Copper Mediated Photocatalytic C–O bond formation; Facile Acetoxylation via Decarboxylation of Aliphatic Carboxylic Acids

Sameera Senaweera and Jon A. Tunge*

Department of Chemistry, The University of Kansas, 2010 Malott Hall, 1251 Wescoe Hall Drive, Lawrence, Kansas 66045, United States

Supporting Information Placeholder

ABSTRACT: Organic molecules bearing acetoxy moiety are important as natural products, drugs, and agricultural chemicals. Synthesis of such molecules via transition metal catalyzed C–O bond formation can be achieved in the presence of a carefully chosen directing group to alleviate the challenges associated with regioselectivity. An alternative approach is to use ubiquitous carboxylic acids as starting materials and perform a decarboxylative coupling. Herein, we report conditions for a photocatalytic, decarboxylative C–O bond formation reaction towards the rapid and facile access to corresponding acetoxylated products. The reaction proceeds in the presence of copper(II) acetate as a cheap and abundant transition metal mediator. Mild reaction conditions allow a broad substrate scope. Outcome of an analysis for a Hammett correlation and a reaction carried out in methanol as the solvent are consistent with a positive charge development during the reaction progress.

In the past few decades, photocatalysis has emerged as a powerful tool of making both carbon–carbon and carbon–heteroatom linkages.[1] Photocatalytic electron transfer allows the access of highly energetic and reactive intermediates of organic molecules (i.e., radical anions and radical cations) which are challenging to access otherwise, which then are converted to corresponding products.[1a] Use of photocatalysis to perform decarboxylative couplings became popular recently, due to the abundance of carboxylic acid starting materials, environmentally benign nature of the transformation[2] and relatively mild conditions employed in photocatalysis. Such reactions usually proceed with no need for preformed organometallic reagents, thus providing an attractive alternative to traditional cross-couplings.[3]

Carboxylic acids offer a unique opportunity to perform site selective functionalization via decarboxylation since the site of reactivity is the carbon atom bearing the carboxylic acid functionality.[2,4] In that context, transition-metal-catalyzed decarboxylative couplings have emerged as a versatile approach in organic synthesis.[5] While decarboxylative coupling methods relying on late and noble transition metals including palladium,[6] rhodium,[7] and silver[8] complexes are more common, naturally abundant metals such as copper[9] and nickel[10] are also gained a significant attention. Whereas, substantial progress has been made towards the development of decarboxylative C–C bond formation reactions, currently, far fewer methods exist which lead to corresponding C–O bond formation reactions.[4]

One of the most common C–O linkages of interest is the C–acetoxy bond. Compounds containing C(sp^3)–acetoxy linkages are important as natural products,[11] drugs,[12] and agrochemicals[13] (Figure 1). Therefore, developing efficient strategies for construction of a C–acetoxy bond is highly desired and only lightly investigated so far.[14] Among such attempts, palladium catalyzed C(sp^2)–H and C(sp^3)–H acetoxylations are prevalent.[15] In 2006, Yu and co-workers reported the first copper catalyzed C(sp^2)–H acetoxylation.[16] Enlightened by that, in 2014, the first copper-mediated unactivated C(sp^3)–H acetoxylation was published by Kanai and co-workers.[17] However, all the above current attempts of C–acetoxy bond formations highly rely on nitrogen containing directing groups such as pyridyl,[15a] oxime,[18] and amidyl[17] moieties.

