



Scheme 2 (a) 4-cyanopyridine boryl radicals-mediated C–I bond homolysis of perfluoroalkyl iodide **1a** monitored by ^{19}F NMR; (b) radical trapping experiment.

by this observation and recent progress from Studer¹¹ and Liu¹² groups that $\text{R}_f\text{-X}$ ($\text{X} = \text{I}, \text{Br}$) reagents can act as inexpensive perfluoroalkyl radical precursor for difunctionalization of alkenes, we envisioned that the perfluoroalkyl radical generated from homolysis of perfluoroalkyl halides $\text{R}_f\text{-X}$ ($\text{X} = \text{I}, \text{Br}$) promoted by 4-cyanopyridine radicals might be trapped by alkenes, and selective cross-coupling of the resulting alkyl radicals with the persistent 4-cyanopyridine-boryl radicals might lead to the perfluoroalkylative pyridylation of alkenes (Scheme 1, down).¹³

Results and discussion

The proposed reaction mechanism of the alkene perfluoroalkylative pyridylation was postulated in Scheme 3. The following steps may be involved: (1) 4-cyanopyridine-boryl radicals (**Int1**) are generated from the homolytic cleavage of the B–B bond of B_2pin_2 by 4-cyanopyridine; (2) **Int1** activates the



Scheme 3 Proposed 4-cyanopyridine-boryl radicals-mediated alkene difunctionalization.

C–I bond of CF_3I (**1b**) to produce the CF_3 radical and **Int3a**, and regenerate 4-cyanopyridine; (3) CF_3 radical adds to 4-methylisopropenylbenzene (**3a**), forming a new alkyl radical (**Int4**); (4) the selective cross-coupling of **Int1** and **Int4** by persistent radical effect,¹⁴ yields the intermediate **Int5**, which is hydrolysed to give the alkene perfluoroalkylation product **4b**. Notably, **Int1** not only catalyze the C–I bond homolysis of perfluoroalkyl halides $\text{R}_f\text{-X}$ ($\text{X} = \text{I}, \text{Br}$), but also serves as the pyridine precursor.

To verify whether the proposed mechanism is thermodynamically or kinetically feasible, we performed DFT calculations with the M06-2X¹⁵ functional to explore the free energy profile of the proposed mechanism for the model reaction of **1b** and **3a** in the presence of **Int1** as a reactive intermediate. The reaction mechanism of generating **Int1** was reported in our previous works.^{10c,d,j,k} The calculated free energy profile and transition state structures are listed in Fig. 1 (the optimized structures of all minimum species are shown in Fig. S1†). First, the association between the iodine atom of **1b** and the carbon atom at the C2 position of the radical **Int1** forms an encounter complex (**Int2a**), which is endergonic by 7.2 kcal mol^{−1}. Then, the transfer of the iodine atom from **1b** to **Int1** to give the CF_3 radical and **Int3a** involves a barrier of 32.6 kcal mol^{−1} (*via* **TS1**) and is endergonic by 20.2 kcal mol^{−1} (relative to the isolated reactants **Int1** and **1b**). It should be mentioned that the homolytic dissociation energy of C–I bond in CF_3I is 49.1 kcal mol^{−1}. These results indicate that the homolysis of C–I bond in CF_3I is indeed assisted by **Int1**. Subsequently, CF_3 radical adds to the alkene **3a** to generate a new alkyl radical **Int4** *via* **TS2**, being exothermic by 11.3 kcal mol^{−1} with a barrier of 29.2 kcal mol^{−1} (with respect to the separated reactants **Int1**, **3a** and **1b**). Finally, the C–C coupling between **Int1** and **Int4** produces an intermediate **Int5** through **TS3** with a barrier of 6.8 kcal mol^{−1} (relative to **Int4** and **Int1**), and the whole process is exothermic by 30.1 kcal mol^{−1} (with respect to the reactants **Int1**, **1b** and **3a**). In addition, the hydrolysis of the intermediate **Int5** will produce the final product **4b**. The results indicate that the proposed alkene perfluoroalkylation is thermodynamically favorable. Alternatively, the C–I bond homolysis by the 4-cyanopyridine-boryl radicals at the C4 position is also investigated (shown in Fig. S2†). This process is endergonic by 31.0 kcal mol^{−1}, with a barrier of 37.7 kcal mol^{−1} (relative to **Int1** and **1b**), suggesting that the pathway is less favorable. Furthermore, we also calculate the isomerization reaction of **Int3a** (see Fig. S3†). Starting from **Int3a**, the intramolecular migration of the iodine atom from C2 atom to B atom *via* **TS4**, could yield another isomer **Int3b**, which further proceeds through the breaking of the B–N bond (*via* **TS5**) to regenerate 4-cyanopyridine. Overall, the rate-determining barrier height of this process is 10.1 kcal mol^{−1} and endergonic by 2.9 kcal mol^{−1} (relative to **Int3a**), indicating that the C–I bond homolysis is a catalytic process by 4-cyanopyridine. Moreover, our calculations suggest that the direct single electron transfer (SET) process between 4-cyanopyridine-boryl radicals and CF_3I is highly endergonic by 60.0 kcal mol^{−1} (see Fig. S4†). Thus, the SET mechanism is unlikely responsible for the generation of the perfluoroalkyl radicals in the reaction.





