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# Photo-Induced C(*sp*<sup>3</sup>)–N Bond Cleavage Leading to Stereoselective Syntheses of Alkenes

Ze-Kun Yang,<sup>[ab+]</sup> Ning-Xin Xu,<sup>[a+]</sup> Chao Wang,<sup>\*[ab]</sup> and Masanobu Uchiyama.<sup>\*[ab]</sup>

**Abstract:** Here we report a versatile Mizoroki-Heck type photoinduced  $C(sp^3)$ -N bond cleavage reaction. Under visible light irradiation (455 nm, blue LEDs) at room temperature, alkyl Katritzky salts react smoothly with alkenes in 1 : 1 molar ratio in the presence of 1.0 mol% of commercially available photoredox catalyst without the need for any base, affording corresponding alkyl-substituted alkenes in good yields with broad functional group compatibility. Notably, the *E*/*Z*-selectivity of the alkene products can be controlled by appropriate choice of the photoredox catalyst.

Alkenes are essential building blocks for organic synthesis, and are ubiquitous in the fields of life science, drug discovery, and material science. The different configurational isomers (*E* and *Z*) of alkenes usually display distinct physicochemical properties and physiological activities,<sup>[1]</sup> and so stereoselective synthesis of alkenes has long been of great interest to synthetic chemists. Currently, the Mizoroki-Heck (M-H) reaction,<sup>[2]</sup> which is a Pdcatalyzed cross-coupling reaction between alkenes and aryl/vinyl halides, is regarded as one of the most useful protocols for the selective synthesis of substituted alkenes.<sup>[3]</sup>

However, despite the high efficiency and applicability of the Pdcatalyzed reaction, it has some some limitations. For example, methodology for cross-coupling by using aliphatic halides, especially those possessing  $\beta$ -hydrogen, is still limited due to the occurrence of rapid  $\beta$ -H elimination as a side reaction. Further, the configuration of the formed C=C bond is determined by the transition structure at the *syn*-extrusion step (periplanar -Pd–C– C–H- 4-membered ring), and hence external control of the *E/Z* selectivity by changing the catalyst or ligand is difficult. Thus, although elegant examples of the Pd-catalyzed reaction involving alkyl halides have been reported,<sup>[4-5]</sup> there is still a need for mechanistically new transformations employing *sp*<sup>3</sup>hybridized substrates other than halides.

The dramatic advances in photo-redox catalysis in recent years<sup>[6]</sup> mean that many single electron-transfer (SET) reactions that previously required harsh conditions, or afforded low yield or selectivity, can now be accessed in a mild, efficient and/or selective manner. Also, in addition to the use of alkyl halides,<sup>[7]</sup> new types of aliphatic coupling partners,<sup>[8]</sup> such as carboxylic

- [a] Z.-K. Yang,<sup>[+]</sup> N.-X Xu,<sup>[+]</sup> Dr. C. Wang, Prof. Dr. M. Uchiyama Graduate School of Pharmaceutical Sciences, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan E-mail: chaowang@mol.f.u-tokyo.ac.jp (C.W.); uchiyama@mol.f.u-tokyo.ac.jp (M.U.)
- [b] Z.-K. Yang,<sup>[+]</sup> Dr. C. Wang, Prof. Dr. M. Uchiyama Cluster for Pioneering Research (CPR), Advanced Elements Chemistry Laboratory, RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan

[+] These authors contributed equally to this work.

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acids, have become available as alkyl radical precursors for the photo-redox SET route to form a  $C(sp^3)-C(sp^2)$  bond with alkenes, expanding the scope of the M-H reaction.

other hand, cross-coupling protocols On the with amines/anilines and their derivatives,<sup>[9-10]</sup> especially ammonium salts<sup>[11]</sup> as halide analogs, have also been well developed recently.<sup>[12-14]</sup> Amine groups occur in many biologically essential compounds and are widely used in industry for the preparation of pharmaceuticals and functional materials. The high stability of amino C-N bonds makes them very resistant to cleavage reactions.<sup>[9]</sup> Ammonium salts can be easily prepared from various amines/anilines, and such C-N bonds exhibit higher reactivity. However, while aryl ammoniums have proved highly reactive with transition metal catalysts,<sup>[12-13]</sup> most alkyl ammoniums are quite inert with low-valence metal catalysts, [14] because alkyl C-N species are weak acceptors for an electron pair or a single electron (SE) from transition metals. In contrast, owing to the low-lying aromatic  $\pi^*$ -orbital, pyridinium salts are excellent electron acceptors.<sup>[15]</sup> Pyridinium salts can easily accept SE to form a neutral radical species, and this reactivity has been utilized in the development of organic photo-redox catalysts.<sup>[6b]</sup> Since 2017, several groups have further extended the utility of pyridinium salts<sup>[15-16]</sup> from SE-acceptor to alkyl radical source, by employing either transition metal catalysis<sup>[17]</sup> or photochemical processes.<sup>[18]</sup> These impressive achievements indicate that the alkyl radical generation protocol via C-N cleavage can open up conceptually new synthetic routes. As the latest development in our work on C-N bond cleavage protocols.<sup>[13]</sup> we herein report our results on  $C(sp^3)$ -N bond cleavage type M-H reaction with alkyl Katritzky salts via a photoredox catalytic process, affording alkyl-substituted alkenes with high yield and selectivity.[19]



