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Hypervalent Compounds

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Silicates as Latent Alkyl Radical Precursors: Visible-Light Photocatalytic Oxidation of Hypervalent Bis-Catecholato Silicon Compounds

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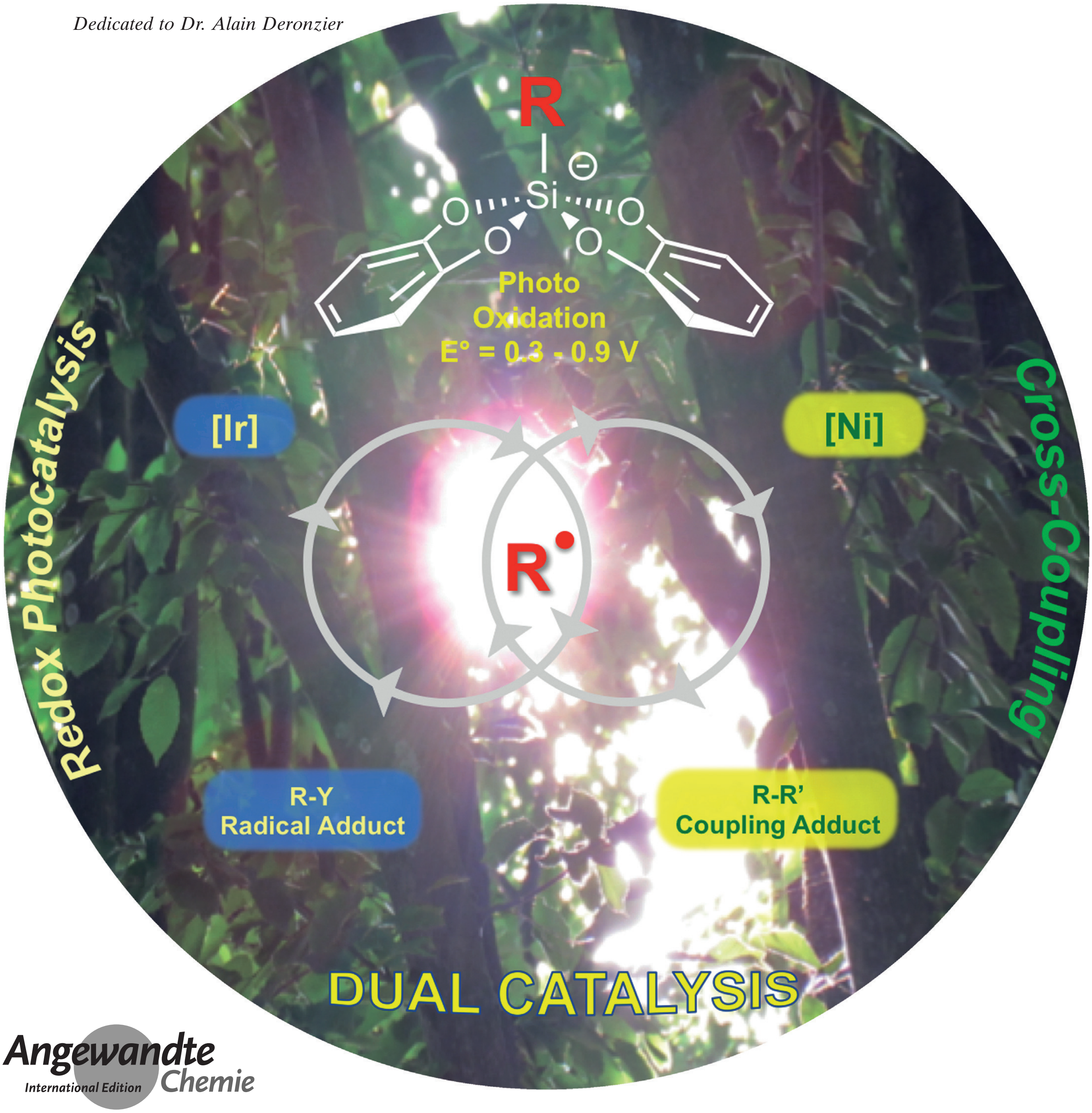
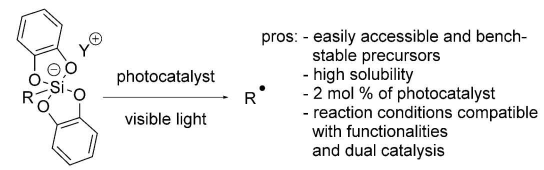
Dedicated to Dr. Alain Deronzier



