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Visible-Light-Driven Difluoroacetamidation of Unactive Arenes and Heteroarenes by Direct C−H Functionalization at Room Temperature

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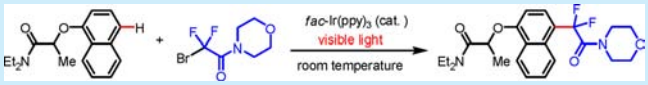
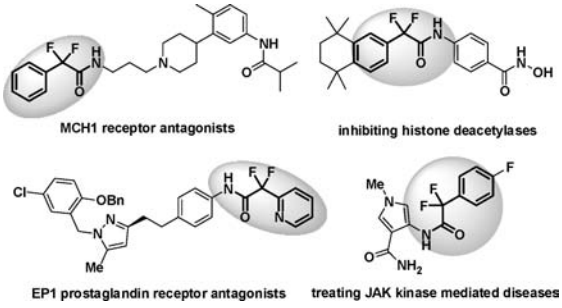
Supporting Information

ABSTRACT: The directed difluoroacetamidation of unactivated arenes and heteroarenes with bromodifluoroacetamides via visible-light photoredox catalysis has been efficiently achieved at room temperature. Broad utility of this transformation is presented, including electronically deficient heteroaromatic and aromatic systems. The mechanistic pathway of the difluoroacetamidation was discussed based on photoluminescence quenching, spin-trapping, and kinetic isotope effect experiments.



Organofluorine compounds are of great importance in the areas of materials, pharmaceuticals, and agrochemicals, since fluorine atoms enjoy privileged roles in life science and materials science-related applications.[1] Compounds containing a trifluoromethyl group have been studied extensively.[2,3] Similar to the trifluoromethyl group, compounds containing partially fluorinated alkyl groups, such as a difluoromethyl group, can often induce many intriguing effects on biologically active molecules.[4] In particular, arenes containing difluoroacetamide on an aromatic ring are often found in molecules that exhibit biological activities (Scheme 1).[5] Typically, these valuable molecules could be prepared by difluorination of a carbonyl moiety with aminosulfur trifluorides, such as diethylaminosulfur trifluoride (DAST) or Deoxofluor,[6] and Cu-mediated cross-couplings between halodifluoromethylated reagents and aryl metal species or aryl halides.[7] The recent breakthrough in the construction of difluoromethylated arenes was mediated by palladium or nickel catalyzed cross-coupling between aryl boronic acids and difluoromethylated halides.[8] While these methods have proven valuable for a variety of applications, they suffer from the disadvantage of requiring aryl precursors bearing activating groups at various positions around an aromatic ring. In this context, the direct difluoroacetamidation of inactive arenes at room temperature would be an appealing alternative.

Scheme 1. Biologically Active Molecules Containing a Difluoroacetamidated Arene Structural Motif



Over the past five years, visible-light photoredox catalysis has attracted widespread research interest owing to its attractive features such as mild and green conditions, excellent functional group tolerance, and high reactivity.[9,10] The excited photocatalyst by visible light at room temperature populates a strongly oxidizing or reducing catalyst that can activate a variety of substrates via photoinduced electron transfer. Seminal works have demonstrated that haloalkanes are efficient precursors for the generation of carbon-centered radicals under photoredox catalytic conditions.[11] Although radical addition to arenes is a promising approach for synthesizing substituted arenes without the reliance on prefunctionalization, the direct difluoroacetamidation of aromatic compounds via visible-light photoredox catalysis has not been reported to date.[12]

Here we report a mild, operationally simple strategy for the direct difluoroacetamidation of unactivated arenes and heteroarenes with bromodifluoroacetamides through a radical-mediated mechanism by visible-light-driven photoredox catalysis. We demonstrate the broad utility of this transformation through addition of difluoroacetamide moieties to a number of arene and heteroarenes. The benefit to medicinal chemistry is also shown through examples of the direct difluoroacetamidation of widely prescribed pharmaceutical agents.