Scheme 1. Outline of the current reaction.

Our basic concept was as follows. First, Katritzky salts **1** would react with the excited photo catalyst (PC) through an SE-redox process,<sup>[18]</sup> releasing alkyl radical **A** and 2,4,6-triphenylpyridine (through aromatizing homolysis of the C–N bond), together with oxidized PC<sup>++</sup> species. Alkyl radical **A** would then add to alkene **2**, affording new radical species **B** that is thermodynamically more stabile.<sup>[7-8]</sup> Next, radical **B**, as a SE reducing agent, would react with PC<sup>++</sup>, to give cation species **C** with regeneration of PC.

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<sup>[7h, 18a]</sup> Cation intermediate **C** then undergoes elimination to form alkene products **3** with the kinetically and thermodynamically favored *E*-configuration. Here, the C–C bond-forming step involves a radical addition step rather than a transition metalmediated insertion/extrusion process, thus avoiding the undesired β-H elimination. On the other hand, although *E*alkenes are thermodynamically more stable than their *Z*-isomers, the uphill *E*-to-*Z* isomerization can be efficiently realized photochemically. Taking account especially of the recently reported photo-catalytic orthogonal *E*-to-*Z* approaches,<sup>[20]</sup> we also considered that the *E*-alkene product might be isomerized *in situ* to the *Z*-form in the presence of a suitable photo-catalyst, thus enabling control of the *E*/*Z* selectivity.



Scheme 1. Proposed mechanism of the current protocol.

To test this approach, we first focused on the reaction of Katritzky salt 1a (readily synthesized from phenylalanine) as a model substrate with p-methoxystyrene 2a (Table 1). The reaction of 1a (1.0 eq.) with an excess of 2a (2.0 eq.) proceeded smoothly in the presence of several types of PC (2.5 mol%) in DMA under visible light irradiation ( $\lambda_{max}$  = 455 nm, blue LEDs) at room temperature for 12 h, affording 2-alkylstyrene derivative 3aa in good yield. When iridium complexes were used as PCs, Z-3aa was obtained as the main product (Entries 1-4). In particular, fac-Ir(ppy)3 delivered Z-selectivity as high as 92% with 87% total yield (Entry 1). Remarkably, the reaction with [Ru(bpy)<sub>3</sub>](PF<sub>6</sub>)<sub>2</sub> as the PC gave E-3aa as the sole product in 86% yield (Entry 4). Next, we evaluated the catalytic reactivity of PCs in different solvents and found that DMSO was the best for both fac-Ir(ppy)<sub>3</sub> (Entries 5-8) and [Ru(bpy)<sub>3</sub>](PF<sub>6</sub>)<sub>2</sub> (Entries 9-10). Performing the reaction in the dark did not afford any product (Entries 11-12), and only a trace of product was observed in the absence of PC (Entry 13). Moreover, the reaction of 1a proceeded with the same high efficiency and selectivity even when a stoichiometric amount of 2a (1.1 eq.) and a lower PC loading (1.0 mmol%) were used (Entries 14-15, optimal conditions). In the case of  $[Ru(bpy)_3](PF_6)_2$ , the reaction was complete within 2 hours (Entries 14). It is also noteworthy that no external base is needed for this reaction.

We next set out to examine the scope of the current reaction. Taking **1a** as a model alkyl radical precursor, we tested a variety of alkene substrates. To our delight, many were available for this protocol (Scheme 3). *Firstly*, the reaction shows excellent chemo-selectivity, with broad functional group compatibility and high yield. Under the optimal conditions,