Abstract: *This works introduces hypervalent bis-catecholato silicon compounds as versatile sources of alkyl radicals upon visible-light photocatalysis. Using* $Ir[(dF(CF_3)ppy)_2(bpy)](PF_6)$ *(*$dF(CF_3)ppy$ *= 2-(2,4-difluorophenyl)-5-trifluoromethylpyridine, bpy = bipyridine) as catalytic photooxidant, a series of alkyl radicals, including highly reactive primary ones can be generated and engaged in various intermolecular homolytic reactions. Based on cyclic voltammetry, Stern–Volmer studies, and supported by calculations, a mechanism involving a single-electron transfer from the silicate to the photoactivated iridium complex has been proposed. This oxidative photocatalyzed process can be efficiently merged with nickel-catalyzed* C_{sp^2}–C_{sp^3} *cross-coupling reactions.*

Over the last decades, radical chemistry has entered mainstream organic synthesis so that homolytic steps are nowadays quite frequently encountered in multistep syntheses of complex molecules.[1] Therefore, the need to access radical intermediates from an increasing number of methodologies and associated precursors remains high, this need being even more vivid for highly reactive entities such as primary radicals. Redox pathways display high versatility as C-centered radicals have been easily generated by single-electron transfer (SET) reduction of substrates bearing electron-withdrawing functional groups. Conversely, SET oxidative processes of electron-rich substrates, for instance organometallics, are well known. Nevertheless, finding organometallic precursors which exhibit sufficient stability and function compatibility is not that obvious.[1,2] Soft carbanions such as ate complexes or hypervalent derivatives are intriguing alternatives with better handling properties. For instance, organoborates and notably alkyl trifluoroborates can be oxidized[3] and have recently been used in various efficient reactions under photocatalytic conditions.[4] However, the main drawbacks reside in the formation of polluting boron fluoride side products and so far the difficulty to generate primary radicals under photocatalytic conditions.[5] Hypervalent silicon compounds are also very attractive targets in terms of accessibility and potential reactivity.[6] A seminal study by Kumada et al. reported the stoichiometric copper(II) oxidation of organopentafluorosilicates to provide organic radicals.[7] However, their extremely low solubility in organic or aqueous media severely limit their use. We considered the more soluble bis-catecholato hypervalent silicon derivatives, first synthesized by Frye,[8] as substrates amenable to the oxidation process. In that context, the reports by Nishigaishi et al. on the photoallylation of benzil-type derivatives[9a] and dicyanoarenes[9b] using an allylbiscatecholato silicate reagent under photoinduced electron transfer (PET) conditions drew our attention. Despite narrow scope and modest yields, these seminal studies drove us to design an unprecedented photocatalyzed oxidation of catechol-based silicates, under low-energy visible-light activation and using readily available photoactive catalysts,[10,11] to generate functionalized alkyl radicals and notably primary ones. The radical intermediates were engaged in a series of homolytic transformations, including dual catalysis involving nickel-catalyzed cross-coupling (Scheme 1).



Scheme 1. Hypervalent silicon compounds as a source of C-radicals.

