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δ C–H (hetero)arylation via Cu-catalyzed radical relay†

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A Cu-catalyzed strategy has been developed that harnesses a radical relay mechanism to intercept a distal C-centered radical for C–C bond formation. This approach enables selective δ C–H (hetero)arylation of sulfonamides via intramolecular hydrogen atom transfer (HAT) by an N-centered radical. The radical relay is both initiated and terminated by a Cu catalyst, which enables incorporation of arenes and heteroarenes by cross-coupling with boronic acids. The broad scope and utility of this catalytic method for δ C–H arylation is shown, along with mechanistic probes for selectivity of the HAT mechanism. A catalytic, asymmetric variant is also presented, as well as a method for accessing 1,1-diaryl-pyrrolidines via iterative δ C–H functionalizations.

Introduction

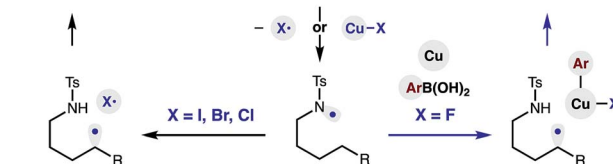
The remote C–H functionalization of amines via intramolecular hydrogen atom transfer (HAT) has enabled a distinct approach to the synthesis of pyrrolidines for over a century.^{1,2} Yet, while this formal δ C–H amination has been interrupted to afford distal halogenation and oxygenation, it has rarely enabled δ C–C bond formation.^{3–5} A mechanistic explanation is that initiation of this radical rearrangement requires homolysis of an N-halo amide to generate the N-centered radical (Fig. 1a). Following selective 1,5-HAT, the translocated δ C \cdot rapidly combines with the solvent-caged halide radical (X \cdot). Finally, intramolecular displacement of the resultant δ C–X bond is then spontaneous if X = I (or requires a strong base if X = Br, Cl). Notably, radical recombination to form C–X is rapid; and we have exclusively observed δ halogenation – even when this reaction is performed with a radical trap (e.g. acrylonitrile) as solvent. Given this challenge, the first examples of intercepting this N \cdot to C \cdot relay for C–C bond formation were only reported recently.⁴ Notably, these solutions (mostly entailing δ addition to acrylates) forgo the intermediacy of X \cdot entirely; and instead, the N \cdot is generated from an N–H or N–O bond.^{4,5}

We proposed the interruption of this century-old X \cdot rearrangement could also be facilitated by use of an N–F precursor. Since F \cdot is highly unstable,⁶ N–F homolysis (and ensuing radical recombination with δ C \cdot) seemed unfavorable.⁷ In fact, a recent example of δ fluorination by HAT required an Fe-catalyzed protocol.⁸ Instead, we anticipated N–F reduction could be mediated by a Cu catalyst that would also enable Suzuki–

Miyaura coupling of the distal organocopper with aryl boronic acids.⁹ A Cu-mediated pathway for C \cdot formation and subsequent arylation also appeared viable – based on pioneering work by Liu and Stahl, who incorporated these elementary steps in their arylation of benzylic C–H bonds.¹⁰

In designing a strategy to enable the first δ C–H arylation via a radical relay mechanism,^{11–14} we proposed a Cu catalyst could

a. Design of an intercepted radical relay to enable δ C–H arylation



b. Cu-catalyzed strategy to initiate and intercept radical relay

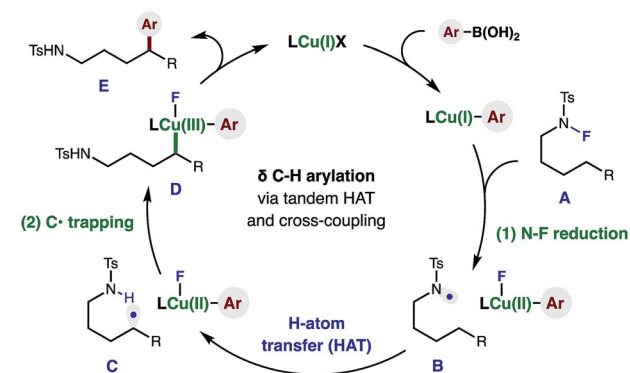


Fig. 1 Cu-catalyzed radical relay enables δ C–H arylation.

