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HAT Reactions Via Photoredox Catalyzed Chlorine Atom Generation**

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Abstract: The selective functionalization of chemically inert C–H bonds remains to be fully realized in achieving organic transformations that are redox-neutral, waste-limiting, and atom-economical. The catalytic generation of chlorine atoms from chloride ions is one of the most challenging redox processes, where the requirement of harsh and oxidizing reaction conditions renders it seldom utilized in synthetic applications. We report the mild, controlled, and catalytic generation of chlorine atoms as a new opportunity for access to a wide variety of hydrogen atom transfer (HAT) reactions owing to the high stability of HCI. The discovery of the photoredox mediated generation of chlorine atoms with Ir-based polypyridyl complex, [Ir(dF(CF₃)ppy)₂(dtbbpy)]CI, under blue LED irradiation is reported.

Chlorine atoms have traditionally been accessed by relatively harsh reaction conditions such as photolysis or thermolysis processes of chlorine gas (Scheme 1. a).^[1] The requirement for such conditions has rendered methodological advancements limited to alkane chlorination reactions because many functional groups are unstable to the conditions or the high reactivity of the generated chlorine atom. Much progress has been made with respect to understanding the highly reactive intermediate in comparison to its more selective bromine counterpart with respect to alkane halogenation reactions.^[2] It has been generally accepted that chlorine atoms are stabilized by solvents such as benzene and pyridine, which can attenuate the highly reactive chlorine atom and influence its ability to be more selective in these processes. A mild and catalytic generation of chlorine atoms would represent a breakthrough into new chemical space and enable studies towards new organic transformations.

Advances in photoredox catalysis have led to the discovery of creative new organic transformations as well as innovative strategies that improve on classic methods of alkyl radical initiation (tributylstannanes, AIBN, triethylborane, peroxides).^[3] The structural architecture of Nature's light-harvesting bio-complexes have inspired chemists ability to harness the energy of a photon for its transformation into kinetic energy.^[4] Transition metal and organic dye based photocatalysts enable the use of less energetic wavelengths to initiate photochemical processes that circumvent degradation pathways associated with direct excitation of organic substrates. Highly reactive excited state complexes trigger reductive or oxidative quenching processes that allow access to highly reactive organic intermediates seldom accessed through other methods.

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۲	Supporting information for this article is given via a link at the end of the document.((Please delete this text if not appropriate))

Examples of photocatalysts such as TBADT and Eosin Y can perform HAT processes, however, the use of photoredox HAT dual catalysis using additives such as thiols, quinuclidines, amides, sulfonamides, and phosphates has become an actively researched method for alkyl radical formation.^[5] Largely unexplored, the catalytic generation of chlorine atoms using photoredox processes would represent an significant advancement towards facile generation of chlorine atoms and their applications towards HAT reactions in organic synthesis and materials science.^[6] To the best of our knowledge, few examples exist of such a process.^[7] Recently, advances in Ir^{III}/Ni⁰ dual photoredox HAT catalysis have enabled the cross-coupling of alkanes (as solvent) with haloarenes through a proposed halogen atom (Br or CI) intermediate (**Scheme 1, b**).^[8]

Scheme 1. Cl atom-mediated transformations in organic synthesis.





Herein we report the photoredox mediated catalytic generation of chlorine atoms and their ability to undergo hydrogen atom transfer (HAT) reactions with a variety of substrates such as alkanes, alcohols, ethers, ester, amides, aldehydes, and silanes, for their applications in the redox-neutral Giese-type addition to activated alkenes (**Scheme 1**, c). The dual catalytic photoredox/HAT strategy targets hydridic C-H bonds facilitated by the electrophilic nature of chlorine atoms, enabling the genesis of relatively nucleophilic radical intermediates that added to electrophilic alkenes. The selective HAT transformation is supported with mechanistic studies that indicate a closed catalytic cycle and the control effect of coordinating solvent over the highly reactive chlorine atom.

