Catalysis

Ruthenium-Catalyzed Site-Selective Trifluoromethylations and (Per)Fluoroalkylations of Anilines and Indoles

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Abstract: Introducing (per)fluoroalkyl groups into arenes continues to be an interesting, but challenging area in organofluorine chemistry. We herein report an *ortho*-selective C–H perfluoroalkylation including trifluoromethylations of anilines and indoles without the need of protecting groups using R_fI and R_fBr as commercially available reagents. The availability and price of the starting materials and the inherent selectivity make this novel methodology attractive for the synthesis of diverse (per)fluoroalkylated building blocks, for example, for bioactive compounds and materials.

The incorporation of (per)fluoroalkyl moieties into (hetero)arenes has been demonstrated to significantly improve their physical and biological properties for various applications.[1,2] Hence, in recent years there is an increasing interest to prepare such molecules by thermal[3,4] and photochemical reactions,[5–7] as well as others.[8–11] Despite these notable achievements, still more practical and convenient methodologies are lacking and there is a need using sophisticated reagents and/or tedious purification due to selectivity problems. Indeed, regio- and chemoselective functionalizations are of crucial importance, because isolation of the resulting pure fluorinated isomers is often very difficult. To avoid these problems, synthetic methods have been developed for the synthesis of perfluoroalkyl arenes starting from the corresponding aryl halides.[10] However, the direct preparation of the desired compounds from arenes via C–H functionalization would be more desirable due to their availability and process step economy.

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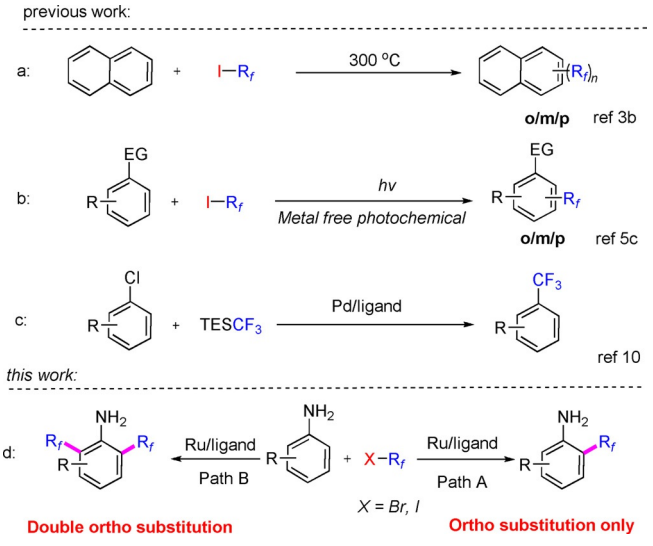
Among the different perfluoroalkylation reagents, especially the corresponding halides R_fX constitute valuable substrates. Since the original work by Fuchikami and Ojima using perfluoroalkyl halides in the presence of copper bronze,[12] several transition metal-catalyzed perfluoroalkylations of arenes have been reported.[13–15] However, in general products are obtained as mixtures, which were often not even isolated and purified. In this respect, the recent work of Zhao and co-workers is noteworthy, who reported a *para*-selective perfluoroalkylation of anilides in the presence of $Mo(CO)_6$ as catalyst.[16]

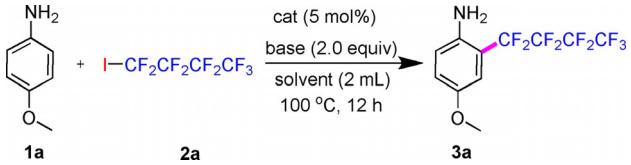
Based on our interest in perfluoroalkylation reactions,[17,18] herein we present the first general and practical methodology for highly *ortho*-selective, direct C–H perfluoroalkylation of anilines under mild reaction conditions (Scheme 1). To the best of our knowledge, there have been no examples reported, which allow introducing R_f groups with high site selectivity.

Recently, our group reported platinum-, nickel- and cobalt-based catalysts for such reactions. However, in no case the regioselectivity problem could be resolved. Hence, we continued to search for more suitable transition metal catalysts. Following this strategy, we used the reaction of 4-methoxyaniline (**1 a**) and *n*-C_4F_9I (**2 a**) as a model system. In an initial screening of catalysts, ruthenium carbene complexes revealed to be active. In general, 5 mol% of the catalyst and 2.0 equiv of base (to trap HX) were used in organic solvents at 100 °C for 12 h. As shown in Table 1, optimization of reaction conditions, including



Scheme 1. Selected methods for introducing trifluoromethyl and perfluoroalkyl groups into arenes.