Our first task was to devise the most reliable access to bis-catecholato silicates. We focused on potassium silicates obtained from the reaction of commercially available or readily prepared trialkoxysilanes with catechol in the presence of potassium methoxide in methanol (method A).[12] We found that the presence of 18-crown-6 (18-C-6) ether was highly beneficial for the stability of the hypervalent derivatives.[13,14] Various bis-catecholato silicates such as primary (**1a–i, 1m–n**), secondary (**1j, 1p**), and aryl (**1k–l**) silicates could be prepared in large scale, isolated as solids, and stored at room temperature without any degradation (Scheme 2). For the more sterically demanding cyclopentyl and *tert*-butyl silicates, we had to use the described preparation of tetraethylammonium silicates,[15] using trichlorosilane precursors (method B) and obtained the corresponding silicates **1p** and **1o** in decent yields. The structures of **1d**, **1j**, **1n**, and **1p** were confirmed by X-ray crystallography (see the Supporting Information, SI).

We next examined their ability to generate carbon-centered radicals under photooxidative conditions. Benzylsilicate **1c** was initially chosen as representative substrate because it was expected to lend itself to easy oxidation thanks to the stability of the resulting radical and because of its known fast trapping by TEMPO.[3b,4a,16] To probe the oxidation process, 2.2 equiv of TEMPO were added in the reaction mixture to trap any formed benzyl radical and to act as sacrificial electron acceptor in the catalytic cycle (Scheme 4).[4a] The screening of different photocatalysts $Ru(bpy)_3(PF_6)_2$ (bpy = bipyridine), $Ir[(dF(CF_3)ppy)_2(bpy)]PF_6$ ($dF(CF_3)ppy$ = 2-(2,4-difluorophenyl)-5-trifluoromethylpyridine), and $Ir[(dF(CF_3)ppy)_2(dtbbpy)]PF_6$ (dtbbpy = 4,4′-di-*tert*-butyl-2,2′-biyridine) under irradiation with blue LEDs (477 nm) was achieved in acetone, MeCN, MeOH, and DMF (SI). A drastic solvent effect was observed when using DMF

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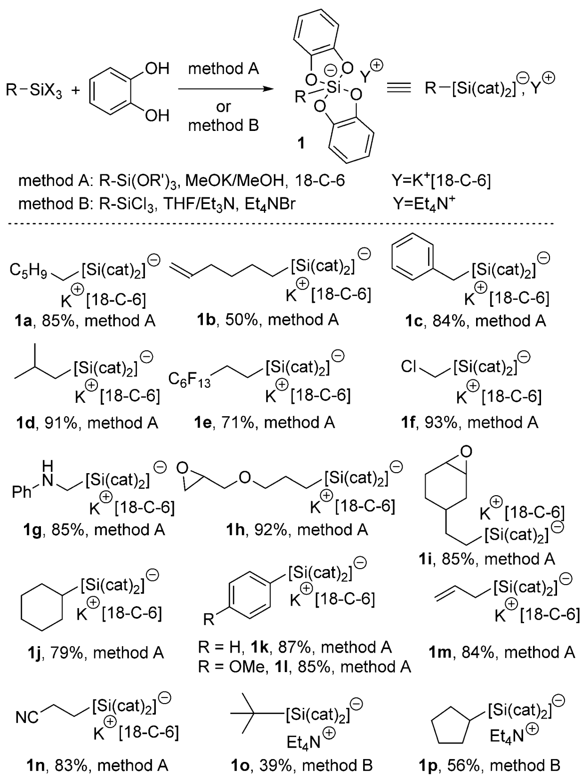
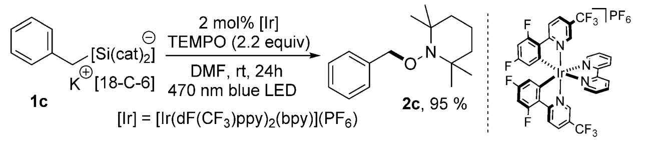


Scheme 2. Preparation of the silicate substrates.

which proved to be clearly superior to all solvents used and gave the best yields of TEMPO adduct **2c** (Scheme 3).