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	2a (1 equiv), 3-X	(x mol%)	"	CO ₂ Me
1aa (3 equiv)	1	Ph-H (0.5 Blue LED, Ar	Cy CO ₂ Me 4aaa		
Entry	х	[mol%]	TBACI [mol%]	Conv. [%]	Yield [%]
1	PF_6	2	10	100	80
2	PF ₆	2	5	100	84
3	PF_6	1	20	100	84
4	PF_6	1		20 ^[b]	0
5	CI	1	5	100	89
6	CI	1		100	84
7	CI	2		100	86(68)
8	CI	2		O ^[c]	0
9	CI	2		O ^[d]	0
10			20	0	0

 Table 1. Optimization of the reaction conditions.
 [a]

To begin, an initial screening of reaction conditions for the photoredox mediated generation of chlorine atoms identified $[Ir(dF(CF_3)ppy)_2(dtbbpy)]PF_6\ (\textbf{3-PF_6},\ 2\ mol\%)$ with TBACI (10 mol%), cyclohexane (1aa, 3 equiv), and dimethyl maleate (2a, 1 equiv) in benzene (0.5 M) under 465 nm LED irradiation led to 4aaa in 80% yield (Table 1, entry 1, see Supporting Information). Thrilled by this result, it was found that lowering the amount of TBACI or photocatalyst were not detrimental to the yield of the reaction (entries 2, 3, and 5). Little conversion was observed in the absence of a chloride source, however, isomerization to the fumarate (2d) was noticed (1.73:1 2a:2d) (entry 4). The isomerization process was not observed in the absence of photocatalyst which could be consistent with background energy transfer mechanisms (entry 10). Considering that conditions employing 1 mol% of 3-PF6 and 5 mol% of TBACI led to near quantitative conversions of 1aa and 2a into 4aaa, we wondered if [Ir(dF(CF₃)ppy)₂(dtbbpy)]Cl (3-Cl) could be used in this transformation as a more convenient source of the photocatalyst and chloride ion.^[9] To our delight, 1 mol% of 3-CI led to product in 84% yield (entry 6). A slight increase in yield was observed when using 2 mol% of the photocatalyst, giving product in 86% yield (68% isolated, entry 7). This loading was used for all further examples to ensure reactivity in challenging examples. Finally, control experiments reveled that photocatalyst, light irradiation, and heat were necessary for the transformation to proceed (entries 8-10).

After establishing the optimal conditions for this transformation, an investigation of the alkane coupling partner tolerance for the dual photoredox HAT catalytic alkylation of maleates/fumarates was performed (**Table 2**, **a**). Cyclopentane, cyclooctane, and adamantane **1ab**-ad underwent the coupling with **2a** in 69%, 53%, and 61% (62:38 $H_A:H_B$) yields, respectively. It should be noted that benzyl C–H bonds on substrates such as





^[a] 40%:34% 4aaa:4bfa.

toluene and mesitylene were ineffective in this transformation. n-Butanol **1ae** underwent the transformation in 36% yield without

^[a] See Experimental Section, reactions run between 60 and 80°C. **2a** = dimethyl maleate; **2d** = dimethyl fumarate. ^[b] **2a** (80%) as 1.73:1 Z:E (**2a:2d**). ^[c] Reaction run at room temperature. ^[d] In absence of irradiation.