Table 1. Ru-catalyzed perfluoroalkylation of 4-methoxyaniline.[a]



1a **2a** **3a**

Entry	Catalyst	Base	Solvent	Yield [%][b]
1	$RuCl_3 \cdot 3H_2O$	$NaHCO_3$	1,4-dioxane	6
2	$[RuCl_2(p\text{-Cymene})]_2$	$NaHCO_3$	1,4-dioxane	19
3	**Ru-1**	$NaHCO_3$	1,4-dioxane	45
4	**Ru-2**	$NaHCO_3$	1,4-dioxane	36
5	**Ru-3**	$NaHCO_3$	1,4-dioxane	31
6	**Ru-4**	$NaHCO_3$	1,4-dioxane	26
7	**Ru-5**	$NaHCO_3$	1,4-dioxane	19
8[c]	**Ru-5**	$NaHCO_3$	1,4-dioxane	38
9[c]	$RuCl_3 \cdot 3H_2O$	$NaHCO_3$	1,4-dioxane	41
10	**Ru-1**	$KHCO_3$	1,4-dioxane	51
11	**Ru-1**	K_2CO_3	1,4-dioxane	72
12	**Ru-1**	Na_2CO_3	1,4-dioxane	58
13	**Ru-1**	Na_2HPO_4	1,4-dioxane	16
14	**Ru-1**	Et_3N	1,4-dioxane	22
15	**Ru-1**	K_2CO_3	THF	49
16	**Ru-1**	K_2CO_3	MeCN	23
17	**Ru-1**	K_2CO_3	MePh	35
18	**Ru-1**	K_2CO_3	DMF	14
19[d]	**Ru-1**	**K_2CO_3**	**1,4-dioxane**	**83 (79)**[e]
20	$RuCl_3 \cdot 3H_2O$	K_2CO_3	1,4-dioxane	73
21	free	K_2CO_3	1,4-dioxane	8

[a] Reaction conditions: **1a** (1.0 mmol), **2** (1.2 mmol), catalyst (5 mol%), base (2.0 mmol), solvent (2.0 mL), 100 °C, 12 h. [b] Determined by ^{19}F NMR analysis using (trifluoromethoxy)benzene as internal standard. [c] 7 mol% NHC ligand was added. [d] **2** (1.3 mmol). [e] Isolated yield in brackets. Structure of catalysts and ligands:

pre-catalysts, bases, and solvents gave the desired product 4-methoxy-2-(perfluorobutyl)-aniline (**3a**) in >80% yield. ^{19}F NMR investigations after the reaction clearly demonstrated that only the mono-substituted aniline **3a** is formed. However, in the presence of an excess of **2a**, tiny amounts (<5%) of double perfluoroalkylation products can be formed.

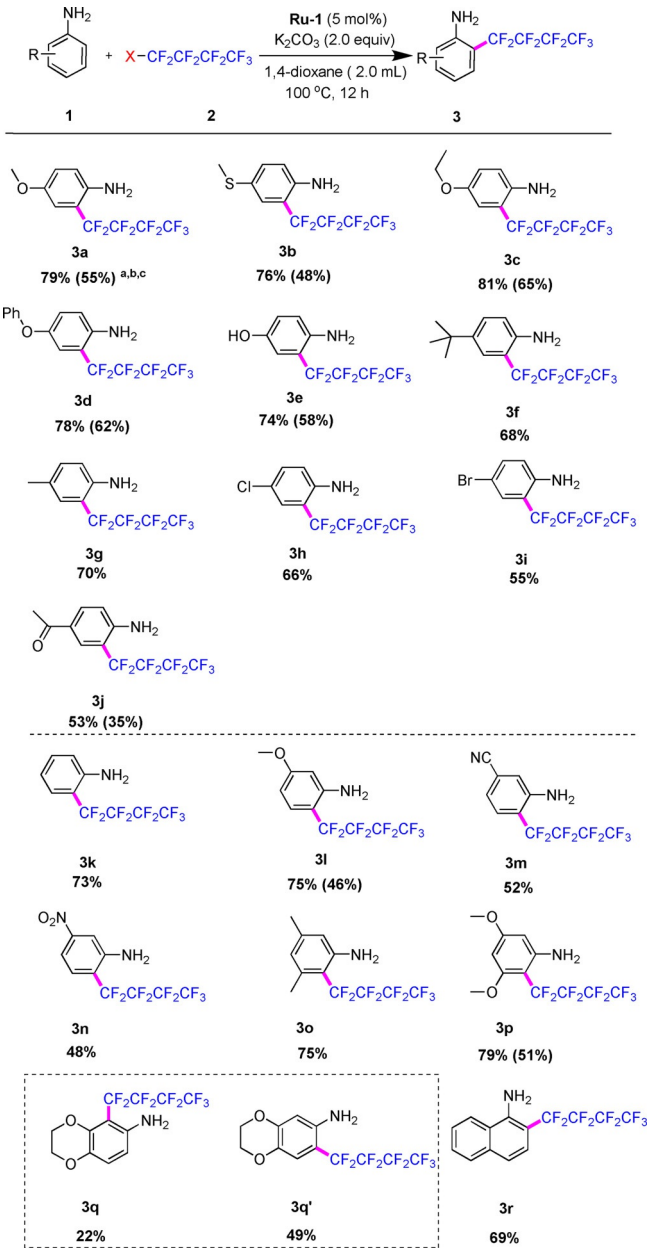
Among the different ruthenium salts and complexes applied, a variety of defined metathesis catalysts proved to be effective for this transformation. In line with this observation, adding 1,3-bis(2,6-diisopropylphenyl)-imidazolium bromide as NHC carbene ligand to simple ruthenium trichloride led to a reasonable active catalyst system (Table 1, entries 8–9). Nevertheless, commercially available **Ru-1** provided the highest product yield. Thus, in the presence of this precursor the influences of base (Table 1, entries 10–14) and solvents (Table 1, entries 15–18) including THF, MeCN, MePh and DMF were studied. Best results (86% of **3a**) were obtained using K_2CO_3 in 1,4-dioxane with an increased amount of **2a** (1.3 mmol; Table 1, entry 19).