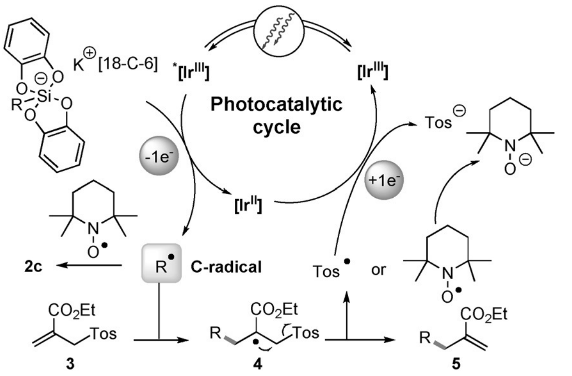
We performed cyclic voltammetry to determine the oxidation potentials of silicates **1**. Clean voltammograms were obtained showing irreversible oxidation waves (SI). Oxidation potentials were determined to be between $+0.34$ V for aminosilicate **1g** to $+0.89$ V versus SCE in DMF for phenylsilicate **1k**. These values suggest that a photoexcited photocatalyst could oxidize all silicates **1** and trigger homolytic cleavage. Although similar yields of TEMPO adduct from benzylsilicate **1c** ($E_{ox}=+0.61$ V) were obtained with all catalysts, we selected the most oxidizing [Ir(dF(CF$_3$)ppy)$_2$-(bpy)]PF$_6$ complex at the excited state as photocatalyst (E Ir^{III}*/Ir$^{II}=+1.32$ V vs. SCE in CH$_3$CN)[17] for all further reactions with silicates **1**.

With the optimized conditions, we engaged silicates **1** in photocatalytic reactions to explore the feasibility of carbon–carbon bond formation. We first focused on the allylation reaction, because we showed in previous works[11] that allylsulfone **3** could be used as a versatile radical acceptor. In agreement with our preliminary findings with TEMPO trapping, we surmised the following photocatalytic cycle as working hypothesis (Scheme 4).



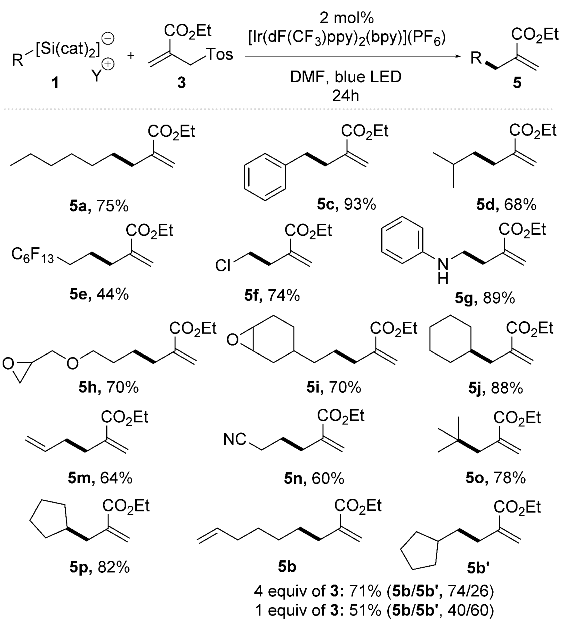
Scheme 3. Spin-trapping experiments with TEMPO for screening of conditions with silicate **1c**.

A SET oxidation of the catechol silicate would occur by the excited *Ir^{III}-dF(CF$_3$), subsequently reduced to Ir^{II}-dF-(CF$_3$). After homolytic cleavage of the C−Si bond of the silicate radical, the resulting C-centered radical adds to the activated allylsulfone **3**, leading to β-sulfonyl radical **4**. Then, fragmentation provides allylation adducts **5** and the sulfonyl radical. By analogy with the TEMPO-trapping catalytic cycle, and as recently evidenced by MacMillan in photocatalytic vinylation reactions,[18] reduction of the sulfonyl radical furnishing the sulfinate anion would regenerate the photocatalyst in its ground state and ensure the propagation of the catalytic cycle.