various electro-donating functional groups, such as OMe (2a-b), SMe (2c), <sup>t</sup>Bu (2d), and even OH (2e-f) or NH<sub>2</sub> (2g) that have an active proton, were compatible with the phenyl ring of styrene. Halogens such as F (2h), Cl (2i), and Br (2j), were tolerated as either a meta- or an ortho-substituent. In most cases, the alkene products 3aa-3aj were obtained in good yields (up to 99%). Unsubstituted styrene 2k and styrene derivative 2l with a bulky aryl ring could be employed in this reaction without difficulty (3ak-3al). Further, 1,1- or 1,2-disubstituted alkenes 2m-q proved to be available for this protocol, providing the tri-substituted alkene products 3am-3aq in moderate to good yield. Secondly, the current protocol offers high and controllable stereoselectivity. When the reactions were carried out in the presence of fac- $Ir(ppy)_3$  catalyst, Z-isomers of **3** were obtained as the major products in most cases. Indeed, the Z-selectivity was over 80% in the reactions of 2c, 2f, 2l, and 2k, and was higher than 90% when **2a** and **2b** were used. Notably, when  $[Ru(bpy)_3](PF_6)_2$  was utilized as the PC, all reactions were E-selective, and only the Eisomers of 3 were observed in all cases. Interestingly, styrene 21 with a bulky mesityl group and 1,2-disubstituted alkene 2m afforded only E-alkene products under both conditions. These results suggest that the alkenylation step of either fac-lr(ppy)3 or [Ru(bpy)<sub>3</sub>](PF<sub>6</sub>)<sub>2</sub> should afford the *E*-isomer as the initial product, and the subsequent E-to-Z isomerization step may be blocked if the substrates are highly sterically demanding. Under the current conditions, reactions of aliphatic alkenes (1-hexene, 2-n-butyl-1hexene, Z-or E-5-decene, etc.), as well as tri-substituted alkenes (e.g., triphenylethene), were sluggish. We are now trying to find suitable conditions to increase the reactivity of these substrates.

Table 1. Screening of reaction conditions.

Ph		•	OMe	Photocatalyst (x mol%) 0.1 M in Solvent blue LEDs, rt., 12 h	R Ar	+ R Ar
<b>1a</b> (1.0 eq.)		<b>2a</b> (n eq.)			3aa-E	3aa-Z
Entry	n (eq.)	PC (x mol%) <sup>e</sup>		Solvent	Yield <sup>f</sup>	$E/Z^f$
1 <sup>a</sup>	2.0	[lr]-1	2.5	DMA	87%	8 / 92
2 <sup>a</sup>	2.0	[lr]-2	2.5	DMA	79%	11 / 89
3 <sup>a</sup>	2.0	[lr]-3	2.5	DMA	58%	24 / 76
4 <sup>a</sup>	2.0	[Ru]	2.5	DMA	86%	100 / 0
5ª	2.0	[lr]-1	2.5	DMF	73%	9/91
6 <sup>a</sup>	2.0	[lr]-1	2.5	DMSO	89%	9/91
7 <sup>a</sup>	2.0	[lr]-1	2.5	MeCN	0%	-
8 <sup>a</sup>	2.0	[lr]-1	2.5	MeOH	0%	-
9 <sup>a</sup>	2.0	[Ru]	2.5	DMF	73%	100 / 0
10 <sup>a</sup>	2.0	[Ru]	2.5	DMSO	93%	100 / 0
11 <sup>b</sup>	2.0	[lr]-1	2.5	DMSO	0 %	-
12 <sup>b</sup>	2.0	[Ru]	2.5	DMSO	0 %	-
13 <sup>°</sup>	2.0	-	2.5	DMSO	8%	100 / 0
14 <sup>a</sup>	1.1	[lr]-1	1.0	DMSO	87%	14 / 86
15 <sup>a,d</sup>	1.1	[Ru]	1.0	DMSO	92%	100 / 0

[a] Conditions: **1a** (0.20 mmol), **2a** (0.40 or 0.22 mmol) and **PC** (2.5 or 1.0 mol%), solvent (2 mL), irradiation with 36 W blue LEDs, rt., 12 h. [b] In the dark. [c] Without PC. [d] Reaction was complete within 2 h. [e] [Ir]-1: *fac*-Ir(ppy)<sub>3</sub>; [Ir]-2: [Ir(dtbbpy)(ppy)<sub>2</sub>](PF<sub>6</sub>); [Ir]-3: [Ir(dF(CF<sub>3</sub>)ppy)<sub>2</sub>(dtbbpy)] (PF<sub>6</sub>); [Ru]: [Ru(bpy)<sub>3</sub>](PF<sub>6</sub>)<sub>2</sub>; [f] Determined by <sup>1</sup>H-NMR analysis. Mesitylene was used as an internal standard for determining the yield.

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Scheme 3. Reaction of Katritzky salt 1a with various alkene substrates 2.