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within the aryl boronic acid (Ar^2). In the latter case, we found the difluoropyridyl arene products to be particularly easy to isolate. Notably, we found that it is not necessary to abstract the H-atom from a benzylic position. In fact, secondary C–H bonds are readily arylated (5–9), in accordance with our previous work on δ C–H aminations.¹⁶ α -Branched amides are also viable (8), although they afford lower diastereoselectivity (1 : 1) than γ substitution (9, 3 : 1).

To showcase the synthetic utility of employing aryl boronic acids within this remote Cu-catalyzed cross-coupling, we embarked on an exhaustive investigation of this component. As shown in Fig. 2, this δ arylation is amenable to electronic perturbation of the $\text{ArB}(\text{OH})_2$ – with both donating and accepting groups tolerated (10–31) – ranging from –OMe to –NO₂ and including orthogonal functional handles, such as bromides, ketones, esters, and sulfones. Similarly, both *ortho* and *meta* substitution, as well as polyaromatics (32), readily participate in this reaction. As further demonstration of the likely utility of this approach to the synthesis of medicinal agents, we employed a family of heteroaryl boronic acids, including those containing N, O, S, and F, and all are amenable to this δ C–H arylation (33–37).

The robust δ regioselectivity observed in these reactions, including an arylation of a single 1-of-15 methylenes (7), led us to further investigate the limits of the selectivity in the key HAT step (Fig. 3). With this question in mind, we subjected an amide with two benzylic C–H bonds at δ and ϵ positions to these catalytic conditions. Selective δ arylation of this probe (38; 14 : 1) confirms 1,5-HAT is highly favored over 1,6-HAT in this reaction. However, this kinetic preference can be thermodynamically overridden if a weaker, benzylic ϵ C–H is pitted against a secondary δ C–H. In this case, 1,6-HAT is slightly favored (39; 1.7 : 1). Importantly, and as a complement to previous work on α C–H arylation,^{10–12} when a molecule containing a distal benzylic C–H bond is employed, no undirected arylation is observed (40; > 20 : 1 δ). Finally, in a three-way competition between δ/ϵ secondary C–H bonds and a ζ benzylic C–H bond, only the product of 1,5-HAT is observed, rather than either 1,6 or 1,7 HAT (41–42; > 20 : 1 δ).



Fig. 3 Regioselectivity probes of intramolecular HAT.



Fig. 4 Pyrrolidine synthesis via iterative δ C–H arylation and δ C–H amination.

Although this δ C–H arylation was enabled by interrupting the classic Hofmann–Löffler–Freitag (HLF) reaction, we questioned if these complementary transformations could be sequentially combined (Fig. 4). For example, we have demonstrated that this Cu-catalyzed δ arylation (I) yields 4-aryl-butyl amides (II), and subsequent AcOI-mediated δ amination affords α diaryl pyrrolidines (III), bearing a tetra-substituted carbon (43–46). We expect this two-step, double C–H functionalization sequence will provide a synthetically enabling route to access medicinally relevant pyrrolidines,¹⁷ in a rapid, modular, and non-classical fashion.

Finally, given the strong dependence of reaction efficiency on ligand choice, as well as the ready availability of enantioenriched bisoxazoline ligands, we tested whether a catalytic, asymmetric version of this δ C–H arylation is possible (eqn (1)). To our delight, we found that employing enantiopure **L1**¹⁸ affords enantioenriched diaryl amide (1, 48% ee). Moreover, decreasing the temperature to –4 °C (and employing a co-solvent with a lower mp) allows access to this 1,1-diaryl-product with 65% ee – affording the first example of an enantioselective, radical C–H arylation.



Conclusions

In summary, we have interrupted the HLF reaction to afford a δ C–H arylation. The regioselectively translocated C[•] of this classic mechanism was intercepted and employed in C–C bond formation by using a Cu catalyst. The two key roles of this catalyst are: (i) to generate N[•] without also forming a δ halogenating X[•], and (ii) to trap the translocated C[•] as an organometallic intermediate. This organocopper species enables cross-coupling with a range of (hetero)aryl boronic acids at the δ position of sulfonamides in a regioselective (and stereoselective) manner. We expect this strategy will facilitate further development of methods to interrupt the classic HLF reaction with valuable C–C bond formation.



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