The initial studies focused on difluoroacetamidation of benzenes with bromodifluoroacetamides **1a** under visible-light irradiation. After carefully screening reaction conditions such as photocatalysts, solvents, and bases (Table S1, Supporting Information), we gladly found that the reaction of benzene with bromodifluoroacetamides **1a** in a CH_2Cl_2 solution containing $Ir(ppy)_3$ as a photocatalyst and potassium acetate

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(KOAc) as a base provided the respective difluoroacetamidated product in 87% yield. Control experiments established the importance of both visible light and the photocatalyst, as no desired reaction was observed in the absence of light and $Ir(ppy)_3$.

Having identified the optimal conditions, we next examined the scope of arenes that participate in this difluoroacetamidation reaction. As shown in Figure 1, a broad array of mono-, di-, and

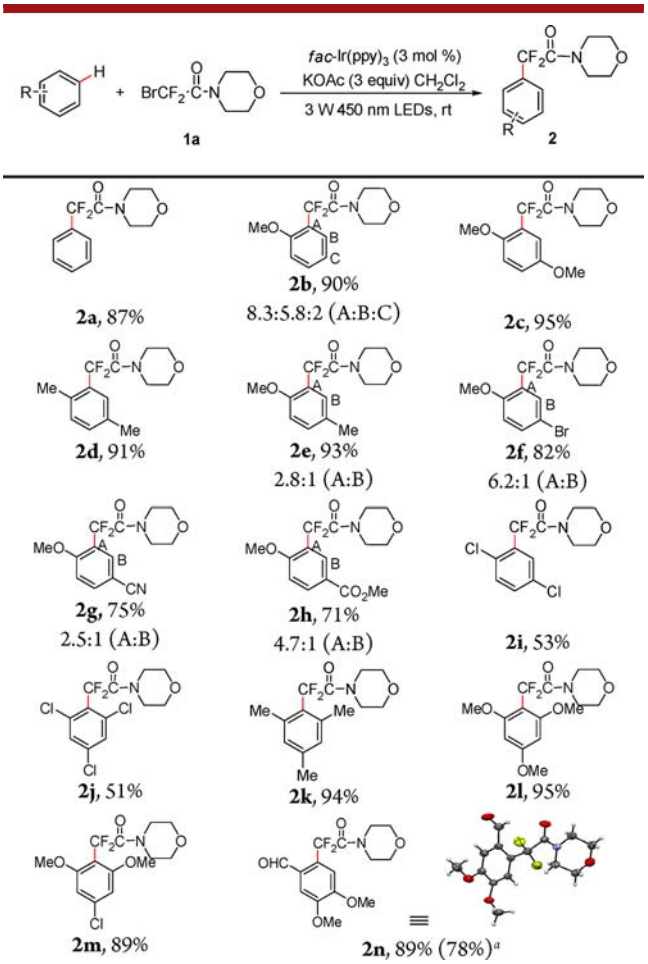

Figure 1. Scope of the difluoroacetamidation of arenes using bromodifluoroacetamide **1a**. Reaction conditions: **1a** (0.2 mmol, 1.0 equiv), arene (2.0 mmol,10 equiv), KOAc (0.6 mmol, 3.0 equiv), and *fac*-$Ir(ppy)_3$ (0.006 mmol, 3.0 mol %) in dry CH_2Cl_2 (2.0 mL) were irradiated with a 3 W blue LED for 24 h at rt. Isolated yield. (a) Reaction carried out on a gram scale.