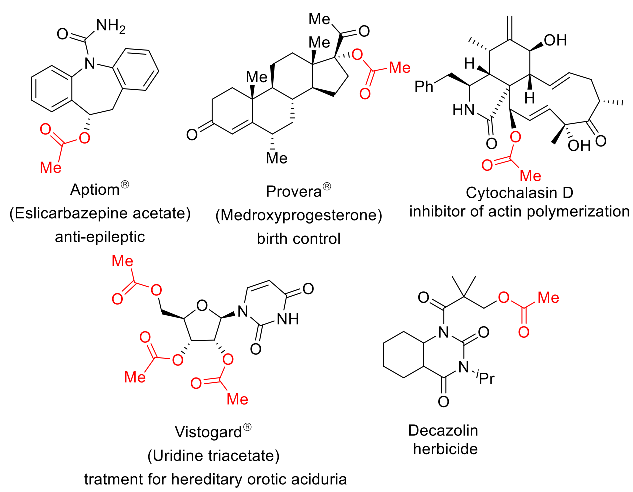
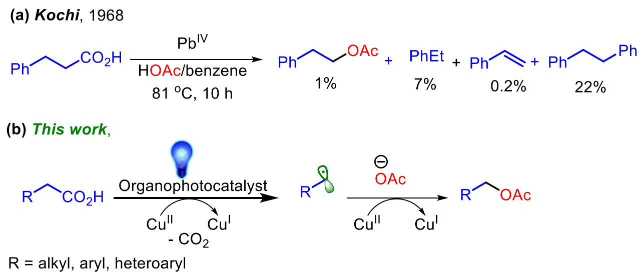


Figure 1. C(sp^3)–acetoxy group in biologically important compounds

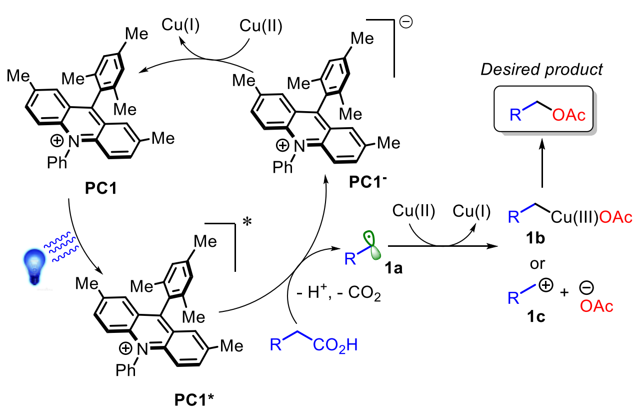
In 1968, Kochi reported an oxidation of alkyl radicals by cationic metal species such as Cu(II) and Pb(IV) (Scheme 1(a)).[19] The reaction employs thermal and photochemical decarboxylation of carboxylic acids with Pb(IV) acetate to form corresponding alkyl radicals followed by oxidation mediated by either Pb(IV) or Cu(II).[20] Oxidized radicals displayed non-selective elimination or substitution to form corresponding olefins and C–acetoxylated product in a complex mixture.[19] Even though, above work led the ground for organic chemists to consider metal mediated oxidation a possibility, synthetic utility of the method was lagged presumably due to, 1) stoichiometric use toxic lead reagents, 2) limited substrate scope, and 3) the problem of generating a mixture of products.

Scheme 1. Strategies for decarboxylate C(sp^3)–acetoxylation



Given that the importance of the development of C–O bond formation reactions, we set out to investigate the feasibility of performing a C–acetoxylation reaction. For that, the idea was to devise a synthetic strategy that merges visible-light-mediated radical decarboxylation with metal mediated oxidation of the radical followed by a C–O bond forming event (Scheme 1(b)).