Reactions of other alkyl Katritzky salts were also examined (Scheme 4). With the use of styrene 2a, substrates synthesized from amino acids such as alanine (1b), isoleucine (1c), valine (1d), and glycine (1e) were successfully converted into the corresponding products with Z- or E- selectivity (3ba-3ea). Notably, Katritzky salt 1e prepared from glycine, which generates a primary carbon radical, is available for this reaction. Similarly, the reaction using Katritzky salt with lactone structure 1f or cyano group 1g also took place selectively, giving the corresponding E- or Z-alkene product 3fa-3ga with good yield and selectivity. Moreover, treatment of benzyl radical precursors 1h and 1i with 1,1-diphenylethylene 2q under the standard conditions also proved to be effective, and tri-substituted alkenes 3hq and 3iq were obtained, respectively, each in around 70% yield. If the carbon radical has no electronwithdrawing group at the  $\alpha$ -position, the energy level of its SOMO will be higher than those derived from 1a-g.<sup>[21]</sup> Hence,

such radicals are more nucleophilic and will interact more strongly with electrophilic alkenes that have low-lying LUMOs. Accordingly, we envisioned that the current catalytic cycle might be further expanded (Scheme 5), that is, nucleophilic radical A may first add to electron-deficient alkene 2' to form a new electrophilic radical A'. This radical species would then react with alkene 2 to generate a more stabilized radical B', which would go through an SE-redox process with PC\*+ to give cation C', finally leading to the three-component coupling product. Gratifyingly, when we used  $[Ir(ppy)_2(dtbbpy)](PF_6)$  as the PC, the anticipated three-component radical reaction proceeded smoothly, affording tri-substituted alkenes 4 in moderate yields. Such selective tandem C-C bond formation processes not only provide solid support for the proposed mechanism, but also offer another example of the potential synthetic utility of such photoredox reactions, due to their high reaction efficiency. We are currently trying to further modify this transformation.

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Scheme 5. Mechanistic design and experimental results for three-component alkenylation reactions.

To further examine the radical mechanistic pathway, we performed the reaction of **1a** and **2a** in the presence of TEMPO under the standard conditions (Scheme 6-a). The formation of **3aa** was completely suppressed, and the TEMPO-alkyl radical adduct was detected, strongly suggesting that generation of the alkyl radical intermediate took place in the initial step of the

current reaction.<sup>[22]</sup> We also investigated the Z/E-selectivity of this reaction. As shown in Scheme 6-b, pure E- and Z-isomers of 3aa were irradiated in the presence of fac-Ir(ppy)<sub>3</sub> or [Ru(bpy)<sub>3</sub>](PF<sub>6</sub>)<sub>2</sub> under the standard conditions. After 12 hours, 90% of E-3aa had isomerized to the Z-form (with Ir-PC), while no isomerization of Z-3aa occurred (with Ru-PC). Such E/Z isomerizations proceed through triplet-triplet energy transfer processes,<sup>[20]</sup> which require a sufficiently high triplet energy of PC. In a recent report,<sup>[20f]</sup> Weaver and co-workers compared the different emissive energies of excited state PC ([Ru(bpy)<sub>3</sub>]<sup>2+</sup>: 46.5 kcal/mol,<sup>[6d]</sup> Ir(ppy)<sub>3</sub>: 55.2 kcal/mol<sup>[23a]</sup>) with the triplet energies of some styrene derivatives (ca. 51-53 kcal/mol);[23b] the results indicated that Ru-catalyzed isomerization should be rather endergonic and slow, while Ir-catalyzed isomerization is energetically favorable. We next examined the time profile of these reactions (Scheme 6-c).[24] The results suggested that formation of 3aa peaked within 2 hours, and only fac-lr(ppy)<sub>3</sub> promoted the isomerization to the Z-isomer, which proceeded gradually for about 10 hours. These results clearly explain how the Z/E-selectivity is determined by the use of different PCs.



Scheme 6. Mechanistic study.

In summary, we have developed an efficient and selective protocol for alkene synthesis *via* photo-redox-mediated  $C(sp^3)$ –N bond cleavage and  $C(sp^3)$ – $C(sp^2)$  bond formation under mild conditions, using commercially available PCs and alkene substrates, as well as naturally abundant amines. The reaction proceeds through a photo-catalytic SET process, and, importantly, the *Z/E*-selectivity of the alkene products can be efficiently controlled simply by choosing the appropriate PC. The current results not only provide a valuable complement to the

original Mizoroki-Heck reaction, but also exemplify a promising method for functionalization of the amino C–N bond without the need for traditional TM catalysts. Work to extend the scope of this reaction and to apply it for the synthesis of a range of functional molecules is in progress.