further lactone formation, however, cyclopentanol 1af underwent the transformation in similar yield, giving lactonized product 4afa. Ethers proved to be effective substrates in this transformation. Common cyclic and acyclic substrates such as THF, pyran, MTBE, *i*Pr- and *n*Bu- ether (1ag-ah, 1aj-al) underwent efficient couplings at the α -position – the most hydric position – in yields ranging from 55% to 70%. Methoxycyclopentane 1ai gave 59% yield of the corresponding product, isolated separately as a 3:1 ratio of the products deriving from HAT at the 3° and 1° positions. Aryl methyl ethers 1am-ao provided the desired products in 59-70% yields showing little difference in donating (OMe) and withdrawing (F) substituents. 1,2-Dimethoxyethane 1ap gave 44% yield of the product corresponding to HAT at the 2° position and 26% yield at the 1° position. Dioolane 1aq and dioxane 1ar coupled efficiently in 70% (10:1 H_A:H_B, H_B 1:1 d.r.) and 80% yields, respectively. Interestingly, ketone 1as gave product in 63% yield chemoselectively towards the relatively nucleophilic -C-H bond or hydridic position as opposed to the relatively electrophilic q-keto C-H bond. Ethyl acetate 1at also gave product at the most hydridic position in 37% yield. Acyclic and cvclic amides 1au-aw furnished the desired product in some of the best vields ranging 74-96%. Notably, a variety of silanes 1ax-bb underwent efficient coupling in 55-81% yields; an interesting alternative to alkanes. Aryl and 1° aldehydes (1bc-be) also engaged in the coupling reaction in good-to-(52-99%). excellent vields The treatment of cyclohexanecarboxaldehyde 1bf under the standard condition gave a mixture of the desired ketone 4bfa along with the decarbonylated product 4aaa in 34% and 40% yields, respectively. Pivaldehyde gave only the decarbonylated product 4bga in 75% yield: a synthetically useful alternative to 2methylpropane in this HAT-based methodology. It should be noted that when using phenylacetaldehyde, no addition of benzyl substituents was observed. Quantitative conversion of the triphenylphosphorane 1bh to the desired product 4bha was observed in this transformation, however, separation from the triphenylphosphine oxide by-products derived from the decomposition of 1bh proved to be difficult. It was found that a one-pot protocol could solve this problem, where benzaldehyde was added after irradiation, giving 4bia in 51% yield (Table 2, b). Notably, when attempting the photochemical transformation with the parent cinnamaldehyde 1bi, no formation of the desired product is observed. Finally, a variety of maleates and fumarates 2b-f underwent coupling with 1aa in good-to-excellent yields ranging 58-87%.

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3	1ag:d ₀-1ag (1:1)	 	58	75:25	3.0	

^[a] Isolated diastereomers in a 1:1 ratio. ^[b] Diastereomer 1 (less polar, 1:1 d.r. with respect to D incorporation); Diastereomer 2 (more polar, 1:1 d.r. with respect to D incorporation). Diastereomers assigned by ¹H NMR analysis. ^[c] 55:45 d.r.

Table 4. Solvent effects on the HAT reactions of 3-CI and 3-Br with 1aa.

	1ai (3 equiv)	Ar Blue LED,	–H Ar, 16 h, .	A 4	CO2Me aia or 4aia' (3º:1º)	
ntry	Ar–H	[M]	x	[mol%]	[%] ^[a]	3°/1°
1	PhH	0.5	CI	2	66	3.6
2	PhH	0.5	Br	2	62	4.2
3	PhH	0.05	CI	2	64	4.4
4	PhH	0.05	Br	2	60	4.8
5	PhH	0.05	CI	1	54	5.4
6	PhMe	0.5	CI	2	70	3.9
7	PhOAc	0.5	CI	2	48	4.4
В	PhCO ₂ Me	0.5	CI	2	40	4.0
9	PhC(O)Me	0.5	CI	2	64	4.0
10	PhCF₃	0.5	CI	2	57	4.1
11	1ag	0.5	CI	2	82	4.1
12	Pyr	0.5	CI	2	72	9.1
13	Pyr	0.5	Br	2	22	7.7
14	Pyr	0.05	CI	2	64	10.0
15	Pyr	0.05	Br	2	16	8.5
16	Pyr	0.05	CI	1	72	9.5

Scheme 2. Photocatalyzed [2 + 2] cycloaddition with 5.



^{[a] 1}H NMR yield using phenyltrimethylsilane as standard (isolated yield of 6).