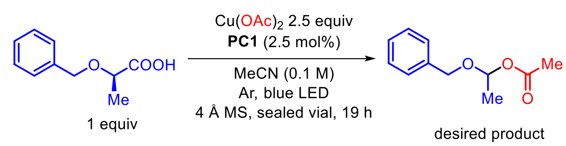
Scheme 2. A plausible mechanism



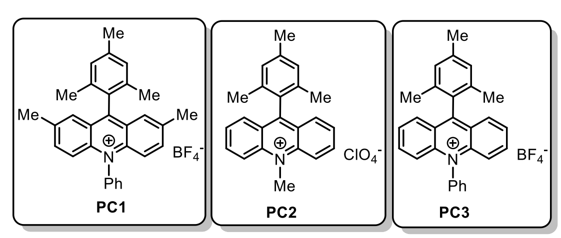
A plausible mechanistic proposal for the anticipated decarboxylative acetoxylation reaction is depicted in Scheme 2. Underivatized alkyl carboxylates typically have oxidation potentials of +1.1-1.3 V vs SCE.[21] Given that Fukuzumi acridinium family of photocatalysts[22] (**PC1**) possess excited state reduction potentials >2.0 V vs SCE,[21, 23] acridiniums were chosen to facilitate the initial electron transfer (i.e., via reductive quenching). A single electron oxidation of the carboxylate to form acyloxyl radical[24] and subsequent rapid rearrangement generates the corresponding alkyl radical after a rapid CO_2 extrusion event.[5, 25] Then, stoichiometric copper(II) was expected to perform, 1) an oxidation of the incipient alkyl radical to form alkylcopper(III) species[26] (or a naked carbocation) and, 2) a reoxidation of the reduced photocatalyst to close the photocatalytic cycle. Finally, the oxidized alkyl species (**1b** or **1c**) would lead to the desired C–acetoxy product either via a reductive elimination from **1b** or via a direct attack by acetate nucleophile (from **1c**). Herein, we report the realization of a copper mediated, photocatalytic C–acetoxylation reaction which resulted a convenient method to rapidly perform decarboxylative acetoxylations using abundant carboxylic acids as starting materials.

We began our investigation with (R)-2-(benzyloxy)propanoic acid as the starting carboxylic acid, 2.5 equiv of $Cu(OAc)_2$, and 9-Mesityl-2,7-dimethyl-10-phenylacridinium tetrafluoroborate (**PC1**) as the photocatalyst. 4 Å molecular sieves were added to absorb residual water in the reaction mixture. To our delight, a clean conversion to the desired product was obtained when MeCN was used as the solvent (Table 1, entry 1). Halogentaed solvents and less polar solvents only yielded either trace products or messy reactions (entry 2-4). Cleaner reaction in MeCN may arise from the additional stabilization of anticipated cationic species (**1b** or **1c**). Interestingly, exclusive formation of the corresponding methoxy addition product was observed when MeOH was used as the solvent (entry 5). Next, we investigated the optimal photocatalyst and effect of the catalyst loading. Two other common acridiniums were tested and produced slightly diminished yields (entry 6-7). The reaction displayed improved rate with more photocatalyst (entry 8-9). A better conversion to the product was obtained when $Cu(OAc)_2$ loading was increased (entry 10-11). The effect of water on the rate of the reaction was determined by spiking reactions with different amounts of water in the absence of molecular sieves (entry 12-13). The results suggest that the reaction is sensitive to water, presumably due to the solvation of cationic species and consequent decline of reaction rate was observed.

Table 1. Optimization of reaction conditions



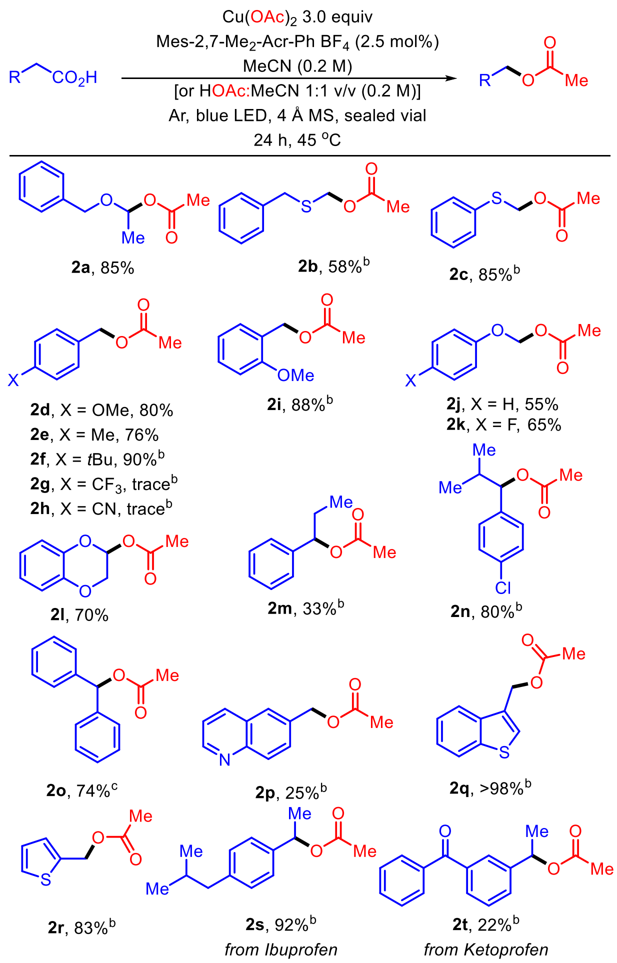
entry	modification	% conv. to the product[a]
1	none	92%
2	DCM instead of MeCN	messy
3	Toluene instead of MeCN	messy
4	ether or dioxane instead of MeCN	<5%
5	MeOH instead of MeCN	0%[b]
6	**PC2** instead of Mes-2,7-Me_2-Acr-Ph BF_4	83%
7	**PC3** instead of Mes-2,7-Me_2-Acr-Ph BF_4	85%
8	5.0 mol% of photocatalyst	88%
9	10.0 mol% of photocatalyst	92%
10	1.2 equiv $Cu(OAc)_2$	80%
11	3.0 equiv $Cu(OAc)_2$	95%
12	with 10 mol% H_2O, no 4 Å MS	86%
13	with 100 mol% H_2O, no 4 Å MS	72%
14	MeCN (0.05 M)	87%
15	**MeCN (0.20 M)**	**92%**
16	MeCN (0.30 M)	83%
17	No light	0%
18	No photocatalyst	0%
19	in air (no degassing)	<5%