Obviously, the stoichiometry of the perfluoroalkylation reagent and the choice of base (Table 1, entries 10–11) have the major influence on the efficiency of this reaction. Thus, a control experiment using simple $RuCl_3 \cdot H_2O$ (5 mol%) in the presence of the carbene ligand (10 mol%) and K_2CO_3 as base was performed using 1.3 equiv of R_fI. Indeed, the desired product **3a** is obtained in 73% yield (Table 1, entry 20). As expected without the metal catalyst, the background reaction occurred only to a negligible extent (Table 1, entry 21).

Regarding the mechanism, we propose the initial formation of a perfluoroalkyl radical via a metal-catalyzed single electron transfer process (SET) is occurring. Such SET processes are well known for several ruthenium complexes.[19] The excellent regioselectivity observed in the model reaction should be a result of the coordination of aniline to the metal center, which determines preferential formation of the *ortho*-perfluoroalkylated product **2a**. To understand this selectivity and the underlying reaction mechanism, several control experiments were carried out under standard conditions (see SI, Table S1). In contrast to aniline, phenol and anisole do not react under identical conditions, which highlights the importance of the amino group for this transformation.

In these latter cases the starting materials were retained in >98%. Interestingly, the use of *N,N*-dimethylaniline led to a mixture of perfluoroalkylated products, which could not be isolated in pure form due to the similar physical properties of the regioisomers. To isolate and/or identify any organometallic intermediate of the catalytic cycle, the complex **Ru-1** (0.1 mmol) was mixed with n-C_4F_9I (0.1 mmol) in 1,4-dioxane (1 mL) and stirred at 100 °C for several hours. Analysis of the crude mixture by ^{19}F NMR revealed unfortunately no obvious changes (see SI for more details).

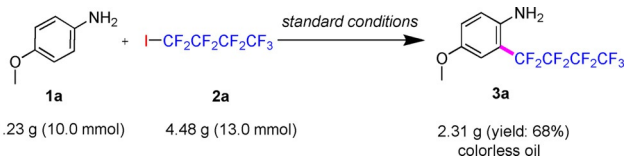
Next, we were interested to explore the substrate scope of anilines of this novel methodology. Thus, reactions of various substituted anilines with *n*-C_4F_9I were examined. Based on the optimization vide supra, the following conditions were applied: 1.3 equiv of **2**, 5 mol% **Ru-1**, 2.0 equiv of K_2CO_3 in 1,4-dioxane (2.0 mL) at 100 °C for 12 h under N_2. Initially, we focused on the functional group tolerance of the catalyst. For this purpose, several electron-rich *para*-substituted anilines (-OMe, -SMe, -OEt, -OPh, -OH, -*t*Bu, -Me) were reacted with *n*-C_4F_9I to afford smoothly the corresponding products in good to excellent yields (Scheme 2, **3a**–**3g**). Apart from *n*-C_4F_9I, also using *n*-C_4F_9Br gave the target compounds, albeit in somewhat lower yields. In addition, anilines with electron-withdrawing groups (-Cl, -Br, -Ac) provided the perfluoroalkylated products in moderate to good yields (Scheme 2, **3h**–**3j**). Notably, halide and ketone substituents on the aniline ring remained untouched demonstrating the excellent chemo-selectivity of the system. In general, the reactivity of the latter substrates is lower than those of electron-rich anilines. Next, we investigated reactions of aniline, 1-naphthylamine, 1,3-disubstituted, and 1,3,5-trisubstituted anilines. In all these cases, the control of regioselectivity is significantly more challenging. Nevertheless, using parent aniline **1k** as substrate perfluoroalkylation occurred specifically in the *ortho*-position giving **3k** in 73% isolated yield. Other isomers (<5%) could not be observed. Next, anilines with *meta*-substitution pattern were tested in this process. Again, both electron-rich (-OMe) and -withdrawing (-CN, -NO_2) substrates expressed good activities for the perfluoroalkylation reaction and only one regioisomer was obtained (Scheme 2, **3l**–**3n**). In addition, anilines with two substituents, such as 3,5-dimethyl and 3,5-dimethoxy can be conveniently employed in



