

Introduction: Over the past decade, photoredox catalysis has rapidly emerged as a powerful platform for synthetic methods development. Through photoinduced electron transfer (PET), this chemistry allows for the generation of highly reactive intermediates under operationally mild conditions, and typically utilizes low-energy visible light. These photoredox catalysts are usually transition metal complexes or organic dyes. When photoexcited by UV or visible light, the catalyst engages in electron or energy transfer events with a ground-state substrate. To date, direct photoexcitation of substrates by visible light to induce reactivity has not been pursued by the synthetic community because the majority do not absorb in the visible region (400–700 nm). An exception is the class of synthetic dyes derived from coal tar, which are ubiquitous in commercial applications for aesthetic purposes (food, textiles, plastics, paints), and have functional roles in biomedical imaging, materials science, catalysis, and lasers. The most important property that makes dyes useful—their ability to absorb visible light—has not been previously exploited for covalent modifications. In this proposed research, we aim to uncover visible-light mediated methods to activate and functionalize coal-tar dyes which are derived from petroleum refining through visible-light photoinduced electron transfer (PET). We envisioned that first-row transition metal complexes will act as redox catalysts and will engage in a photoinduced electron transfer (PET) to photoexcited dyes (**1b**), resulting in the formation of an ion pair (**1c**). This ion-pair will then collapse to form an organometallic species (**1d**) in which the metal has undergone a net 2-electron oxidation. After transmetalation, the resulting electron-deficient organometallic intermediate (**1f**) will facilitate reductive elimination with traditionally challenging partners for cross-coupling reactions, thus enabling access to a diverse array of covalently modified dye (**1g**) (**Figure 1**). We anticipate that mechanistic understanding of this method will open the door to the discovery of new visible light-mediated reactions based on substrate photoexcitation.

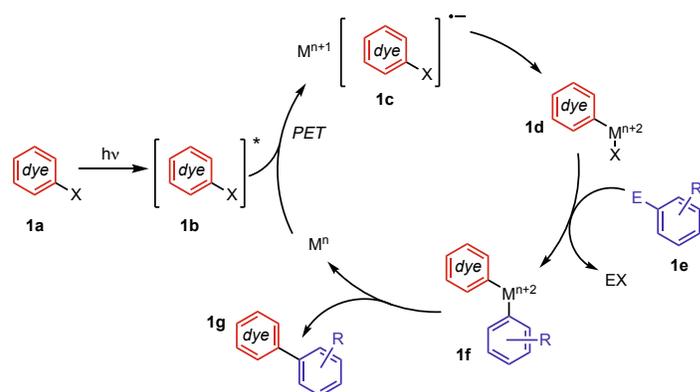
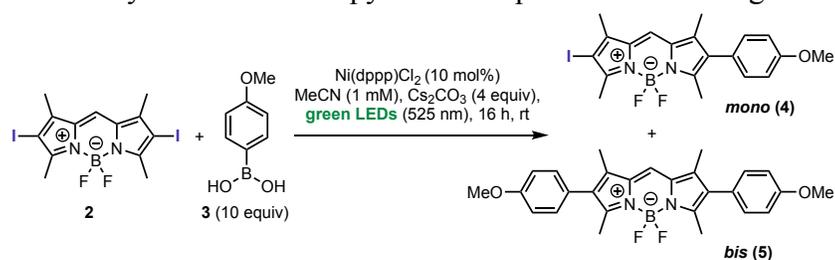


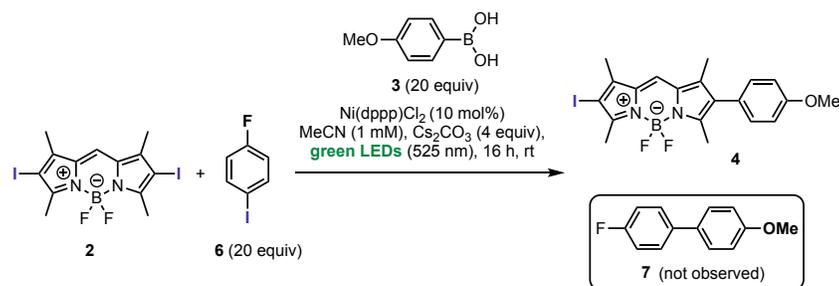
Figure 1. Proposed mechanism.

Preliminary Results: We tested the hypothesis in Figure 1 using boron-dipyrromethene (BODIPY) dyes, a class of dyes derived from pyrroles and prized for their brightness and narrow emission profiles. When BODIPY dye **2** was treated with 4-methoxyphenyl boronic acid (**3**) in the presence of Ni(dppp)Cl₂ under irradiation with green (525 nm) LED light, we observed Suzuki–Miyaura coupling to selectively form the desired mono-substituted BODIPY dye (**4**) in good yield (**Scheme 1**). Product is not observed in the absence of light or catalyst. Notably, compared to traditional palladium catalyzed Suzuki–Miyaura coupling conditions, the photoinduced cross-coupling reaction was highly regioselective, exclusively favoring the mono-functionalized product (**4**) (**4:5** > 20:1). To further validate the selectivity of this current methodology, **2** was subjected to the optimized reaction condition with a large

Scheme 1. Photoinduced Suzuki–Miyaura coupling of BODIPY dye **2**.