[a] determined by crude NMR, [b] exclusive methoxide addition was observed

Then, we briefly examined the possibility of concentrate the reaction (entry 14-16). To our delight, the reaction tolerated up to 0.2 M. Diminished rate at above 0.2 M can be rationalized by the significant turbidity observed at the latter time of the reaction which is due to the formation of low valent copper species. Light scattering created by turbidity and subsequent photon-starvation[27] may lead to reduced rates. Finally, we carried out some control reactions to demonstrate the photocatalytic nature of the reaction (entry 17-18) and the need of inert atmosphere for the reaction to proceed (entry 19).

Table 2. Scope of the photocatalytic, decarboxylative acetoxylation

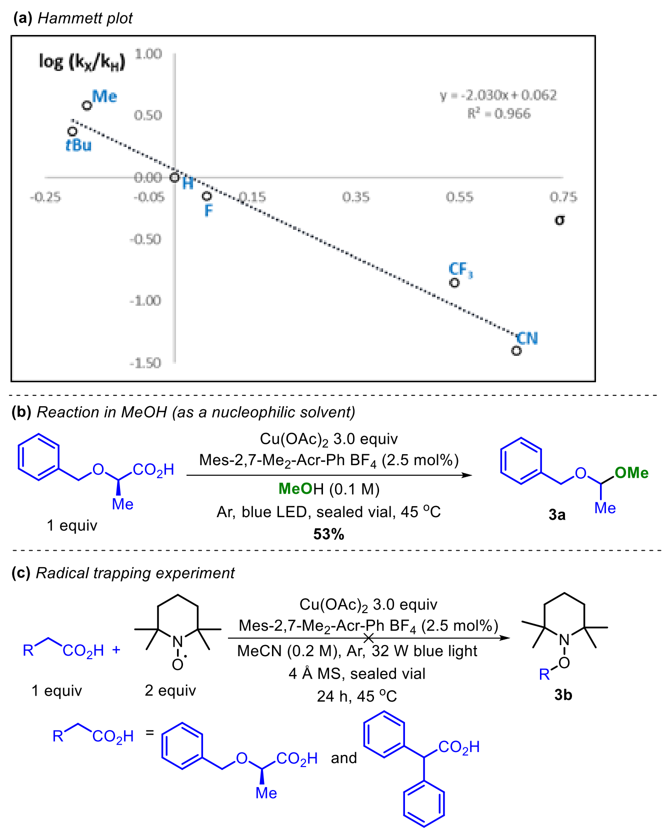


[a]using MeCN as the solvent, [b]using 1:1 HOAc/ MeCN (v/v) as the solvent mixture, [c]isolated product contained 14% dimer, corrected yield of the product is presented