Scheme 2. Selective Ru-catalyzed perfluoroalkylation of anilines. [a] Reaction conditions: aniline (1.0 mmol), *n*-C_4F_9I (1.3 mmol), **Ru-1** (5 mol%), K_2CO_3 (2.0 equiv). and 1,4-dioxane (2.0 mL), 100 °C, 12 h. [b] Isolated yield. [c] *n*-C_4F_9Br (1.5 mmol) used for the reaction in brackets.

this reaction with high site-selectivity (Scheme 2, **3o**, **3p**). Finally, when using 2,3-dihydrobenzo[b][1,4]dioxin-6-amine **1q** we obtained two *ortho*-substituted regioisomers in 49 and 22% yield (Scheme 2, **3q**, **3q'**), respectively. Similarly to the model system, also for these substrates *n*-C_4F_9Br could be successfully used as perfluoroalkyl source and the *ortho*-perfluoroalkylated anilines were obtained in moderate to good yields (Scheme 2, **3k**, **3l**, **3p**). In all these cases the perfluoroalkylated products are easily obtained in pure form due to the high selectivity of the process.

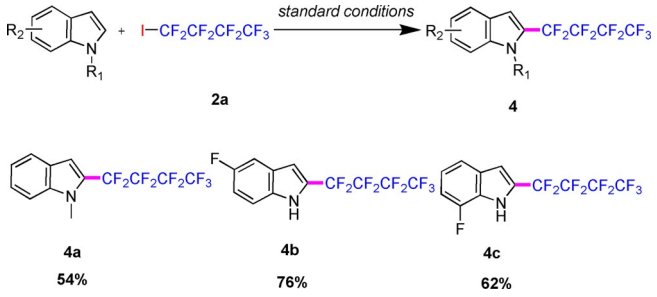
To demonstrate the synthetic utility of our protocol on multi-g-scale, the reaction of 4-methoxyaniline (10.0 mmol)



Scheme 3. Gram-scale synthesis of **3a**.

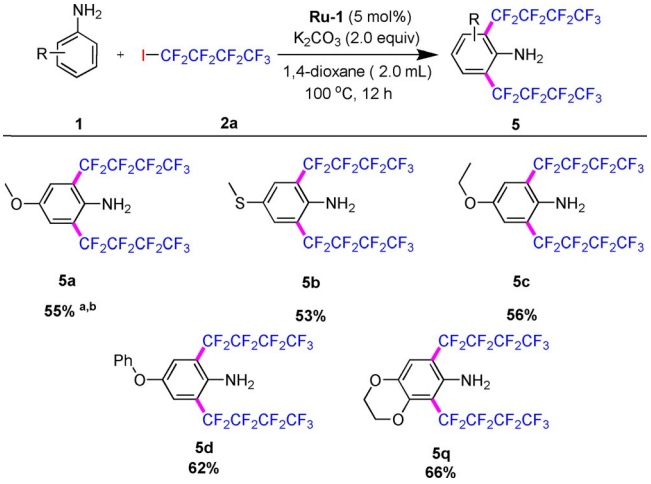
with *n*-C_4F_9I (13.0 mmol) was performed and gave the corresponding product only in slightly lower yield (Scheme 3).

Indoles are an important class of heterocyclic compounds. Indeed, numerous natural products contain this electron-rich scaffold. Thus, we explored the reactivity of **4a–c** with **2a** in this process. We were pleasured to find that selective perfluorobutylation occurred selectively at the C-2 position with or without N protection (Scheme 4).



Scheme 4. Ru-catalyzed perfluoroalkylation of indoles.

During the initial optimization of this procedure, we found small amounts of double perfluoroalkylation. Following this original observation, we investigated the reaction of aniline **1a** with a larger excess of **2a**. Surprisingly, the di-*ortho*-perfluoroalkylated aniline **5a** is obtained in 55% isolated yield using 3.0 equiv of **2a**. As shown in Scheme 5, other anilines **1b–d**, **q** presented similar reactivity and gave the desired *ortho*/*ortho*-