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- a) R. Alvarez, B. Vaz, H. Gronemeyer, A. R. de Lera, *Chem. Rev.* 2014, 114, 1-125. b) C. Dugave, L. Demange, *Chem. Rev.* 2003, *103*, 2475-2532.
- a) T. Mizoroki, K. Mori, A. Ozaki, Bull. Chem. Soc. Jpn. 1971, 44, 581-581. b) R. F. Heck, J. P. Nolley, J. Org. Chem. 1972, 37, 2320-2322.
- For representative reviews, see: a) C. C. Johansson Seechurn, M. O. Kitching, T. J. Colacot, V. Snieckus, *Angew. Chem. Int. Ed.* 2012, *51*, 5062–5085; *Angew. Chem.* 2012, 124, 5150–5175; b) *The Mizoroki-Heck Reaction* (Ed.: M. Oestreich), Wiley-VCH, Weinheim, 2009; c) C. Torborg, M. Beller, *Adv. Synth. Catal.* 2009, *351*, 3027-3043; d) K. C. Nicolaou, P. G. Bulger, D. Sarlah, *Angew. Chem., Int. Ed.*, 2005, *44*, 4442-4489.
- [4] For recent reviews, see: a) Z.-H. Ouyang, R.-J. Song, J.-H. Li, *Chem. Asian J.* 2018, *13*, 2316-2332; b) A. Kaga, S. Chiba, *ACS Catal.* 2017, 7, 4697-4706; c) Z. Qureshi, C. Toker, M. Lautens, *Synthesis* 2017, *49*, 1-16; d) T. Iwasaki, N. Kambe, *Top. Curr. Chem.* 2016, *374*, 1-36.
- For leading examples see: a) L. Firmansjah, G. C. Fu, J. Am. Chem. [5] Soc. 2007, 129, 11340-11431; b) K. S. Bloome, R. L. McMahen, E. J. Alexanian, J. Am. Chem. Soc. 2011, 133, 20146-20148; c) C. M. McMahon, E. J. Alexanian, C. M. McMahon, E. J. Alexanian, Angew. Chem. Int. Ed. 2014, 53, 5974-5977; Angew. Chem. 2014, 126, 6084-6087; d) Y. Zou, J. S. Zhou, Chem. Commun. 2014, 50, 3725-3728; e) M. Parasram, V. O. laroshenko, V. Gevorgyan, J. Am. Chem. Soc. 2014, 136, 17926-17929; f) J.-H. Fan, W.-T. Wei, M.-B. Zhou, R.-J. Song, J.-H. Li, Angew. Chem. Int. Ed. 2014, 53, 6650-6654; Angew. Chem. 2014, 126, 6768-6772; g) Z. Feng, Q.-Q. Min, H.-Y. Zhao, J.-W. Gu, X. Zhang, Angew. Chem. Int. Ed. 2015, 54, 1270-1274; Angew. Chem. 2015, 127, 1286-1290; h) Z. Li, A. García-Domínguez, C. Nevado, J. Am. Chem. Soc. 2015, 137, 11610-11613 .i) X. Dong, Y. Han, F. Yan, Q. Liu, P. Wang, K. Chen, Y. Li, Z. Zhao, Y. Dong, H. Liu, Org. Lett. 2016, 18, 3774-3777.
- [6] For some representative reviews, see: a) J. K. Matsui, S. B. Lang, D. R. Heitz, G. A. Molander, ACS Catal. 2017, 7, 2563-2575; b) N. A. Romero, D. A. Nicewicz, Chem. Rev. 2016, 116, 10075-10166; c) D. Ravelli, S. Protti, M. Fagnoni, Chem. Rev. 2016, 116, 9850-9913; d) C. K. Prier, D. A. Rankic, D. W. C. MacMillan, Chem. Rev. 2013, 113, 5322-5363; e) J. Xuan, W. -J. Xiao, Angew. Chem. Int. Ed. 2012, 51, 6828-6838; f) J. M. R. Narayanam, C. R. J. Stephenson, Chem. Soc. Rev. 2011, 40, 102-113.
- [7] For recent examples of photo-induced M–H reactions with alkyl halides, see: a) D. Kurandina, M. Rivas, M. Radzhabov, V. Gevorgyan, V. Org. Lett. 2018, 20, 357-360. b) D. Kurandina, M. Parasram, V. Gevorgyan, Angew. Chem. Int. Ed. 2017, 56, 14212-14216; Angew. Chem. 2017, 129, 14400–14404; c) G.-Z. Wang, R. Shang, W.-M. Cheng, Y. Fu, J. Am. Chem. Soc. 2017, 139, 18307-18312; d) J. Xie, J. Li, V. Weingand, M. Rudolph, A. S. K. Hashmi, Chem. Eur. J. 2016, 22, 12646-12650;

e) W. Liu, L. Li, Z. Chen, C.-J. Li, *Org. Biomol. Chem.* 2015, 13, 6170-6174; f) S. Sumino, T. Ui, Y. Hamada, T. Fukuyama, I. Ryu, *Org. Lett.* 2015, *17*, 4952-4955; g) S. Paria, V. Kais, O. Reiser, *Adv. Synth. Catal.* 2014, 356, 2853-2858; h) Q. Liu, H. Yi, J. Liu, Y. Yang, X. Zhang, Z. Zeng, A. Lei, *Chem. Eur. J.* 2013, *19*, 5120-5126.