With optimum conditions in hand, we evaluated the scope of the reaction (Table 2). During the scope investigation, we found that for some substrates, improved kinetics and cleaner reactions can be obtained by addition of acetic acid as a component of the solvent mixture (HOAc:MeCN 1:1 v/v). Consequently, better yields for those products were achieved. The reaction proceeds with a good to excellent yield with carboxylic acids possess benzyloxy- and benzylthio- (**2a**-**b**) and phenylthiol- moieties (**2c**). For above substrates, an additional stabilization of the alkyl radical and the cationic species formed is expected from the electron rich heteroatom next to the reaction center.[28] Numerous benzyl carboxylic acids were also engaged in the reaction with good to excellent yields, especially the once with electron donating groups on the arene (**2d**-**f**). Further investigation of the scope of this reaction revealed that phenoxyacetic acid (**2j**) and its 4-fluoro derivative (**2k**) were also susceptible to the reaction. Delightfully, secondary carboxylic acids were also found to be excellent substrates (**2l**-**o**, **2s**-**t**). Among them, clean reactions obtained to make the fused ring acetate (**2l**) and the product bearing a chlorine (**2n**) are noteworthy. Product **2n** shows that the substrates having sterically congested groups α- to the reaction center are also tolerated. While a product derived from quinoline[29] (**2p**) was suffered from diminished yields presumably due to π-deficiency of the starting arene, electron rich heteroarenes and fused heterocyclic acids produced excellent yields (**2q**,**r**). Finally, we subjected two commercially available drug molecules; Ibuprofen and Ketoprofen to our reaction conditions to rapidly obtain corresponding C–acetoxy products (**2s**-**t**).

Next, we set out to explore mechanistic insights of the reaction. During the course of investigating scope of the reaction, we observed that phenylacetic acids with electron withdrawing groups (**2g**-**h**) had only trace product formations with compared to their electron donating counterparts. We speculated that this phenomenon may due to the poor resonance stabilization of the radical (**1a**) and/or a positively charged benzylic species (**1b** and **c**) formed during the reaction progress. To systematically study this, we carried out a Hammett study (Scheme 3(a)).[30] Pairwise comparisons were done to evaluate relative rates of competition reactions between phenylacetic acid and selected *para*-substituted phenylacetic acids. At low conversion (ca. 20%), relative rate (k_X/k_H) was determined and a Hammett plot was constructed using σ-para values.[31] A negative ρ value (-2.0) is consistent with a buildup of positive charge along the reaction pathway.[32]

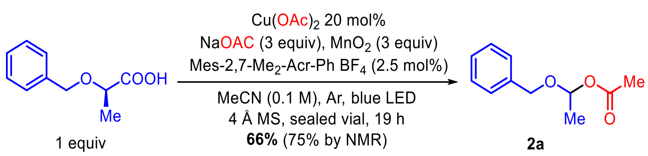
Scheme 3. Mechanistic experiments



Then, we attempted to assess whether the substitution event at the photogenerated alkyl radical occurs via a formal single electron oxidation of this species by the Cu(II) and subsequent acetate substitution of the resulting carbocation. For that, we sought to trap the cationic intermediate with methoxide ion by performing the reaction in MeOH as the solvent (Scheme 3(b)). Unlike a recent attempt by Glorius and co-workers[33] where they did not observe the alkoxy-trapped product using a similar system in their decarboxylative olefination, our reaction proceeded cleanly with a 53% isolated yield to the desired methoxy addition product. This suggests that radical undergo a single electron oxidation which involves the formation of carbocation intermediate(s). Then, a radical trapping experiment was carried out to trap the incipient radical which is formed via photocatalytic decarboxylation (Scheme 3(c)). Addition of TEMPO as a radical scavenger significantly retarded the rate of C–O bond formation with no detectable formation of the TEMPO adduct (**3b**). Diminished product formation is consistent with intermediacy of radical species.