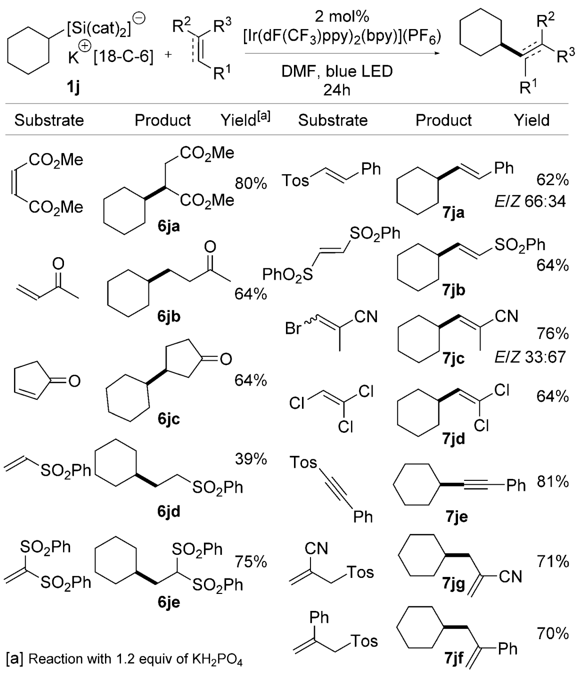


Scheme 4. Proposed catalytic cycle.

With this photocatalytic cycle proposal in mind, we explored the behavior of silicates **1** toward radical allylation with allylsulfone **3** (4 equiv). This drove us to use this reaction as a probe for the radical addition of other radicals (Scheme 5). The scope of engaged substrates proved quite large ranging from primary to tertiary substrates. Particularly noteworthy is the compatibility of the process with valuable functionalities such as oxirane (**5i**). A new example of intermolecular α-aminomethylation (**5g**),[4d] featuring a chemoselective oxidation of the silicate moiety at the expense of the methyleneaniline function,[10k] and even the previously undescribed radical α-chloromethylation (**5f**) was rendered possible in satisfactory yields. Hexenyl silicate **1b** provided a mixture of allylation product **5b** and 5-*exo-trig*-allylation tandem **5b′**, with the ratio logically depending on the amount of **3**. However, aryl silicates **1l** and **1k** failed to give any adduct contrary to previous observations of aryl radical allylations.[11b–c,19] Our next objective was to delineate the scope of radical processes and we first focused on the reactivity of cyclohexyl substrate **1j** vis-à-vis of various radical acceptors (Scheme 6). Giese-type reactions proved to be possible with a variety of activated olefins from moderate (**6jd**) to high yields (**6ja**, **6je**). Quite interestingly, vinylation could be achieved with vinylsulfones to give adducts **7ja**–**7jb** or bromomethacrylonitrile to yield unsaturated nitrile **7jc**. Trichloroethylene is a versatile acceptor[20] because it furnishes dichloroolefin **7jd** which can be a precursor of a terminal alkyne, while a disubstituted alkyne can



Scheme 5. Allylation reaction of various silicates **1**.



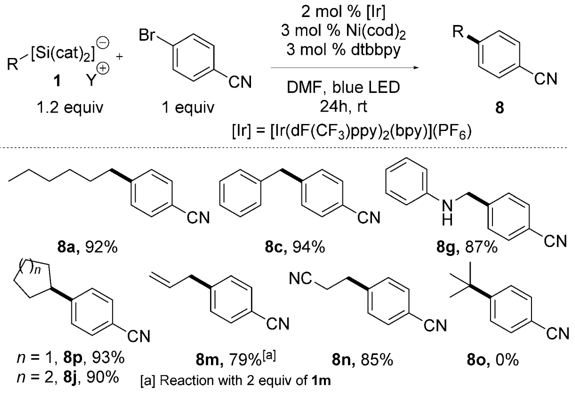
Scheme 6. Scope of intermolecular additions.

be obtained by direct alkynylation (**7je**) using an alkynylsulfone precursor.[21]