Given the exciting results found during the investigation of this transformation, mechanistic studies were conceived to -develop an understanding of the underlying mechanistic

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	R ^{•H}	2a (1 equiv),	3-CI (2 mol%	6) D/ł	CO2N	le
R*D 1ag or d-1ag (3 equiv)		PhH Blue LED	(0.5 M) , Ar, 16 h, ∆	R CO ₂ Me 4aga or d-4aga		
Entry	R–H/D	H₂O [equiv]	D₂O [mol%]	Yield ^[a] [%]	4:d-4	KIE [H/D]
1	1ag THF		10	65 ^[b]	0:100	
2	d₀-1ag	10		72 ^[c]	100:0	

pathways. First of which, isotope labelling experiments were performed to assess where deuterium incorporation may occur (Table 3). These studies also allowed for the evaluation of the extent to which chain reactions may occur. THF 1ag in the presence of D₂O (10 equiv) gave solely the deuterium incorporated d-4aga without the observation of any scrambling in 65% yield (Entry 1). This result is indicative of 1) the radical intermediate formed after coupling with 2a must then be reduced as opposed to undergoing chain reaction with a THF equivalent (leading to incorporation of an H), 2) the product is not in equilibrium with any other intermediates, and 3) ether substrates proceed via a closed cycle mechanism. The opposite experiment was performed using d8-1ag in the presence of water (10 equiv) and gave the expected H-incorporated product in 72% yield, further validating the hypothesis (Entry 2). Furthermore, a competition experiment using a 1:1 mixture of 1ag:d₈-1ag gave a 3:1 mixture of products derived from the addition favouring the 1ag (KIE = 3, Entry 3). This result supports the occurrence of a HAT process.^[2e]

After establishment that the reaction pathway likely proceeds through a closed cycle, we wondered if the ratio of products observed in the reaction of 1ai could be increased selectively towards the 3° position (Table 4). Using a solvent that can attenuate the high reactivity of the chlorine atom would a valuable methodological advancement in HAT be transformations. First, the comparison of 3-CI and 3-Br counterions were evaluated at various concentrations in benzene (Entries 1-5). The reactions proceeded in 54-66% yields with 3-Br being slightly more selective at low concentration (4.8 vs 4.4, Br:Cl) however, 3-Cl giving efficient reactivity with a 5.4 selectivity at low concentration and 1 mol% catalyst loading (3-Br gave little conversion at 1 mol%). To our surprise, little change to the yield and selectivity of the transformation was observed when varying the electronics of the arene-based solvent (Entries 6-10). Spanning functional groups such as Me, OAc, CO2Me, C(O)Me, and CF3, yields and selectivity ranged 40-70% and 3.9-4.4 (3-Cl 2 mol%, 0.5 M), respectively, the results were similar to those of benzene; an unexpected result given the body of literature that propose the π -complexation of chlorine atoms.^[2,10] Using **1ai** as the solvent similarly gave the product in 82% yield with a selectivity of 4.1 (Entry 11). One may conclude that little complexation of chlorine atoms is evident considering these solvents or that a background chain reaction may be at play. Pleasingly, when switching to pyridine (an efficient complex forming solvent), the selectivity soared to 9.1 (Entry 12). Further, the selectivity of 3-Br was found to be lower than 3-CI, 7.7, which demonstrates that a chlorine atom can be rendered less reactive than its mild bromine atom comparison (Entry 13): a result that challenges conventional wisdom with respect to chlorine atom reactivity. Lowering the concentration, the selectivity was improved to 10.0 with 3-CI, besting 3-Br (Entries 14-16). These results show great potential to furthering our knowledge in selective HAT transformations and will be explored further on more complex substrates in the future.