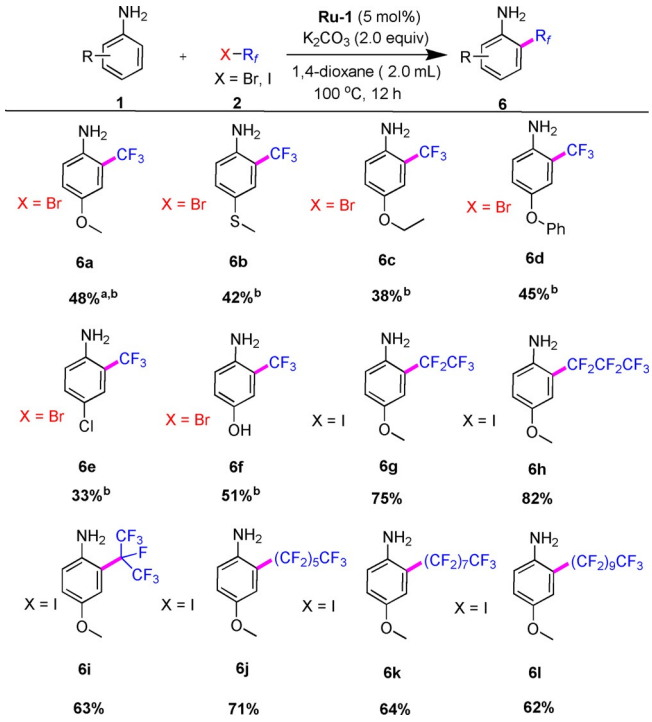


Scheme 5. Ru-catalyzed double-perfluoroalkylation of anilines. [a] Reaction conditions: aniline (1.0 mmol), *n*-C_4F_9I (3.0 mmol), **Ru-1** (5 mol%), K_2CO_3 (2.0 equiv.) and 1,4-dioxane (2.0 mL), 100 °C, 12 h. [b] Isolated yield.

disubstituted compounds in 53–66% isolated yield. It should be noted that such 2,6-difunctionalized anilines are otherwise very difficult to access.

Regarding the various perfluoroalkylation reactions, certainly trifluoromethylation is the most important transformation, especially for the synthesis of new bio-active compounds. Hence, diverse state-of-the-art reagents for laboratory scale synthesis including Umemoto's,[20] Togni's,[21] Langlois',[22] and Ruppert-Prakash's reagent[23] as well as $CuCF_3$[24] were developed in the past decades. However, due to their price and availability, the use of these reagents on >kg-scale is highly problematic. In contrast, CF_3Br is available on multi-100 kg-scale and less expensive compared to the above-mentioned reagents. Nevertheless, we want to make clear that also this reagent has ozone depleting properties, which are forbidden by the Montreal protocol. Hence, appropriate safety measures should be taken. As shown in Scheme 6, CF_3Br allows for *ortho*-selective functionalization of *para*-substituted anilines with acceptable yields (Scheme 6, **6a**–**6f**). Similarly, using **Ru-1** other perfluoroalkyl iodides (C_2F_5I, C_3F_7I, $C_6F_{13}I$, $C_8F_{17}I$, and $C_{10}F_{21}I$) reacted well with 4-methoxyaniline (**1a**) to give the corresponding target compounds in moderate to good yields and excellent selectivities (Scheme 6, **6g**–**6l**). In the context of building blocks for bio-active compounds, it is worth mentioning that heptafluoroisopropyl iodide **2i** afforded the corresponding product in 63% yield (Scheme 6, **6i**).

In conclusion, we have developed an efficient and practical *ortho*-selective mono- and di(per)fluoroalkylation methodology of free anilines and indoles. In the presence of the stable and commercially available pre-catalyst **Ru-1** various *meta*- and *para*-substituted anilines, including mono- and disubstituted ones, gave the corresponding products without the need for protecting groups in high purity. The availability of the starting materials and the high selectivity make the process attractive for the synthesis of all kinds of perfluoroalkyl-substituted anilines, including trifluormethyl derivatives.



Scheme 6. Substrate scope of trifluoromethyl and perfluoroalkyl halides. [a] Reaction conditions: **1** (1.0 mmol), R_fX (1.3 mmol), **Ru-1** (5 mol%), K_2CO_3 (2.0 equiv). and 1,4-dioxane (2.0 mL), 100 °C 12 h. [b] 4 mL solution of CF_3Br in 1,4-dioxane (0.06 mol L^{-1}) was used, and yield based on CF_3Br.

Experimental Section

Perfluoroalkylation of anilines with *n*-C_4F_9I: aniline (1.0 mmol), *n*-C_4F_9I (1.3 mmol), **Ru-1** (5 mol%), K_2CO_3 (2.0 equiv). and 1,4-dioxane (2.0 mL) were added to a reaction tube. Then, the tube was degassed with argon three times and heated at 100 °C for 12 h. After cooling to room temperature, the solvent was removed under vacuum conditions, and the products were purified through silica gel chromatography by using hexane and ethyl acetate as the eluents.

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Conflict of interest

The authors declare no conflict of interest.