To have a better insight into the mechanism, we performed fluorescence quenching studies of Ir(dF(CF$_3$)ppy)$_2$-(bpy)*, noted *Ir^{III}-dF(CF$_3$), with silicates **1c** and **1j**. A significant decrease of fluorescence intensity was observed upon gradual addition of the silicates **1**. A plot of the intensity ratio $I°/I$ versus the concentration of **1** showed a linear relation, following the Stern–Volmer law which allowed to determine the quenching rate constants k_q ($7.9\times10^9\,\text{M}^{-1}\text{s}^{-1}$ and $13.6\times10^9\,\text{M}^{-1}\text{s}^{-1}$ for **1c** and **1j**, respectively). This led us to the following mechanism proposal. From the Stern–Volmer analysis and consistent with the oxidation potentials difference, silicates **1** appear as very efficient reductive quench of the photoexcited state *Ir^{III}-dF(CF$_3$). Electron donation by silicates **1** would trigger a Si–C bond rupture, liberating free radical R$^•$. Conversely, the generated Ir^{II}-dF(CF$_3$) would be oxidized to regenerate the Ir^{III}-dF(CF$_3$) catalytic species by reacting either with TEMPO, or the sulfonyl or halide radicals generated in the allylation and related reactions as shown in Scheme 4. In the case of intermolecular addition onto activated olefins, the resulting radical stabilized by a carbonyl (or sulfonyl) moiety would evolve to the corresponding enolate and further protonation by KH$_2$PO$_4$ would deliver the final adduct **6**. Interestingly, no reaction occurs in the absence of photocatalyst or in the dark (SI). This mechanistic proposal is also supported by DFT calculations (SI).

To illustrate the breakthrough brought by the photocatalytic oxidation of catechol-based silicates, we looked at the possibility of dual catalysis,[10l] focusing on photoredox/nickel[4g–i,22] C$_{sp^2}$–C$_{sp^3}$ cross-coupling reactions between 4-bromobenzonitrile and a series of alkyl silicates **1**. To rule out a possible Hiyama reaction between the silicates and the aryl bromide under nickel catalysis, a series of blank experiments was conducted (SI). No reaction occurred in the absence of nickel, light, and/or photocatalyst, strongly supporting the crucial role of each partner in this dual catalysis. While the *tert*-butyl radical could not be involved in this coupling, the reaction proved to work perfectly with stabilized, allyl and benzyl, and secondary radicals as well as α-amino-stabilized primary radicals[22a] yielding excellent yields of coupling products **8m**, **8c**, **8j**, **8p**, and **8g** (Scheme 7). To our delight, even unstabilized primary radicals could be successfully engaged as highlighted by the formation of products **8a** and **8n**. These last results establish silicates as very valuable and promising partners in photoredox/nickel cross-coupling dual catalysis.

In conclusion, we have demonstrated that bis-catecholato silicates can be efficiently used for the generation of alkyl radicals. These silicates are bench-stable solids, easy to synthesize and to handle, notably because of their solubility. Upon mild photocatalytic conditions, their oxidation delivers



Scheme 7. Scope of the dual catalysis featuring unstabilized primary radicals.

functionalized alkyl radicals and notably unstabilized primary ones that readily engage in conjugate addition, allylation, alkynylation, vinylation, and nickel-catalyzed cross-coupling reactions. The latter findings clearly open exciting prospects in dual catalysis transformations.

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[1] a) *Radicals in Organic Synthesis* (Eds.: P. Renaud, M. P. Sibi), Wiley-VCH, Weinheim, **2001**; b) *Encyclopedia of Radicals in Chemistry, Biology and Materials* (Eds.: C. Chatgilialoglu, A. Studer), Wiley, Chichester, **2012**.

[2] a) A. Gansäuer, H. Bluhm, *Chem. Rev.* **2000**, *100*, 2771; b) U. Jahn in *Radicals in Organic Synthesis III* (Eds.: M. Heinrich, A. Gansäuer), Springer, Heidelberg, **2012**, p. 121, 191 and 323 (*Topics in Current Chemistry*, *320*); c) A. Studer, D. P. Curran, *Nat. Chem.* **2014**, *6*, 765, and references therein.