- [8] For recent examples of photo-induced decarboxylative M–H reactions, see: a) H. Cao, H. Jiang, H. Feng, J. M. C. Kwan, X. Liu, J. Wu, J. Am. Chem. Soc. 2018, 140, 16360-16367; b) C. Zheng, W.-M. Cheng, H.-L. Li,R.-S. Na, R. Shang, R. Org. Lett. 2018, 20, 2559-2563; c) Z.-H. Xia, C.-L. Zhang, Z.-H. Gao, S. Ye, Org. Lett. 2018, 20, 3496-3499; d) G.-Z. Wang, R. Shang, Y. Fu, Org. Lett. 2018, 20, 888-891; e) W. Kong; C. Yu; H. An; Q. Song, Org. Lett. 2018, 20, 349-352; f) M. Koy, F. Sandfort, A. Tlahuext-Aca, L. Quach, C. G. Daniliuc, F. Glorius, Chem. Eur. J. 2018, 24, 4552-4555.
- [9] K. Ouyang, W. Hao, W.-X. Zhang, Z. Xi, Chem. Rev. 2015, 115, 12045–12090.
- [10] a) T. Koreeda, T. Kochi, F. Kakiuchi, J. Am. Chem. Soc. 2009, 131, 7238-7239; b) Y. Xie, J. Hu, Y. Wang, C. Xia and H. Huang, J. Am. Chem. Soc. 2012, 134, 20613-20616; c) M. Tobisu, K. Nakamura, N. Chatani, J. Am. Chem. Soc. 2014, 136, 5587-5590; d) Y. Zhao, V. Snieckus, Org. Lett. 2014, 16, 3200-3203; e) A. Hernán-Gómez, A. R. Kennedy, E. Hevia, Angew. Chem. Int. Ed. 2017, 56, 6632-6635; Angew. Chem. 2017, 129, 6732-6735; f) H. Yu, B. Gao, B. Hu, H. Huang, Org. Lett. 2017, 19, 3520-3523; g) X. Cong, F. Fan, P. Ma, M. Luo, H. Chen, X. Zeng, J. Am. Chem. Soc. 2017, 139, 15182-15190; h) Z.-C. Cao, X.-L. Li, Q.-Y. Luo, H. Fang, Z.-J. Shi, Org. Lett. 2018, 20, 1995-1998; i) Z.-C. Cao, S.-J. Xie, H. Fang, Z.-J. Shi J. Am. Chem. Soc. 2018, 140, 13575-13579.
- [11] E. Wenkert, A.-L. Han, C.-J. Jenny, J. Chem. Soc., Chem. Commun. 1988, 975-976.
- [12] For representative examples, see: a) S. B. Blakey, D. W. C. MacMillan, C. J. Am. Chem. Soc. 2003, 125, 6046-6047; b) J. T. Reeves, D. R. Fandrick, Z. Tan, J. J. Song, H. Lee, N. K. Yee, C. H. Senanayake, Org. Lett. 2010, 12, 4388-4391; c) L.-G. Xie, Z.-X. Wang, Angew. Chem. 2011, 123, 5003-5006; Angew. Chem. Int. Ed. 2011, 50, 4901-4904; d) F. Zhu, J.-L. Tao, Z.-X. Wang, Org. Lett. 2015, 17, 4926-4929; e) H. Zhang, S. Hagihara, K. Itami, Chem. Eur. J. 2015, 21, 16796-16800; f) J. Hu, H. Sun, W. Cai, X. Pu, Y. Zhang, Z. Shi, J. Org. Chem. 2016, 81, 14-24; g) T. Moragas, M. Gaydou, R. Martin, R. Angew. Chem. 2016, 128, 5137-5141; Angew. Chem. Int. Ed. 2016, 55, 5053-5057; h) W.-C. Dai, Z.-X. Wang, Chem. Asian J. 2017, 12, 3005-3009.
- [13] Our works on aryl ammonium C–N bond cleavage reactions: a) D.-Y. Wang, M. Kawahata, Z.-K. Yang, K.Miyamoto, S. Komagawa, K. Yamaguchi, C. Wang, M. Uchiyama, *Nature Commun.* 2016, *7*, 12937; b) Z.-K. Yang, D.-Y. Wang, H. Minami, H. Ogawa, T. Ozaki, T. Saito, K. Miyamoto, C. Wang, M. Uchiyama, *Chem. Eur. J.* 2016, *22*, 15693-15699; c) H. Ogawa, Z.-K. Yang, H. Minami, T. Saito, C. Wang, M. Uchiyama, *ACS Catal.* 2017, *7*, 3988-3994; d) D.-Y. Wang, K. Morimoto, Z.-K. Yang, C. Wang, M. Uchiyama, *Chem. Asian J.* 2017, *12*, 2554-2557; e) Z.-K. Yang, N.-X. Xu, R. Takita, A. Muranaka, C. Wang, M. Uchiyama, *Nat. Commun.* 2018, *9*, 1587; f) D.-Y. Wang, Z.-K. Yang, C. Wang, A. Zhang, M. Uchiyama, *Angew. Chem. Int. Ed.* 2018, *57*, 3641-3635; *Angew. Chem.* 2018, *130*, 3703-3707.
- [14] For examples on reactions of activated alkyl (e.g. benzyl or propagyl) ammoniums, see: a) P. Maity, D. M. Shacklady-McAtee, G. P. A. Yap, E. R. Sirianni, M. P. Watson, J. Am. Chem. Soc. 2013, 135, 280-285; b) Y.-Q. Yi, W.-C. Yang, D.-D. Zhai, X.-Y. Zhang, S.-Q. Li, B.-T. Guan, Chem. Commun. 2016, 52, 10894-10897; c) C. H. Basch, K. M. Cobb, M. P. Watson, Org. Lett. 2016, 18, 136-139; d) M. Guisán-Ceinos, V. Martín-Heras, M. Tortosa, J. Am. Chem. Soc. 2017, 139, 8448-8451; e) W. Yu, S. Yang, F. Xiong, T. Fan, Y. Feng, Y. Huang, J. Fu, T. Wang, Org. Biomol. Chem. 2018, 16, 3099-3103; f) T. Pillaiyar, E. Gorska, G. Schnakenburg, C. E. Müller, J. Org. Chem. 2018, 83, 9902-9913. For a recent report on photo-induced benzyl ammonium C–N cleavage reaction, see: g) L.-L. Liao, G.-M. Cao, J.-H. Ye, G.-Q.