Finally, an attempt was made to perform the reaction with catalytic copper(II). A copper catalyst along with a proper external oxidant would turn over the low valent copper species formed during re-oxidation of photocatalyst and the oxidation of alkyl radical. Inspired by the pioneering work by Chemler and co-workers[34] we decided to use MnO_2 as the terminal oxidant for our transformation in the presence of stoichiometric NaOAc as an external acetate source. To our delight, the reaction proceeded cleanly to afford the desired product in 75% (by NMR) and 66% isolated yield. However, a detailed cost analysis showed us that the use of stoichiometric $Cu(OAc)_2$ is cheaper than the use of catalytic copper along with an external acetate source and an oxidant (see SI for details). Therefore, we decided to stick to the initial conditions employing stoichiometric copper.

Scheme 4. Reaction with catalytic copper



In conclusion, we have successfully developed a C(sp^3)–acetoxylation via decarboxylation. Bench stable and abundant carboxylic acids were used as starting materials with no need of activating groups such as phthalimide esters. The reaction is photocatalytic in nature and utilizes cheap copper(II) acetate both as the terminal oxidant and the acetate source. Mild reaction conditions allowed the reaction to proceed with a good scope including alkyl-, arylacetic-, and heteroaryl acetic- acids. Mechanistic investigations are consistent with the formation of a radical species and a positively charged alkyl species during the progression of the reaction. Overall, this work demonstrates that the metal mediated single electron transfer along with photocatalysis can be an avenue to realize decarboxylative couplings with nucleophilic reaction partners. Utilization of the idea to achieve other C–heteroatom linkages is underway in our laboratory.

ASSOCIATED CONTENT

Supporting Information

Complete experimental procedures, additional optimization experiments, and product characterization. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

tunge@ku.edu

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENT

$$ … Support for the NMR instrumentation was provided by NIH Shared Instrumentation Grant # S10RR024664 and NSF Major Research Instrumentation Grant # 0320648.