[3] For representative works, see: a) Y. Nishigaichi, T. Orimi, A. Takuwa, *J. Organomet. Chem.* **2009**, *694*, 3837; b) G. Sorin, R. M. Mallorquin, Y. Contie, A. Baralle, M. Malacria, J.-P. Goddard, L. Fensterbank, *Angew. Chem. Int. Ed.* **2010**, *49*, 8721; *Angew. Chem.* **2010**, *122*, 8903; c) G. A. Molander, V. Colombel, V. A. Braz, *Org. Lett.* **2011**, *13*, 1852; d) J. W. Lockner, D. D. Dixon, R. Risgaard, P. S. Baran, *Org. Lett.* **2011**, *13*, 5628; e) S. R. Neufeldt, C. K. Seigerman, M. S. Sanford, *Org. Lett.* **2013**, *15*, 2302

[4] a) Y. Yasu, T. Koike, M. Akita, *Adv. Synth. Catal.* **2012**, *354*, 3414; b) K. Miyazawa, Y. Yasu, T. Koike, M. Akita, *Chem. Commun.* **2013**, *49*, 7249; c) T. Koike, M. Akita, *Synlett* **2013**, 2492; d) K. Miyazawa, T. Koike, M. Akita, *Adv. Synth. Catal.* **2014**, *356*, 2749; e) Y. Li, T. Koike, *Org. Chem. Front.* **2015**, *2*, 319; f) H. Huang, G. Zhang, L. Gong, S. Zhang, Y. Chen, *J. Am. Chem. Soc.* **2014**, *136*, 2280; g) J. C. Tellis, D. N. Primer, G. A. Molander, *Science* **2014**, *345*, 433; h) D. N. Primer, I. Karakaya, J. C. Tellis, G. A. Molander, *J. Am. Chem. Soc.* **2015**, *137*, 2195; i) O. Gutierrez, J. C. Tellis, D. N. Primer, G. A. Molander, M. C. Kozlowski, *J. Am. Chem. Soc.* **2015**, *137*, 4896.

[5] Primary radicals are difficult to generate by photocatalytic oxidation of trifluoroborates,[4a] except when stabilizing groups are present[4a,e] or when an external oxidative quencher is used, which leads to a different catalytic cycle[4f] that is presumably not compatible with conjugate addition and dual catalysis.

[6] a) R. R. Holmes, *Chem. Rev.* **1990**, *90*, 17; b) C. Chuit, R. J. P. Corriu, C. Reye, J. C. Young, *Chem. Rev.* **1993**, *93*, 1371.

[7] J.-I. Yoshida, K. Tamao, T. Kakui, A. Kurita, M. Murata, K. Yamada, M. Kumada, *Organometallics* **1982**, *1*, 369.

[8] C. L. Frye, *J. Am. Chem. Soc.* **1964**, *86*, 3170.

[9] a) Y. Nishigaichi, A. Suzuki, A. Takuwa, *Tetrahedron Lett.* **2007**, *48*, 211; b) D. Matsuoka, Y. Nishigaishi, *Chem. Lett.* **2014**, *43*, 559.