10.1002/chem.201900886

Sun, W.-J. Zhou, Y.-Y. Gui, S.-S. Yan, G. Shen, D.-G. Yu, J. Am. Chem. Soc. 2018, 140, 17338-17342.

- [15] A. R. Katritzky, G. De Ville, R. C. Patel, *Tetrahedron* 1981, 37, 25–30.
- [16] a) Bapat, J. B.; Blade, R. J.; Boulton, A. J.; Epsztajn, J.; Katritzky, A. R.; Lewis, J.; Molina-Buendia, P.; Nie, P.-L.; Ramsden, C. A. *Tetrahedron Lett.* **1976**, *17*, 2691-2694; b) A. R. Katritzky, U. Gruntz, D. H. Kenny, M. C. Rezende, H. Sheikh, J. Chem. Soc. Perkin Trans. *1* **1979**, 430-432.
- [17] a) C. H. Basch, J. Liao, J. Xu, J. J. Piane, M. P. Watson, *J. Am. Chem. Soc.* 2017, *139*, 5313-5316; b) J. Liao, W. Guan, B. P. Boscoe, J. W. Tucker, J. W. Tomlin, M. R. Garnsey, M. P. Watson, *Org. Lett.* 2018, *20*, 3030–3033.
- [18] a) F. J. R. Klauck, M. J. James, F. Glorius, Angew. Chem. Int. Ed. 2017, 56, 12336-12339; Angew. Chem. 2017, 129, 12505-12509; b) J. Wu, L. He, A. Noble, V. K. Aggarwal, J. Am. Chem. Soc. 2018, 140, 10700-10704; c) F. Sandfort, F. Strieth-Kalthoff, F. J. R. Klauck, M. J. James, F. Glorius, Chem. Eur. J. 2018, 24, 17210-17214; d) M.-M. Zhang, F. Liu, Org. Chem. Front. 2018, 5, 3443-3446; e) M. Ociepa, J. Turkowska, D. Gryko, ACS Catal. 2018, 8, 11362-11367; f) F. J. R. Klauck, H. Yoon, M. J. James, M. Lautens, F. Glorius, ACS Catal. 2019, 9, 236-241. For a thermo-induced SET reaction, see: g) J. Hu, G. Wang, S. Li, Z. Shi, Angew. Chem. Int. Ed. 2018, 57, 15227-15231; Angew. Chem. 2018, 130, 15447-15451.
- Just before we were ready to submit our present manuscript, Xiao, Lu and co-workers independently reported a similar reaction: X. Jiang, M.-M. Zhang, W. Xiong, L.-Q. Lu, W.-J. Xiao, *Angew. Chem. Int. Ed.* 2019, *58*, 2402-2406; *Angew. Chem.* 2019, *131*, 2424-2428. *E/Z* selectivity of the reaction was not discussed in their work.
- [20] For selected reviews, see: a) J. Metternich, R. Gilmour, Synlett 2016, 27, 2541–2552; b) K. Zhan, Y. Li, Catalysts 2017, 7, 337, doi: 10.3390/catal7110337; c) Q.-Q. Zhou, Y.-Q. Zou, L.-Q. Lu, W.-J. Xiao, Angew. Chem. Int. Ed. 2019, 58, 1586-1604; Angew. Chem. 2019, 131, 1600-1619. For selected recent examples, see: d) J. J. Molloy, J. B. Metternich, C. G. Daniliuc, A. J. B. Watson, R. Gilmour, Angew. Chem. Int. Ed. 2018, 57, 3168-3172. Angew. Chem. 2018, 130, 3222-3226; e) K. Nakajima, X. Guo, Y. Nishibayashi, Chem. Asian J. 2018, 13, 3653-