Fig. 1 Computed Gibbs free energy profile of the alkene carbopyridylation via 4-cyanopyridine boryl radicals. The optimized structures of transition states are also displayed. Interatomic distances are in Å.

Based on the predicted reactivity, we first examined the proposed alkene difunctionalization using 4-cyanopyridine, perfluorobutyl iodide **1a**, 4-methylisopropenylbenzene **3a** as model substrates. The optimization details are given in ESI.† We found that the desired product could be obtained in 74% yield at 80 °C in the presence of B_2pin_2 with *N,N*-diisopropylethylamine (DIPEA) as additives (Scheme 4a). Control experiments suggest that this transformation occurs *via* a thermally induced process, as decreased yield was observed at lower

(a) Optimal reaction conditions



(b) Trapping the intermediates by HRMS



Scheme 4 Control experiments.

temperatures. The requirement of a relatively high temperature (80 °C) are in qualitative accord with the DFT results discussed above. Moreover, the generation of intermediates **Int3a** (or its isomer **Int3b**), and the compound **7-like** (from the addition of **Int1** and the perfluorobutyl radical) in the presence of **1a**, 4-cyanopyridine and B_2pin_2 under the standard conditions were confirmed by high resolution mass spectroscopy (HRMS) experiments, which provide direct evidence on the C–I homolysis mechanism of **1a** *via* 4-cyanopyridine-boryl radicals (see Fig. S5 and S6†). In addition, the intermediacy of the cross-coupling intermediate **Int5-like** as well as the by-product I-Bpin could be detected by the HRMS analysis of the reaction mixture of the perfluorobutyl, 4-cyanopyridine and 4-methylisopropenylbenzene **3a** under the standard conditions (Scheme 4b, Fig. S7 and S8†). Finally, the addition of the perfluoroalkyl radical to alkenes could be further confirmed by a radical clock experiment using vinyl cyclopropane **3r** as the substrate (see Fig. S9† for details). In combination, the studies revealed a unique strategy for the generation of perfluoroalkyl radicals and for subsequent perfluoroalkylative pyridylation of alkenes using the inexpensive 4-cyanopyridine/ B_2pin_2 system.

Then, we examined the substrate scope of the carbon radical precursor with 4-methylisopropenylbenzene **3a** as the radical acceptor (see Table 1). With perfluoroalkyl iodides ($C_nF_{2n+1}-I$), the corresponding α -perfluoroalkyl- β -pyridylation product could be obtained in moderate to good yields (**4a–4e**, **4g**, **4i**).

Table 1 Substrate scope for the radical precursor^a



^a Reaction conditions: **1** (0.2 mmol), $B_2(pin)_2$ (0.3 mmol), 4-cyanopyridine **2** (0.3 mmol), 4-methylisopropenylbenzene **3a** (0.4 mmol), MTBE (1.0 mL), DIPEA (0.2 mmol), 24 h, 80 °C. Isolated yield. ^b 5 mmol scale. **1e** (7.5 mmol), $B_2(pin)_2$ (7.5 mmol), 4-cyanopyridine (7.5 mmol), MTBE (15.0 mL), DIPEA (5.0 mmol), 24 h, 80 °C. Me = methyl, Et = ethyl.