REFERENCES

1. (a) Fagnoni, M.; Dondi, D.; Ravelli, D.; Albini, A., *Chem. Rev.* **2007**, *107*, 2725-2756; (b) Prier, C. K.; Rankic, D. A.; MacMillan, D. W. C., *Chem. Rev.* **2013**, *113*, 5322-5363; (c) Shaw, M. H.; Twilton, J.; MacMillan, D. W. C., *J. Org. Chem.* **2016**, *81*, 6898-6926.
2. Weaver, J. D.; Recio, A.; Grenning, A. J.; Tunge, J. A., *Chem. Rev.* **2011**, *111*, 1846-1913.
3. (a) B., L. S.; C., C. K.; S., W. R.; M., L. T.; A., T. J., *Eur. J. Org. Chem.* **2016**, *2016*, 3331-3334; (b) Patra, T.; Maiti, D., *Chemistry – A European Journal* **2017**, *23*, 7382-7401.
4. Xu, K.; Wang, Z.; Zhang, J.; Yu, L.; Tan, J., *Org. Lett.* **2015**, *17*, 4476-4478.
5. Hilborn, J. W.; Pincock, J. A., *J. Am. Chem. Soc.* **1991**, *113*, 2683-2686.
6. for selected examples see, (a) Myers, A. G.; Tanaka, D.; Mannion, M. R., *J. Am. Chem. Soc.* **2002**, *124*, 11250-11251; (b) Tanaka, D.; Romeril, S. P.; Myers, A. G., *J. Am. Chem. Soc.* **2005**, *127*, 10323-10333; (c) Rayabarapu, D. K.; Tunge, J. A., *J. Am. Chem. Soc.* **2005**, *127*, 13510-13511; (d) Waetzig, S. R.; Tunge, J. A., *J. Am. Chem. Soc.* **2007**, *129*, 4138-4139; (e) Wang, C.; Piel, I.; Glorius, F., *J. Am. Chem. Soc.* **2009**, *131*, 4194-4195.
7. for selected examples see, (a) Zhong-Ming, S.; Pinjing, Z., *Angew. Chem. Int. Ed.* **2009**, *48*, 6726-6730; (b) Mochida, S.; Hirano, K.; Satoh, T.; Miura, M., *Org. Lett.* **2010**, *12*, 5776-5779; (c) Fei, P.; Zhi-Quan, L.; Hui, W.; Hu, L.; Jian, S.; Zhang-Jie, S., *Angew. Chem. Int. Ed.* **2013**, *52*, 2063-2067; (d) Neely, J. M.; Rovis, T., *J. Am. Chem. Soc.* **2014**, *136*, 2735-2738; (e) Yuanfei, Z.; Huaiqing, Z.; Min, Z.; Weiping, S., *Angew. Chem. Int. Ed.* **2015**, *54*, 3817-3821.
8. for selected examples see, (a) Wang, Z.; Zhu, L.; Yin, F.; Su, Z.; Li, Z.; Li, C., *J. Am. Chem. Soc.* **2012**, *134*, 4258-4263; (b) Wang, P.-F.; Wang, X.-Q.; Dai, J.-J.; Feng, Y.-S.; Xu, H.-J., *Org. Lett.* **2014**, *16*, 4586-4589; (c) Feng, H.; Xinxin, S.; Dianhu, Z.; Long, L.; Qilong, S., *Angew. Chem. Int. Ed.* **2014**, *53*, 6105-6109; (d) Jian, K.; Shijun, H.; Jin, L.; Min, Z.; Weiping, S., *Angew. Chem. Int. Ed.* **2015**, *54*, 2199-2203.
9. (a) Rui, S.; Yao, F.; Yan, W.; Qing, X.; Hai-Zhu, Y.; Lei, L., *Angew. Chem. Int. Ed.* **2009**, *48*, 9350-9354; (b) Hai-Peng, B.; Liang, Z.; Yong-Min, L.; Chao-Jun, L., *Angew. Chem. Int. Ed.* **2009**, *48*, 792-795; (c) Ranjit, S.; Duan, Z.; Zhang, P.; Liu, X., *Org. Lett.* **2010**, *12*, 4134-4136; (d) Zhang, Y.; Patel, S.; Mainolfi, N., *Chemical Science* **2012**, *3*, 3196-3199; (e) Feng, Q.; Song, Q., *J. Org. Chem.* **2014**, *79*, 1867-1871.
10. (a) Yoshino, Y.; Kurahashi, T.; Matsubara, S., *J. Am. Chem. Soc.* **2009**, *131*, 7494-7495; (b) Ke, Y.; Cheng, Z.; Peng, W.; Yan, Z.; Haibo, G., *Chemistry – A European Journal* **2014**, *20*, 7241-7244; (c) Noble, A.; McCarver, S. J.; MacMillan, D. W. C., *J. Am. Chem. Soc.* **2015**, *137*, 624-627.
11. May, J. A.; Ratan, H.; Glenn, J. R.; Losche, W.; Spangenberg, P.; Heptinstall, S., *Platelets* **1998**, *9*, 227-232.
12. (a) Sneader, W., *Drug Discovery: A History*. Wiley: **2005**; (b) Galiana, G. L.; Gauthier, A. C.; Mattson, R. H., *Drugs in R&D* **2017**, *17*, 329-339.
13. Crafts, A. S., *Modern Weed Control*. University of California Press: **1975**.