3657; f) W. Cai, H. Fan, D. Ding, Y. Zhang, W. Wang, *Chem. Commun.* 2017, 53, 12918-12921; g) A. Singh, C. J. Fennell, J. D.Weaver, *Chem. Sci.* 2016, 7, 6796-6802; h) D. C. Fabry, M. A. Ronge, M. Rueping, *Chem. Eur. J.* 2015, *21*, 5350-5354; i) K. Singh, S. J. Staig, J. D. Weaver, *J. Am. Chem. Soc.* 2014, *136*, 5275-5278; j) Q.-Y. Lin, X.-H. Xu, F.-L. Qing, *J. Org. Chem.* 2014, *79*, 10434-10446.

- [21] Reactions of these radicals, such as n-hexyl, 2'-phenylethyl, cyclohexyl, etc., were sluggish and only trace products were obtained under the current conditions. On the other hand, a complementary method was described in Xiao and Lu's work (ref. 19). In their case, the use of a different photocatalyst ( $Ir(4-Fppy)_2(bpy)PF_6$ ) and 1,1-diarylethene instead of styrene (probably as a stronger radical acceptor), and addition of a base (probably for facilitating the final elimination step) can promote the reactions of these radicals.
- [22] Luminescence quenching experiments and/or Stern-Volmer analysis for both Ir and Ru-PC with Katritzky salt have been reported; see ref. 18 and 19. We also performed luminescence quenching experiments and Stern-Volmer analysis for Ru-PC with both 1a and 2a (see SI). We found that both oxidative (1a) and reductive (2a) quenching took place. However, addition of TEMPO gave only the capture product from 1a (Scheme 6-a), indicating that oxidative quenching is the major route in the current reaction.
- [23] a) A. Singh, K. Teegardin, M. Kelly, K. S. Prasad, S. Krishnan, J. D. Weaver, *J. Organomet. Chem.* **2015**, 776, 51-59; b) T. Ni, R. A. Caldwell, L. A. Melton, *J. Am. Chem. Soc.* **1989**, *111*, 457-464.
- [24] The quantum yields of both reactions were determined to be  $\Phi = 0.137$  (Ir) and 0.270 (Ru), respectively. We also performed light/dark experiments, and the results showed that the current transformations require continuous irradiation with visible light. Note that radical-chain propagation mechanism cannot be conclusively ruled out simply by the results of light/dark experiments, for a recent critical report, see: M. A. Cismesia, T. P. Yoon, *Chem. Sci.* **2015**, *6*, 5426-5434. Hence, according to the results of quantum yield measurements and luminescence quenching experiments, it at least appears that chain propagation is not the major pathway.

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# COMMUNICATION



Under visible light irradiation (455 nm, blue LEDs) at room temperature, alkyl Katritzky salts react smoothly with alkenes in 1 : 1 molar ratio in the presence of 1.0 mol% of commercially available photoredox catalyst without the need for any base, affording corresponding alkyl-substituted alkenes in good yields with broad functional group compatibility. Notably, the *E*/*Z*-selectivity of the alkene products can be controlled by appropriate choice of the photoredox catalyst.

Ze-Kun Yang, Ning-Xin Xu, Chao Wang,\* and Masanobu Uchiyama\*

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Photo-Induced C(*sp*<sup>3</sup>)–N Bond Cleavage Leading to Stereoselective Syntheses of Alkenes