Other electron-rich-, styryl-, and enone-based alkenes were examined, however, little reactivity or decomposition was observed (see SI). As observed in **Table 1** (entry 4), we hypothesized that triplet-triplet energy transfer processes may

have been responsible for this lack of desired product formation. When considering that the triplet energy of **3-PF**₆ is 61 kcal/mol, cinnamate **5** (55 kcal/mol) known to undergo photocatalyzed [2 + 2] cycloadditions was used as acceptor with and without cyclohexane, where cyclobutane **6** was isolated in excellent yield in both cases (**6**:**6**', 7:1 d.r., **Scheme 2**).^[11] In an attempt to mitigate the background triplet-triplet energy transfer pathways, the use of acridinium salts (react through the singlet state) or the CI salt of an oxidizing Ir-complex [Ir(dF(CF₃)dtbbpy)₂(5,5'-dCF₃bpy)]PF₆ with a relatively low triplet energy (48 kcal/mol), were found to be ineffective in the coupling of **1aa** with a variety of alkenes.^[6e, 7]

After obtaining several mechanistic data, a product forming pathway may be proposed (Figure 1). Upon excitation of 3, reductive quenching of chloride may occur (3*, $E_{1/2}^{M^*/M^-} = +1.21$ V vs SCE; TBACI, E_{1/2}^{red} = +2.03 V vs SCE),^[8b, 9] albeit under large uphill thermodynamic requirements, giving chlorine atom and Ir^{II} (3-A). This interaction may be facilitated by the requirement of heat for the transformation to proceed and the proximity of the chloride ion. Stern-Volmer fluorescence quenching experiments found this process to be feasible when considering kinetics (**3-PF**₆, $k_q^{TBACI} = 1.1 \pm 0.1 \times 10^6 \text{ M}^{-1}\text{s}^{-1}$; **3-CI**, $k_q^{TBACI} = 8.2 \pm 0.9 \times 10^5 \text{ M}^{-1}\text{s}^{-1}$). Several alkene types may undergo background activation through triplet-triplet energy transfer processes and was elegantly demonstrated in Hong's recent study (3-PF₆, $k_a^{\text{cyclohexeneone}} = 3.2 \times 10^8 \text{ M}^{-1}\text{s}^{-1}$).^[12] Quenching of 2a was found to be slower than chloride in our study (**3-PF**₆, $k_q^{2a} = 6.3 \pm 0.7 \times 10^5 \text{ M}^{-1}\text{s}^{-1}$; **3-CI**, $k_q^{2a} = 7.0 \pm 1.6 \times 10^5 \text{ M}^{-1}$ 10⁵ M⁻¹s⁻¹) and may explain why maleates and fumarates are tolerated under the described conditions. Upon generation of the electrophilic chlorine atom, complexation to a solvent such as pyridine may take place (Pyr-CI), where the chlorine atom can undergo HAT with a variety of substrates, giving nucleophilic alkyl radical I.^[10] This radical can add efficiently to an activated alkene, giving intermediate II. When coupled with alkanes, silanes, and ethers, intermediate II undergoes SET with 3-A (II, $E_{1/2}^{\text{red}} = -0.6 \text{ V vs SCE}; \text{ 3-A}, E_{1/2}^{\text{MM-}} = -1.37 \text{ V vs SCE}),^{[50, 7,9,13, 7,9]}$ ^{14]} regenerating **3** and furnishing the desired product. It should be noted that substrates such as aldehydes are known to undergo chain reaction processes and this transformation is likely no exception.[15]

Figure 1. Proposed mechanism.

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In summary, the catalytic generation of highly reactive chlorine atoms using photoredox mediated activation of chloride has been achieved. The chlorine atoms engaged with a variety of hydridic C–H bonds including alkanes, alcohols, ethers, ester, amides, aldehydes, and silanes, for the redox-neutral Giese-type addition of alkyl radicals to activated alkenes. Mechanistic studies showed a closed catalytic cycle with ethers, the attenuation of chlorine atoms to be more selective than bromine atoms with pyridine as the solvent, and that background energy transfer pathways were at play. These results challenge the currently accepted information about chlorine atoms and future studies evaluating these highly reactive intermediates in the context of synthesis will be reported in due course.