trisubstituted benzenes can serve as competent substrates (**2a**–**2n**, 51–95% yield). In general, arenes bearing electron-withdrawing substituents afforded lower yields than those with electron-donating groups. Many versatile functional groups, such as halides, aldehyde, ester, nitrile, or ether, were all tolerated under the reaction conditions, highlighting the potential of the method in organic synthesis. For the arenes bearing different substituents, the corresponding products were formed as a mixture of regioisomers (Figure 1, **2b**, **2e**–**2h**), indicating a radical substitution process may be involved. It seems that the site selectivity of these reactions is effected by both the electron density of arenes and the stability of radical intermediates (captodative stabilization[13]). Because the aminocarbonyldifluoromethyl radical is electrophilic, the aminocarbonyldifluoromethyl groups prefer to locate in the position where there is greater electron density (Figure 1, **2e**–**2h**). However, when 3,4-dimethoxybenzaldehyde was employed as the substrate, only amide **2n** was isolated in 89% yield. The structure of amide **2n** was also established by X-ray crystal analysis. In addition, a gram-scale reaction of 3,4-dimethoxybenzaldehyde is successful and **2n** was isolated in 78% yield.

We next turned our attention to heteroarenes whose frameworks have been realized as valuable motifs in biological and medical chemistry (Figure 2). Unsurprisingly, an array of

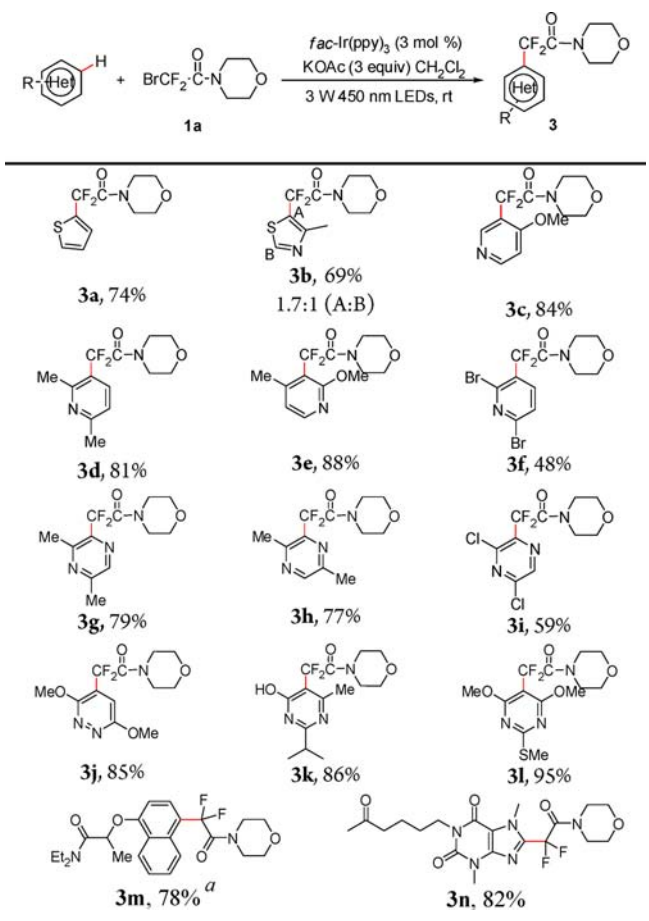

Figure 2. Scope of the difluoroacetamidation of heteroarenes using bromodifluoroacetamide **1a**. Reaction conditions: **1a** (0.2 mmol, 1.0 equiv), heteroarene (2.0 mmol, 10 equiv), KOAc (0.6 mmol, 3.0 equiv), and *fac*-$Ir(ppy)_3$ (0.006 mmol, 3.0 mol %) in dry CH_2Cl_2 (2.0 mL) were irradiated with a 3 W blue LED for 36 h at rt. Isolated yield. (a) Irradiated for 24 h at rt.

thiophene, pyridine, pyrazine, pyridazine, and pyrimidine substrates are compatible with this new difluoroacetamidation approach (**3a**–**3l**, 48–95% yield), although a prolonged reaction time (36 h) was needed. The electron-rich thiophenes, which are sensitive in the presence of the high temperatures and/or strong oxidants required for many previously reported C–H activations, underwent difluoroacetamidation in moderate to good yield under our photochemical conditions (**3a**–**3b**). The electronically deficient nitrogen-containing heteroaromatics (such as 2,6-dibromopyridine) were also operative, but the yields were much lower. The efficiency was notably improved when electron-donating groups were located on the heteroaromatic ring; the corresponding products were obtained with good selectivity. In addition, the visible-light driven difluoroacetamidation was applicable to complex aromatic rings such as napropamide[14]

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and pentoxifylline.[15] Both of them could be difluoroacetamidated in good yield (Figure 2, **3m**, **3n**).