Keywords: anilines · *ortho*-substitution · perfluoroalkylation · Ru catalyst · site-selectivity

[1] a) P. Kirsch in *Modern Fluoroorganic Chemistry*, Wiley-VCH, Weinheim, Germany, **1996**; b) I. Ojima, *Fluorine in Medicinal Chemistry and Chemical Biology*, Wiley-Blackwell, Chichester, UK, **2009**.
[2] a) C. N. Neumann, T. Ritter, *Angew. Chem. Int. Ed.* **2015**, *54*, 3216–3221; *Angew. Chem.* **2015**, *127*, 3261–3267; b) J. A. Ma, D. Cahard, *Chem. Rev.* **2004**, *104*, 6119–6146.
[3] a) A. B. Cowell, C. Tamborski, *J. Fluorine Chem.* **1981**, *17*, 345–356; b) L. K. San, E. V. Bukovsky, I. V. Kuvychko, A. A. Popov, S. H. Strauss, O. V. Boltalina, *Chem. Eur. J.* **2014**, *20*, 4373–4379.
[4] a) Y. Macé, E. Magnier, *Eur. J. Org. Chem.* **2012**, 2479–2494; b) T. Kitazume, T. Ikeya, *J. Org. Chem.* **1988**, *53*, 2349–2350; c) D. Y. Mikhaylov, T. V. Gryaznova, Y. G. Budnikova, O. G. Sinyashin, *Russ. Chem. Bull.* **2010**, *59*, 1918–1920; d) M. Médebielle, S. Fujii, K. Kato, *Tetrahedron* **2000**, *56*, 2655–2664.
[5] a) D.-F. Jiang, C. Liu, Y. Guo, J.-C. Xiao, Q.-Y. Chen, *Eur. J. Org. Chem.* **2014**, 6303–6309; b) L. Cui, Y. Matusaki, N. Tada, T. Miura, B. Uno, A. Itoh, *Adv. Synth. Catal.* **2013**, *355*, 2203–2207; c) M. Nappi, G. Bergonzini, P. Melchiorre, *Angew. Chem. Int. Ed.* **2014**, *53*, 4921–4925; *Angew. Chem.* **2014**, *126*, 5021–5025; d) N. J. Straathof, H. P. Gemoets, X. Wang, J. C. Schouten, V. Hessel, T. Noel, *ChemSusChem* **2014**, *7*, 1612–1617; e) S. Barata-Vallejo, D. E. Yerien, A. Postigo, *Eur. J. Org. Chem.* **2015**, 7869–7875; f) C.-Y. He, J.-W. Gu, X. Zhang, *Tetrahedron Lett.* **2017**, *58*, 3939–3941.
[6] a) J. W. Beatty, J. J. Douglas, R. Miller, R. C. McAtee, K. P. Cole, C. R. J. Stephenson, *Chem* **2016**, *1*, 456–472; b) Y. Wang, J. Wang, G. X. Li, G. He, G. Chen, *Org. Lett.* **2017**, *19*, 1442–1445; c) E. Torti, S. Protti, M. Fagnoni, *Chem. Commun.* **2018**, *54*, 4144–4147; d) Y. Ouyang, X. H. Xu, F. L. Qing, *Angew. Chem. Int. Ed.* **2018**, *57*, 6926–6929; *Angew. Chem.* **2018**, *130*,