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- a) G. A. Russell, H. C. Brown, J. Am. Chem. Soc. 1955, 77, 4031; b) J.
 S. Pilgrim, A. McIlroy, C. A. Taatjes, J. Phys. Chem. A 1997, 101, 1972.
- [2] a) H. O. Pritchard, J. B. Pyke, A. F. Trotman-Dickenson, J. Am. Chem. Soc. 1955, 77, 2629; b) G. A. Russell, J. Am. Chem. Soc. 1957, 79, 2977; c) G. A. Russell, J. Am. Chem. Soc. 1958, 80, 4987; d) C. Walling, M. F. Mayahi, J. Am. Chem. Soc. 1959, 81, 1485; e) E. Tschuikow-Roux, J. Niedzielski, F. Faraji, Can. J. Chem. 1985, 63, 1093; f) S. Forgeteg, T. Berces, J. Photochem. Photobiol. A: Chem. 1993, 73, 187; g) J. E. Chateauneuf, J. Org. Chem. 1999, 64, 1054.
- [3] For recent reviews, see: a) J. M. R. Narayanam, C. R. J. Stephenson, Chem. Soc. Rev. 2011, 40, 102; b) J. Xuan, W.-J. Xiao, Angew. Chem. Int. Ed. 2012, 51, 6828; c) C. K. Prier, D. A. Rankic, D. W. C. MacMillan, Chem. Rev. 2013, 113, 5322; d) D. Ravelli, S. Protti, M. Fagnoni, Chem.

Rev. 2016, 116, 9850; e) K. L. Skubi, T. R. Blum, T. P. Yoon, Chem.
Rev. 2016, 116, 10035; f) N. A. Romero, D. A. Nicewicz, Chem. Rev.
2016, 116, 10075; g) M. Silvi, P. Melchiorre, Nature 2018, 554, 41; For classic radical methodology: h) Radicals in Organic Synthesis (Eds.: P. Renaud, M. P. Sibi), Wiley-VCH, Weinheim, 2001; i) Encyclopedia of Radicals in Chemistry, Biology and Materials, Vols. 1 and 2 (Eds.: C. Chatgilialoglu, A. Studer), Wiley, Chichester, 2012.