To evaluate the structure−reactivity relationship of bromodifluoroacetamides **1**, we prepared structurally diverse bromodifluoroacetamides **1** (see Supporting Information) and applied them in the visible-light-driven difluoroacetamidation with benzene. It was found that both *N*,*N*-disubstituted amides (Figure 3, **4a**−**4c**) and *N*-monosubstituted amides (Figure 3, **4d**−**4f**) proved to be efficient in the reaction. The broad utility of this transformation is presented by various amino moieties of the amides, such as piperidine, piperazine, cyclooctanamine, cyclopropylmethanamine, and aniline.

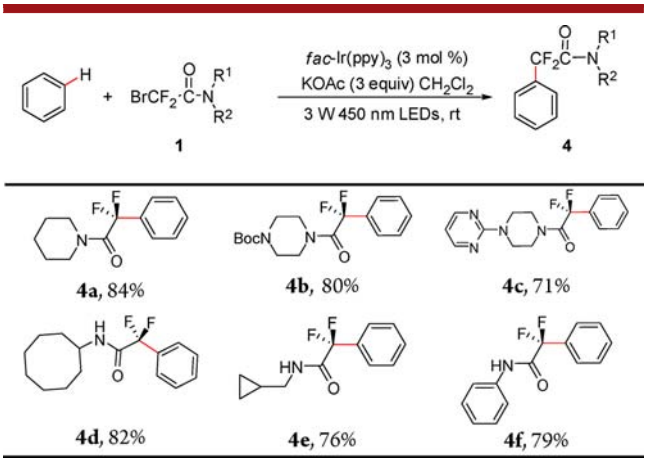

Figure 3. Scope of the amides for the reaction. Reaction conditions: **1** (0.2 mmol, 1.0 equiv), benzene (2.0 mmol,10 equiv), KOAc (0.6 mmol, 3.0 equiv), and *fac*-Ir(ppy)$_3$ (0.006 mmol, 3.0 mol %) in dry CH_2Cl_2 (2.0 mL) were irradiated with a 3 W blue LED for 24 h at rt. Isolated yield.

The mechanism of the fluoroacylation was studied by photoluminescence quenching, electron spin resonance (ESR) spin-trapping, and kinetic isotope effect (KIE) experiments. The photoluminescence of *fac*-Ir(ppy)$_3$ was quenched by bromodifluoroacetamides **1a** with a rate constant of 6.97×10^3 L·mol^{-1} (Figure 4a, left). In contrast, no quenching took place with the addition of benzene into the same solution of *fac*-Ir(ppy)$_3$. As the energy transfer from the excited *fac*-Ir(ppy)$_3$ to **1a** is negligible, the photoluminescence quenching is therefore attributed to the electron transfer (ET) from the excited *fac*-Ir(ppy)$_3$ to bromodifluoroacetamides **1a**. The ET procedure should generate electron-deficient radical **5** along with *fac*-Ir^{IV}(ppy)$_3$. To verify the generation of the aminocarbonyldifluoromethyl radical **5** in the initial step of the reaction, 5,5-dimethyl-1-pyrroline-*N*-oxide (DMPO) was employed as a spin trap. It is clearly shown in Figure 4a (right) that when the solution of DMPO, *fac*-Ir(ppy)$_3$, and **1a** in anaerobic CH_2Cl_2 was irradiated with a 3 W-blue LED, an intense EPR signal (Figure 4b) was observed that exhibited a general 1:1:1:1:1:1 pattern (g = 2.0065, α_N = 13.9 G, α_H = 17.0 G). The value of α_N/α_H is 0.85, indicating an electron-deficient carbon-centered radical was trapped by DMPO. On the basis of our observations and literature reports,[16] the above signal should be attributed to the adduct of DMPO with difluoromethyl radical **5**. In the visible-light-driven difluoroacylation (Figure 4c), the addition of difluoromethyl radical **5** to benzene gives radical intermediate **6**. Further ET from radical **6** to *fac*-Ir^{IV}(ppy)$_3$ affords carbocation intermediate **7** and regenerates the photocatalyst. Finally, intermediate **7** is deprotonated, regenerating the aromatic system and leading to