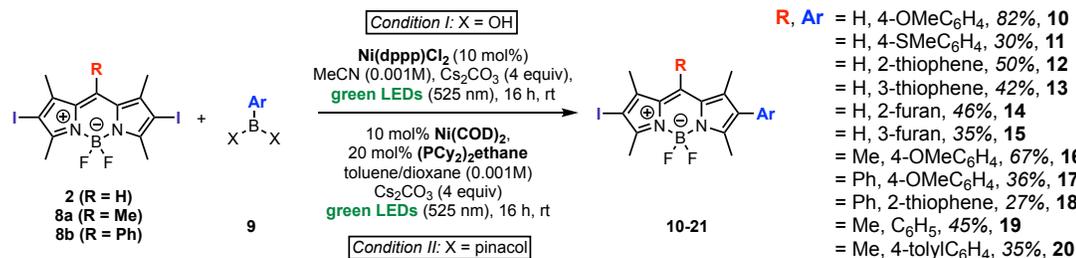


Scheme 1. Photoinduced Suzuki–Miyaura coupling of BODIPY dye **2**.



Scheme 2: Competition experiments for dye **2** with 4-fluoriodobenzene.

amount of 4-fluoriodobenzene (**6**). Product is not observed in the absence of light or catalyst. Notably, compared to traditional palladium catalyzed Suzuki–Miyaura coupling conditions, the photoinduced cross-coupling reaction was highly regioselective, exclusively favoring the mono-functionalized product (**4**) (**4:5** > 20:1). To further validate the selectivity of this current methodology, **2** was subjected to the optimized reaction condition with a large



Scheme 3. Scope of photoinduced Ni-catalyzed Suzuki–Miyaura coupling.

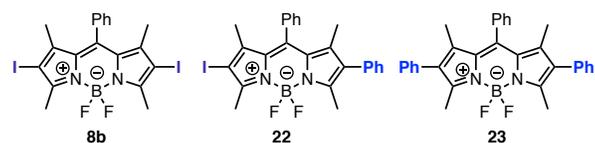
coupled product, while maintaining the same selectivity for the BODIPY product **4**. That is, only the substrate that could be excited by green light underwent cross coupling under these conditions. This selectively provides preliminary support for our hypothesis of a cross-coupling mechanism promoted by substrate photoexcitation.

With optimal reaction conditions identified, we turned our attention towards the scope and limitations of this photoinduced Suzuki-Miyaura coupling, and it was quickly realized that the optimized conditions in Scheme 1 (Condition I) are compatible mainly with electron-rich boronic acids (**10-18**, **Scheme 3**). To expand the scope to electron-poor and -neutral arylboronic acids, we evaluated other nickel catalysts, bases, solvents and additives, arriving at Condition II (**19-21**). Importantly, product **1** is not observed under these conditions in the absence of light.

We next turned our attention towards the photophysics of these BODIPY dyes in order to further understand the origin of mono-selectivity. Transient absorption spectroscopy was performed in collaboration with the Weiss lab (Northwestern). Based on these data, we hypothesize that the excited-state dyes must undergo intersystem crossing (ISC) to the triplet state to undergo productive reaction. ISC is more efficient for substrate **8b**, which has two heavy I atoms, compared to the the product **22**. This hypothesis is consistent with the observation that **22** has a higher fluorescence quantum yield than **8b**. Intersystem crossing efficiency represents a novel approach to engineer selectivity for cross-coupling reactions of polyhalogenated substrates. This hypothesis will be explored in further spectroscopic studies, and based on this understanding, other polyhalogenated dyes will be tested under the optimized coupling conditions.

Table 1. Photophysical properties of the BODIPY dyes

dye	λ_{abs}^a (nm)	λ_{em}^a (nm)	ϵ (M ⁻¹ cm ⁻¹)	τ_F (ns)	τ_T (μ s) ^b	Φ_F
8b	531	548	25,176	0.13	56.4	1.7
22	521	545	97,720	0.74	48.9	5.2
23	504	517	36,714	3.86	n.d.	20.2



^aIn toluene (1.0 × 10⁻⁵ M). ^bMeasured by transient absorption in toluene (1.0 × 10⁻⁶ M).

Conclusions: In summary, we have developed a Ni-catalyzed photoinduced Suzuki–Miyaura cross-coupling reaction of BODIPY dyes. This coupling has exclusive selectivity for mono-arylation from a bis-iodo substrate. We propose that the reactivity arises from substrate photoexcitation. Preliminary photophysical measurements suggest that the selectivity arises from the difference in ISC efficiency between the starting material and the product. Our efforts are currently focused on further optimizing the reaction conditions, expanding the scope to other coal-tar dyes, and understanding the mechanism in more detail.

Impact: Funding from ACS PRF has allowed the PI, a graduate student, and a postdoctoral researcher to pursue this fundamental research, which potentially represents a new mechanism for cross-coupling reactions. The preliminary small-molecule data obtained using these funds allowed the PI to obtain an Air Force Office of Scientific Research Young Investigator Program award, which has supported our efforts to the extend this reactivity to polymerization. The PI has presented these results at several ACS meetings and we anticipate that this work will result in several publications.

excess of 4-fluoroiodobenzene (**6**), which does not absorb visible light (**Scheme 2**). The reaction showed neither conversion of the 4-fluoroiodobenzene by ¹⁹F NMR, nor formation of 4-fluorobiphenyl