7042 – 7045; e) D. E. Yerien, M. V. Cooke, M. C. García Vior, S. Barata-Vallejo, A. Postigo, *Org. Biomol. Chem.* **2019**, *17*, 3741.
[7] a) D. E. Yerien, R. Conde, S. Barata-Vallejo, B. Camps, B. Lantaño, A. Postigo, *RSC Adv.* **2017**, *7*, 266 – 274; b) P. B. Arockiam, L. Guillemard, J. Wencel-Delord, *Adv. Synth. Catal.* **2017**, *359*, 2571 – 2579; c) I. Ghosh, J. Khamrai, A. Savateev, N. Shlapakov, M. Antonietti, B. König, *Science* **2019**, *365*, 360 – 366.
[8] a) N. Kamigata, T. Ohtsuka, T. Fukushima, M. Yoshida, T. Shimizu, *J. Chem. Soc. Perkin Trans. 1* **1994**, 1339 – 1346; b) N. Kamigata, T. Ohtsuka, M. Yoshida, T. Shimizu, *Synth. Commun.* **1994**, *24*, 2049 – 2055; c) N. Kamigata, T. Ohtsuka, T. Shimizu, *Phosphorus Sulfur Silicon Relat. Elem.* **1994**, *95 – 96*, 491 – 492; d) R. N. Loy, M. S. Sanford, *Org. Lett.* **2011**, *13*, 2548 – 2551; e) X.-T. Huang, Z.-Y. Long, Q.-Y. Chen, *J. Fluorine Chem.* **2001**, *111*, 107 – 113; f) C. Wakselman, M. Tordeux, *J. Chem. Soc. Chem. Commun.* **1987**, 1701 – 1703; g) K. Natte, R. V. Jagadeesh, L. He, J. Rabeah, J. Chen, C. Taeschler, S. Ellinger, F. Zaragoza, H. Neumann, A. Brückner, M. Beller, *Angew. Chem. Int. Ed.* **2016**, *55*, 2782 – 2786; *Angew. Chem.* **2016**, *128*, 2832 – 2836.
[9] a) I. Popov, S. Lindeman, O. Daugulis, *J. Am. Chem. Soc.* **2011**, *133*, 9286 – 9289; b) H. Morimoto, T. Tsubogo, N. D. Litvinas, J. F. Hartwig, *Angew. Chem. Int. Ed.* **2011**, *50*, 3793 – 3798; *Angew. Chem.* **2011**, *123*, 3877 – 3882; c) M. G. Mormino, P. S. J. F. Hartwig, *Org. Lett.* **2014**, *16*, 1744 – 1747.
[10] E. J. Cho, T. D. Senecal, T. Kinzel, Y. Zhang, D. A. Watson, S. L. Buchwald, *Science* **2010**, *328*, 1679 – 1681.
[11] a) D. Leifert, D. G. Artiukhin, J. Neugebauer, A. Galstyan, C. A. Strassert, A. Studer, *Chem. Commun.* **2016**, *52*, 5997 – 6000; b) T. Shirai, M. Kanai, Y. Kuninobu, *Org. Lett.* **2018**, *20*, 1593 – 1596; c) L. Wu, F. Wang, P. Chen, G. Liu, *J. Am. Chem. Soc.* **2019**, *141*, 1887 – 1892.
[12] T. Fuchikami, I. Ojima, *J. Fluorine Chem.* **1983**, *22*, 541 – 556.
[13] a) X. Bao, L. Liu, J. Li, S. Fan, *J. Org. Chem.* **2018**, *83*, 463 – 468; b) S. Zhang, H. Neumann, M. Beller, *Chem. Eur. J.* **2018**, *24*, 67 – 70; c) K. Aikawa, Y. Nakamura, Y. Yokota, W. Toya, K. Mikami, *Chem. Eur. J.* **2015**, *21*, 91 – 100; d) T. Knauber, F. Arikan, G. V. Röschenthaler, L. J. Gooßen, *Chem. Eur. J.* **2011**, *17*, 2689 – 2697; e) M. Moreno-Mañas, R. Pleixats, S. Villarroya, *Synlett* **1999**, *12*, 1996 – 1998.
[14] a) L. Strekowski, H. Lee, S.-Y. Lin, A. Cyarny, D. V. Derveer, *J. Org. Chem.* **2000**, *65*, 7703 – 7706; b) K. A. McReynolds, R. S. Lewis, L. K. G. Ackerman, G. G. Dubinina, W. W. Brennessel, D. A. Vicic, *J. Fluorine Chem.* **2010**, *131*, 1108 – 1112; c) M. Oishi, H. Kondo, H. Amii, *Chem. Commun.* **2009**, 1909 – 1911; d) J. Monteiro, P. F. Carneiro, P. Elsner, D. M. Roberge, P. G. M. Wuts, K. C. Kurjan, B. Gutmann, C. O. Kappe, *Chem. Eur. J.* **2017**, *23*, 176 – 186.
[15] a) A. Hafner, A. Bihlmeier, M. Nieger, W. Klopper, S. Bräse, *J. Org. Chem.* **2013**, *78*, 7938 – 7948; b) N. D. Litvinas, P. S. Fier, J. H. Hartwig, *Angew. Chem. Int. Ed.* **2012**, *51*, 536 – 539; *Angew. Chem.* **2012**, *124*, 551 – 554.
[16] C. Yuan, P. Dai, X. Bao, Y. Zhao, *Org. Lett.* **2019**, *21*, 6481 – 6484.