[10] For selected reviews, see: a) J. M. R. Narayanaman, C. R. J. Stephenson, *Chem. Soc. Rev.* **2011**, *40*, 102; b) F. Teplý, *Collect. Czech. Chem. Commun.* **2011**, *76*, 859; c) J. Xuan, W.-J. Xiao, *Angew. Chem. Int. Ed.* **2012**, *51*, 6828; *Angew. Chem.* **2012**, *124*, 6934; d) M. A. Ischay, T. P. Yoon, *Eur. J. Org. Chem.* **2012**, 3359; e) L. Shi, W. Xia, *Chem. Soc. Rev.* **2012**, *41*, 7687; f) C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.* **2013**, *113*, 5322; g) D. P. Hari, B. König, *Angew. Chem. Int. Ed.* **2013**, *52*, 4734; *Angew. Chem.* **2013**, *125*, 4832; h) M. Reckenthäler, A. G. Griesbeck, *Adv. Synth. Catal.* **2013**, *355*, 2727; i) Ref. [4c]; j) J. Xuan, L.-Q. Lu, J.-R. Chen, W.-J. Xiao, *Eur. J. Org. Chem.* **2013**, 6755; k) J. Hu, J. Wang, T. H. Nguyen, N. Zheng, *Beilstein J. Org. Chem.* **2013**, *9*, 1977; l) M. N. Hopkinson, B. Sahoo, J.-L. Li, F. Glorius, *Chem. Eur. J.* **2014**, *20*, 3874; m) D. M. Schultz, T. P. Yoon, *Science* **2014**, *343*, 985; For recent books, see: n) *Chemical Photocatalysis* (Ed.: B. König), DeGruyter, Berlin, **2013**; o) *Photochemically generated intermediates in Synthesis* (Eds.: A. Albini, M. Fagnoni), Wiley, Hoboken, **2013**.

[11] a) M. H. Larraufie, R. Pellet, L. Fensterbank, J. P. Goddard, E. Lacôte, M. Malacria, C. Ollivier, *Angew. Chem. Int. Ed.* **2011**, *50*, 4463; *Angew. Chem.* **2011**, *123*, 4555; b) S. Donck, A. Baroudi, L. Fensterbank, J.-P. Goddard, C. Ollivier, *Adv. Synth. Catal.* **2013**, *355*, 1477; c) A. Baralle, L. Fensterbank, J.-P. Goddard, C. Ollivier, *Chem. Eur. J.* **2013**, *19*, 10809.

[12] G. Cerveau, C. Chuit, R. J. P. Corriu, L. Gerbier, C. Reye, J.-L. Aubagnac, B. El Amrani, *Int. J. Mass Spectrom. Ion Phys.* **1988**, *82*, 259.

[13] U. Dettlaff-Weglikowska, E. Hey-Hawkins, H. G. von Schering, *Z. Naturforsch. B* **1991**, *46*, 609.

[14] S. Yamaguchi, S. Akiyama, K. Tamao, *Organometallics* **1999**, *18*, 2851.

[15] R. H. Holmes, R. O. Day, V. Chandrasekhar, J. J. Harland, J. M. Holmes, *Inorg. Chem.* **1985**, *24*, 2016.

[16] V. W. Bowry, K. U. Ingold, *J. Am. Chem. Soc.* **1992**, *114*, 4992.

[17] D. Hanss, J. C. Freys, G. Bernardinelli, O. S. Wenger, *Eur. J. Inorg. Chem.* **2009**, 4850.

[18] A. Noble, D. W. C. MacMillan, *J. Am. Chem. Soc.* **2014**, *136*, 11602.

[19] Stern–Volmer studies and oxidation potentials (SI) are consistent with an oxidation of **1k** by the photoactivated [Ir]. The aryl radical may be generated and lead to alternative outlets such as coupling with the photocatalyst (J. J. Devery III, J. J. Douglas, J. D. Nguyen, K. P. Cole, R. A. Flowers II, C. R. J. Stephenson, *Chem. Sci.* **2015**, *6*, 537).

[20] R. V. Kaberdin, V. I. Potkin, *Russ. Chem. Rev.* **1994**, *63*, 641.

[21] A.-P. Schaffner, V. Darmency, P. Renaud, *Angew. Chem. Int. Ed.* **2006**, *45*, 5847; *Angew. Chem.* **2006**, *118*, 5979.

[22] a) Z. Zuo, D. Ahneman, L. Chu, J. Terrett, A. G. Doyle, D. W. C. MacMillan, *Science* **2014**, *345*, 437; b) A. Noble, S. J. McCarver, D. W. C. MacMillan, *J. Am. Chem. Soc.* **2015**, *137*, 624; c) L. Chu, J. M. Lipshultz, D. W. C. MacMillan, *Angew. Chem. Int. Ed.* **2015**, *54*, 7927–7931; *Angew. Chem.* **2015**, *127*, 8040–8044.

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