Notably, the sterically congested substrate, perfluoro-isopropyl iodide, reacted smoothly to afford the desired product in moderate yield (**4j**, 45%). 1-Chlorotetrafluoro-2-iodoethane

could also be converted into the desired product **4k** in good yield *via* the selective cleavage of C–I bond. For the perfluoroalkyl bromides, the desired products (**4f**, **4h**, **4l**, **4m**) could be formed in moderate yields under the standard conditions. The reaction of C₆F₁₃I, 4-cyanopyridine and alpha-methyl styrene on a 5 mmol scale in the presence of B₂pin₂ readily afforded **4e** in 71% yield (1.8 g).

Table 2 Substrate scope for the alkenes^a



^a Reaction conditions: **1a** (0.2 mmol), B₂(pin)₂ (0.3 mmol), 4-cyanopyridine (0.3 mmol), alkene (0.4 mmol), MTBE (1.0 mL), DIPEA (0.2 mmol), 24 h, 80 °C. Isolated yield. Me = methyl, Et = ethyl, ^tBu = *tert*-butyl.

Next, the substrate scope of alkenes was evaluated. As shown in Table 2, alpha-methyl styrene bearing a variety of functional groups (such as Br, MeS, CF₃O, MeSO₂, CN, CF₃, CO₂Me *etc.*) on the phenyl rings, were well compatible with this protocol, offering corresponding carbopyridylation products with quaternary carbon center (**5aa–5as**) in moderate to good yields (43–74%). Alpha-methyl naphthalenes also reacted to provide the desired products in good yields (**5ba**, 73% and **5bb**, 70%). Furthermore, other alpha-methyl arylethene containing fused heterocycles, such as benzofuran, phenanthrene, fluorene and carbazole, could be converted into the corresponding products **5c–5f** in moderate to good yields. The reactions of more sterically congested alpha-ethyl and -propyl styrenes provided the desired products (**5ga–5h**) in moderate yields. In addition, 1,1-disubstituted unactivated alkenes could also smoothly transform into the corresponding products (**5i–5k**, 45–54% yields). However, the reactions of methacrylate and 4-methoxystyrene only afforded the carbopyridylation products **5l** and **5m** in lower yields. With internal alkenes as substrates, no corresponding carbopyridylation products can be detected under standard conditions. Our DFT calculations suggest that the barrier heights for the addition of trifluoromethyl radical to internal alkene or terminal monosubstituted styrene are higher than that of disubstituted styrene by 1.2–3.4 kcal mol⁻¹ (see Table S1†). This result may be responsible for the experimental facts described above. Thus, internal alkenes or terminal monosubstituted styrenes are not suitable for the present transformation.

Both pyridine and perfluoroalkyl groups are prevalent motifs in drugs and natural products. The simultaneous incorporation of these two groups into bioactive molecules might improve their properties, such as reactivity and metabolic stability and selectivity.^{2,6} As illustrated in Table 2, four complicated alkene substrates derived from abietic acid, gemfibrozil, 1-adamantaneacetic acid, and cholesterol, readily underwent the carbopyridylation to give products **5n–5q** in moderate to good yields.

Conclusions

In summary, we reported a metal- and photo-free synthetic method for perfluoroalkylative pyridylation of alkenes. Density functional theory calculations and control experiments indicate the *in situ* prepared 4-cyanopyridine-boryl radicals from 4-cyanopyridine and B₂(pin)₂, which not only activates the C–I bond homolysis but also serves as a pyridine precursor, play a key role in this transformation. A high functional group tolerance and broad substrate scope were achieved. This method provides a scalable and operationally simple protocol for difunctionalization of alkenes with inexpensive 4-cyanopyridine/B₂(pin)₂



reagents. We anticipated that the present approach would be useful for the construction of molecules with complexity and late stage modification of drugs and natural products.

Conflicts of interest

There are no conflicts to declare.

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