[17] L. He, K. Natte, J. Rabeah, C. Taeschler, H. Neumann, A. Brückner, M. Beller, *Angew. Chem. Int. Ed.* **2015**, *54*, 4320 – 4324; *Angew. Chem.* **2015**, *127*, 4394 – 4398.
[18] S. Zhang, N. Rotta-Loria, F. Weniger, J. Rabeah, H. Neumann, C. Taeschler, M. Beller, *Chem. Commun.* **2019**, *55*, 6723 – 6726.
[19] T. Koike, M. Akita, *Visible-Light-Induced Redox Reactions by Ruthenium Photoredox Catalyst*, *Topics in Organometallic Chemistry*, **2015**, *48*, 371 – 395.
[20] a) J. Jacquet, S. Blanchard, E. Derat, M. Desage-El Murr, L. Fensterbank, *Chem. Sci.* **2016**, *7*, 2030 – 2036; b) G. Dagousset, A. Carboni, E. Magnier, G. Masson, *Org. Lett.* **2014**, *16*, 4340 – 4343; c) W. An, N. Ha, H. M. Lee, Y. R. Malpani, D.-H. Lee, Y.-S. Jung, S. B. Han, *Adv. Synth. Catal.* **2015**, *357*, 3949 – 3960; d) R. Tomita, Y. Yasu, T. Koike, M. Akita, *Beilstein J. Org. Chem.* **2014**, *10*, 1099 – 1106.
[21] a) M. Fu, L. Chen, Y. Jiang, Z.-X. Jiang, Z. Yang, *Org. Lett.* **2016**, *18*, 348 – 351; b) Z. He, P. Tan, J. Hu, *Org. Lett.* **2016**, *18*, 72 – 75; c) S. P. Pitre, C. D. McTiernan, J. C. Scaiano, *Acc. Chem. Res.* **2016**, *49*, 1320 – 1330; d) J. Zheng, Z. Deng, Y. Zhang, S. Cui, *Adv. Synth. Catal.* **2016**, *358*, 746 – 751; e) L.-Z. Yu, Q. Xu, X.-Y. Tang, M. Shi, *ACS Catal.* **2016**, *6*, 526 – 531; f) N. Y. Yang, Z. L. Li, L. Ye, B. Tan, X. Y. Liu, *Chem. Commun.* **2016**, *52*, 9052 – 9055; g) K. Shen, Q. Wang, *Org. Chem. Front.* **2016**, *3*, 222 – 226; h) K. N. Lee, Z. Lei, C. A. Morales-Rivera, P. Liu, M. Y. Ngai, *Org. Biomol. Chem.* **2016**, *14*, 5599 – 5605; i) Y. Kuninobu, M. Nishi, M. Kanai, *Org. Biomol. Chem.* **2016**, *14*, 8092 – 8100; j) D. Katayev, J. Vaclavik, F. Bruning, B. Commare, A. Togni, *Chem. Commun.* **2016**, *52*, 4049 – 4052; k) Y. L. Ji, J. J. Luo, J. H. Lin, J. C. Xiao, Y. C. Gu, *Org. Lett.* **2016**, *18*, 1000 – 1003.
[22] a) Q. Y. Lin, X. H. Xu, F. L. Qing, *J. Org. Chem.* **2014**, *79*, 10434 – 10446; b) C. Zhang, *Adv. Synth. Catal.* **2014**, *356*, 2895 – 2906; c) A. Maji, A. Hazra, D. Maiti, *Org. Lett.* **2014**, *16*, 4524 – 4527; d) L. Li, X. Mu, W. Liu, Y. Wang, Z. Mi, C. J. Li, *J. Am. Chem. Soc.* **2016**, *138*, 5809 – 5812; e) Q. Lefebvre, N. Hoffmann, M. Rueping, *Chem. Commun.* **2016**, *52*, 2493 – 2496; f) X.-H. Cao, X. Pan, P.-J. Zhou, J.-P. Zou, O. T. Asekun, *Chem. Commun.* **2014**, *50*, 3359; g) Y. Ji, T. Brueckl, R. D. Baxter, Y. Fujiwara, I. B. Seiple, S. Su, D. G. Blackmond, P. S. Baran, *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 14411 – 14415.
[23] a) M. Nagase, Y. Kuninobu, M. Kanai, *J. Am. Chem. Soc.* **2016**, *138*, 6103 – 6106; b) R. P. Singh, J. n. M. Shreeve, *Tetrahedron* **2000**, *56*, 7613 – 7632; c) B. Bayarmagnai, C. Matheis, E. Risto, L. J. Gooßen, *Adv. Synth. Catal.* **2014**, *356*, 2343 – 2348; d) H. Serizawa, K. Aikawa, K. Mikami, *Chem. Eur. J.* **2013**, *19*, 17692 – 17697; e) Y. Li, F. Liang, Q. Li, Y. C. Xu, Q. R. Wang, L. Jiang, *Org. Lett.* **2011**, *13*, 6082 – 6085; f) G. K. S. Prakash, A. K. Yudin, *Chem. Rev.* **1997**, *97*, 757 – 786.
[24] a) P. Novák, A. Lishchynskyi, V. V. Grushin, *Angew. Chem. Int. Ed.* **2012**, *51*, 7767 – 7770; *Angew. Chem.* **2012**, *124*, 7887 – 7890; b) A. Zanardi, M. A. Novikov, E. Martin, J. Benet-Buchholz, V. V. Grushin, *J. Am. Chem. Soc.* **2011**, *133*, 20901 – 20913.

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