethenyl)quinuclidium tetrafluoroborate (**1e**, 60 mg, 0.20 mmol) using 1,1-diphenylethylene (**2a**, 180 mg, 1.0 mmol) and $(TMS)_3SiNH(^tBu)$ (160 mg, 0.51 mmol). Purification by flash column chromatography on NaBr-treated silica gel (CH_2Cl_2/MeOH, 80:20) and recrystallization (CH_2Cl_2/Et_2O) afforded **3q** (44.2 mg, 0.0954 mmol, 48%) as a white solid.

Mp 194 °C (dec).

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^{1}H NMR (500 MHz, CD_3OD): δ = 2.02–2.05 (m, 6 H), 2.19–2.20 (m, 1 H), 3.25 (d, *J* = 8.0 Hz, 2 H), 3.62 (t, *J* = 8.0 Hz, 6 H), 4.37 (t, *J* = 7.5 Hz, 1 H), 5.34 (brs, 1 H), 5.65 (d, *J* = 4.5 Hz, 1 H), 7.20 (t, *J* = 7.5 Hz, 2 H), 7.30 (t, *J* = 7.5 Hz, 4 H), 7.38 (d, *J* = 7.5 Hz, 4 H).

^{13}C NMR (126 MHz, CD_3OD): δ = 20.6, 25.1, 35.4, 50.7, 56.5, 113.3, 127.9, 129.0, 129.8, 144.5, 152.7.

^{19}F NMR (471 MHz, CD_3OD): δ = –72.5 (d, *J* = 708 Hz).

HRMS (ESI-MS, positive): *m*/*z* calcd for $C_{23}H_{28}N$: 318.2222 $[M]^+$; found: 318.2236.

HRMS (ESI-MS, negative): *m*/*z* calcd for PF_6: 144.9642 $[M]^-$; found: 144.9639.

Conflict of Interest

The authors declare no conflict of interest.

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Supporting Information

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