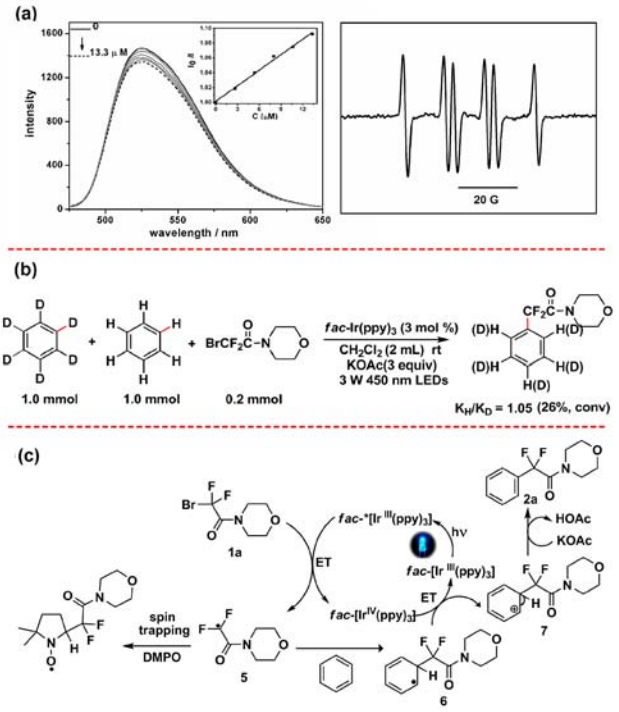

Figure 4. (a) Left: Photoluminescence quenching of *fac*-Ir(ppy)$_3$ 5.00×10^{-5} M) with progressive addition of **1a** in anaerobic CH_2Cl_2. Right: ESR spectrum of a solution of *fac*-Ir(ppy)$_3$ (3.0×10^{-3} M), **1a** (0.10 M), and DMPO (0.50 M) in anaerobic CH_2Cl_2. (b) KIE experiments. (c) Proposed mechanism of the reaction.

the desired difluoroacetamidated benzene. To understand the rate-determining step for the photoreaction, the reaction of a 1:1 mixture of benzene and benzene-d_6 with **1a** was carried out under the conditions described for Figure 4b. The intermolecular KIE was found to be 1.05 after 26% conversion, indicating that the deprotonation of intermediate **7** is not a rate-limiting step of the difluoroacetamidation.

In summary, we describe a mild visible-light-driven method for directed difluoroacetamidation of unactivated arenes and heteroarenes with bromodifluoroacetamides. The present protocol proceeds smoothly at room temperature, does not require prefunctionalization, and displays a broad scope toward aromatic and heteroaromatic systems with a wide range of functional group tolerance. Additionally, the reaction mechanism was well studied by photoluminescence quenching, spin-trapping, and kinetic isotope effect experiments. Further investigations of other fluoroacylations via visible-light photocatalysis are ongoing in our laboratory.

■ ASSOCIATED CONTENT

Supporting Information

Experimental details including synthesis, characterization data of products, and crystallographic data of **2n** (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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