- [4] V. Balzani, A. Credi, M. Venturi, ChemSusChem 2008, 1, 26.
- [5] For reviews, see: a) S. Protti, M. Fagnoni, D. Ravelli, ChemCatChem 2015, 7, 1516; b) L. Capaldo, D. Ravelli, Eur. J. Org. Chem. 2017, 2056;; For selected examples, see: c) J. D. Cuthbertson, D. W. C. MacMillan, Nature 2015, 519, 74; d) J. L. Jeffrey, J. A. Terrett, D. W C. MacMillan, Science 2015, 349, 1532; e) M. H. Shaw, V. W. Shurtleff, J. A. Terrett, J. D. Cuthbertson, D. W. C. MacMillan, Science 2016, 352, 1304; f) G. J. Choi, Q. Zhu, D. C. Miller, C. J. Gu, R. R. Knowles, Nature 2016, 539, 268; g) J. C. K. Chu, T. Rovis, Nature, 2016, 539, 272; h) D.-F. Chen, J. C. K. Chu, T. Rovis, J. Am. Chem. Soc. 2017, 139, 14897; i) K. A. Margrey, W. L. Czaplyski, D. A. Nicewicz, E. J. Alexanian, J. Am. Chem. Soc. 2018, 140, 4213. j) H. Tanaka, K. Sakai, A. Kawamura, K. Oisaki, M. Kanai, Chem. Commun. 2018, 54, 3215; k) J. Twilton, M. Christensen, D. A. DiRocco, R. T. Ruck, I. W. Davies, D. W. C. Macmillan, Angew. Chem. Int. Ed. 2018, 57, 5369; I) I. A. Perry, T. F. Brewer, P. J. Sarver, D. M. Schultz, D. A. DiRocco, D. W. C. MacMillan, Nature 2018, 560, 70; For catalyst mediated HAT, see: m) M. Okada, T. Fukuyama, K. Yamada, I. Ryu, D. Ravelli, M. Fagnoni, Chem. Sci. 2014, 5, 2893; n) X.-Q. Hu, J.-R. Chen, W.-J. Xiao, Angew. Chem. Int. Ed. 2017, 56, 1960; o) X.-Z. Fan, J.-W. Rong, H.-L. Wu, Q. Zhou, H.-P. Deng, J. D. Tan, C.-W. Xue, L.-Z. Wu, H.-R. Tao, J. Wu, Angew. Chem. Int. Ed. 2018, 57, 8514; p) A. Hu, J.-J. Guo, H. Pan, Z. Zuo, Science 2018, 361, 668.
- a) J. Kiwi, M. Gratzel, *Chem. Phys. Lett.* **1981**, *78*, 241; b) S. A. M.
 Wehlin, L. Troian-Gautier, G. Li, G. J. Meyer, *J. Am. Chem. Soc.* **2017**, 139, 12903.
- [7] Photoredox generation of chlorine atom was reported during preparation of this manuscript: H.-P. Deng, Q. Zhou, J. Wu, Angew. Chem. Int. Ed. 2018, In Press.
- [8] a) D. R. Heitz, J. C. Tellis, G. A. Molander, J. Am. Chem. Soc. 2016, 138, 12715; b) B. J. Shields, A. G. Doyle, J. Am. Chem. Soc. 2016, 138, 12719.
- [9] M. S. Lowry, J. I. Goldsmith, J. D. Slinker, R. Rohl, R. A. Pascal Jr., G. G. Malliaras, S. Bernhard, *Chem. Mater.* 2005, *17*, 5712.
- [10] R. Breslow, M. Brandl, J. Hunger, N. Turro, K. Cassidy, K. Krogh-Jespersen, J. D. Westbrook, J. Am. Chem. Soc. 1987, 109, 7204.
- a) S. K. Pagire, A. Hossain, L. Traub, S. Kerres, O. Reiser, *Chem. Commun.* 2017, 53, 12072; b) T. Lei, C. Zhou, M.-Y. Huang, L.-M. Zhao, B. Yang, C. Ye, H. Xiao, Q-Y. Meng, V. Ramamurthry, C.-H. Tung, L.-Z. Wu, *Angew. Chem. Int. Ed.* 2017, 56, 15407.
- [12] G. S. Lee, S. H. Hong, Chem. Sci. 2018, 9, 5810.
- [13] N. Bortolamei, A. A. Isse, A. Gennaro, *Electrochim. Acta* 2010, 55, 8312.
- [14] For examples of silanes, see: a) R. Zhou, Y. Y. Goh, H. Liu, H. Tao, L. Li, J. Wu, Angew. Chem. Int. Ed. 2017, 56, 16621; b) H. Qrareya, D. Dondi, D. Ravelli, M. Fagnoni, ChemCatChem 2015, 7, 3350; for examples of alkanes, see: c) P. S. Skell, H. N. Baxter, J. M. Tanko, V. Chebolu, J. Am. Chem. Soc. 1986, 108, 6300; d) S. M. Aschmann, R. Atkinson, Int. J. Chem. Kinet. 1995, 27, 613.
- [15] J. Jiang, R. Ramozzi, S. Moteki, A. Usui, K. Maruoka, K. Morokuma, J. Org. Chem. 2015, 80, 9264.

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Radical Reactions

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HAT Reactions Via Photoredox Catalyzed Chlorine Atom Generation



A HAT trick. The generation of highly reactive chlorine atoms through photoredox mediated reductive quenching of $*[Ir(dF(CF_3)ppy)_2(dtbbpy)]^+$ with chloride is reported. The C–H functionalization of a variety of alkanes, alcohols, ethers, ester, amides, aldehydes, and silanes through hydrogen atom transfer (HAT) processes with chlorine atoms underwent efficient redox-neutral coupling reactions with activated alkenes. The catalytic nature of the polarity matched transformation was further investigated through mechanistic studies.