14. (a) Kiyokawa, K.; Yahata, S.; Kojima, T.; Minakata, S., *Org. Lett.* **2014**, *16*, 4646-4649; (b) Bhadra, S.; Dzik, W. I.; Goossen, L. J., *J. Am. Chem. Soc.* **2012**, *134*, 9938-9941.
15. for selected examples see, (a) Dick, A. R.; Hull, K. L.; Sanford, M. S., *J. Am. Chem. Soc.* **2004**, *126*, 2300-2301; (b) Chen, M. S.; White, M. C., *J. Am. Chem. Soc.* **2004**, *126*, 1346-1347; (c) Desai, L. V.; Hull, K. L.; Sanford, M. S., *J. Am. Chem. Soc.* **2004**, *126*, 9542-9543; (d) Wang, D.-H.; Hao, X.-S.; Wu, D.-F.; Yu, J.-Q., *Org. Lett.* **2006**, *8*, 3387-3390; (e) Ramesh, G.; Jue, L.; Jian-Guang, L.; Jiao-Jie, L.; Dong-Hui, W.; Xiao, C.; Clement, N. I.; Chengyun, G.; M., F. B.; Jin-Quan, Y., *Angew. Chem. Int. Ed.* **2005**, *44*, 7420-7424; (f) Rit, R. K.; Yadav, M. R.; Sahoo, A. K., *Org. Lett.* **2012**, *14*, 3724-3727.
16. Chen, X.; Hao, X.-S.; Goodhue, C. E.; Yu, J.-Q., *J. Am. Chem. Soc.* **2006**, *128*, 6790-6791.
17. Wang, Z.; Kuninobu, Y.; Kanai, M., *Org. Lett.* **2014**, *16*, 4790-4793.
18. Li, Y.-Q.; Yang, Q.-L.; Fang, P.; Mei, T.-S.; Zhang, D., *Org. Lett.* **2017**, *19*, 2905-2908.
19. Bacha, J. D.; Kochi, J. K., *J. Org. Chem.* **1968**, *33*, 83-93.
20. Kochi, J. K.; Bemis, A., *J. Am. Chem. Soc.* **1968**, *90*, 4038-4051.
21. Griffin, J. D.; Zeller, M. A.; Nicewicz, D. A., *J. Am. Chem. Soc.* **2015**, *137*, 11340-11348.
22. (a) Fukuzumi, S.; Kotani, H.; Ohkubo, K.; Ogo, S.; Tkachenko, N. V.; Lemmetyinen, H., *J. Am. Chem. Soc.* **2004**, *126*, 1600-1601; (b) Kotani, H.; Ohkubo, K.; Fukuzumi, S., *J. Am. Chem. Soc.* **2004**, *126*, 15999-16006.
23. (a) Hamilton, D. S.; Nicewicz, D. A., *J. Am. Chem. Soc.* **2012**, *134*, 18577-18580; (b) Ohkubo, K.; Mizushima, K.; Iwata, R.; Souma, K.; Suzuki, N.; Fukuzumi, S., *Chem. Commun.* **2010**, *46*, 601-603.
24. Andrieux, C. P.; Gonzalez, F.; Savéant, J. M., *J. Electroanal. Chem.* **2001**, *498*, 171-180.
25. Alicia, F.; Ryan, T.; Teri, F.; Justin, S.; R., R. L., *J. Phys. Org. Chem.* **2011**, *24*, 809-820.
26. (a) Kochi, J. K., *Science* **1967**, *155*, 415-424; (b) Kochi, J. K.; Bemis, A.; Jenkins, C. L., *J. Am. Chem. Soc.* **1968**, *90*, 4616-4625.
27. Andrews, R. S.; Becker, J. J.; Gagné, M. R., *Angew. Chem. Int. Ed.* **2012**, *51*, 4140-4143.
28. Jagannadham, V.; Amyes, T. L.; Richard, J. P., *J. Am. Chem. Soc.* **1993**, *115*, 8465-8466.
29. Tobisu, M.; Hyodo, I.; Chatani, N., *J. Am. Chem. Soc.* **2009**, *131*, 12070-12071.
30. (a) Hammett, L. P., *Chem. Rev.* **1935**, *17*, 125-136; (b) Hammett, L. P., *J. Am. Chem. Soc.* **1937**, *59*, 96-103.
31. McDaniel, D. H.; Brown, H. C., *J. Org. Chem.* **1958**, *23*, 420-427.
32. Anslyn, E. V.; Dougherty, D. A.; Dougherty, E. V.; Books, U. S., *Modern Physical Organic Chemistry*. University Science Books: **2006**.
33. Tlahuext-Aca, A.; Candish, L.; Garza-Sanchez, R. A.; Glorius, F., *ACS Catalysis* **2018**, 1715-1719.
34. (a) Zeng, W.; Chemler, S. R., *J. Am. Chem. Soc.* **2007**, *129*, 12948-12949; (b) Bovino, M. T.; Chemler, S. R., *Angew. Chem. Int. Ed.* **2012**, *51*, 3923-3927; (c) Liwosz, T. W.; Chemler, S. R., *J. Am. Chem. Soc.* **2012**, *134*, 2020-2023; (d) Miller, Y.; Miao, L.; Hosseini, A. S.; Chemler, S. R., *J. Am. Chem. Soc.* **2012**, *134*, 12149-12156.