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## Reduction of SF<sub>5</sub>CF<sub>3</sub> via iridium catalysis: radical trifluoromethylation of aromatics†

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**The greenhouse gas SF<sub>5</sub>CF<sub>3</sub> acts as CF<sub>3</sub> source for the photocatalytic trifluoromethylation of arenes on using [Ir(dtbbpy)(ppy)<sub>2</sub>]PF<sub>6</sub> (4,4'-di-*tert*-butyl-2,2'-dipyridyl, ppy = 2-phenylpyridine) as catalyst. The trifluoromethylation of C<sub>6</sub>D<sub>6</sub> in the presence of 1-octanol results in the concomitant generation of 1-fluorooctane, presumably by intermediate SF<sub>4</sub>.**

The CF<sub>3</sub> group plays an important role in medicinal chemistry in part due to their ability to increase the lipophilicity of compounds, and thereby enhance the rate of absorption and transport of drugs across the blood–brain barrier.<sup>1</sup> In 1963 Bedard *et al.* reported on the thermal homolysis of the trifluoromethyl derivatives CF<sub>3</sub>I, CF<sub>3</sub>Br, CF<sub>3</sub>Cl to achieve a radical trifluoromethylation of halobenzenes.<sup>2,3</sup> Silver trifluoroacetate and TiO<sub>2</sub> as a photocatalyst were also used to form CF<sub>3</sub> radicals in order to synthesize trifluoromethylated aromatics.<sup>4</sup> Kamigata *et al.* demonstrated the trifluoromethylation of aromatics on using a ruthenium(II)phosphine complex as a catalyst and trifluoromethanesulfonylchloride as CF<sub>3</sub> source in a thermal reaction.<sup>5</sup> In 2011 MacMillan *et al.* published a photocatalytic trifluoromethylation of aromatics with [Ru(phen)<sub>3</sub>]Cl<sub>2</sub> (phen = phenanthroline) as catalyst again using F<sub>3</sub>CSO<sub>2</sub>Cl as a source for the trifluoromethyl group.<sup>6</sup> The research group of Hu *et al.* described a photochemical trifluoromethylation reaction in which an electron donor–acceptor complex between an aromatic thiophenolate anion and trifluoromethylphenylsulfone initiates a single electron transfer, and therefore the generation of CF<sub>3</sub> radicals.<sup>7</sup> In other photocatalytic trifluoromethylations of aromatics CF<sub>3</sub>SO<sub>2</sub>Na<sup>8</sup> or trifluoromethanesulfonic anhydride<sup>9</sup> were used as trifluoromethyl radical source. Note also that in 2009 MacMillan *et al.* reported on an enantioselective trifluoromethylation of aldehydes *via* a photoredox process coupled with organocatalysis on using the Ir redox catalyst [Ir(dtbbpy)(ppy)<sub>2</sub>]PF<sub>6</sub>

(4,4'-di-*tert*-butyl-2,2'-dipyridyl, ppy = 2-phenylpyridine). In an reductive quenching cycle CF<sub>3</sub>I is being reduced to give a CF<sub>3</sub> radical.<sup>10</sup> Furthermore, [Ir(dtbbpy)(ppy)<sub>2</sub>]PF<sub>6</sub> was used in a photocatalytic approach for the trifluoromethylation of alkynes.<sup>11</sup> Note that apart from CF<sub>3</sub> transfer other fluoroalkyl groups can be transferred as well *via* photocatalysis.<sup>12</sup>

In the last few years the activation of the greenhouse gas SF<sub>6</sub> and its use as fluorinating agent has been studied extensively.<sup>13–18</sup> Conversions are often initiated by an electron transfer to SF<sub>6</sub> to yield SF<sub>6</sub><sup>•−</sup>. The latter can either transform into a SF<sub>5</sub> radical and a fluoride or SF<sub>5</sub><sup>−</sup> and a fluoro radical.<sup>16,17,19</sup> Examples for the photochemical activation of SF<sub>6</sub> include the application of the photocatalysts [Ru(phen)<sub>3</sub>]Cl<sub>2</sub>,<sup>6</sup> 4,4-dimethoxybenzophenone<sup>15</sup> or [Ir(dtbbpy)(ppy)<sub>2</sub>]PF<sub>6</sub>.<sup>18</sup> The SF<sub>6</sub> derivative SF<sub>5</sub>CF<sub>3</sub> has also a high global warming potential and a long atmospheric life-time.<sup>20</sup> It is assumed that SF<sub>5</sub>CF<sub>3</sub> is a breakdown product of SF<sub>6</sub> in high-voltage equipment. The latter contains fluoropolymers which are sources for CF<sub>3</sub> moieties that can react with SF<sub>5</sub> radicals formed by high voltage discharges.<sup>20</sup> However, electron transfer to SF<sub>5</sub>CF<sub>3</sub> can result in the generation of SF<sub>5</sub><sup>−</sup> and a CF<sub>3</sub> radical. Thus, the formation of SF<sub>5</sub><sup>−</sup> has been observed in low-energy attachment experiments by mass spectrometry.<sup>21,22</sup> SF<sub>5</sub>CF<sub>3</sub> activation processes are rare and in solution only one example is known in the literature, to the best of our knowledge.<sup>14</sup>

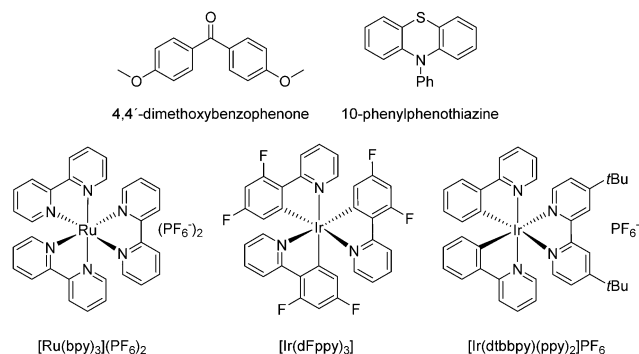
In this contribution we report on an unprecedented trifluoromethylation of aromatic compounds by photocatalytic generation of CF<sub>3</sub> radicals from the greenhouse gas SF<sub>5</sub>CF<sub>3</sub>.

Irradiation of SF<sub>5</sub>CF<sub>3</sub> at a wavelength of 353 nm in C<sub>6</sub>D<sub>6</sub> in the presence of 4,4'-dimethoxybenzophenone as an organic photocatalyst (Scheme 1) led to the generation of small amounts of α,α,α-trifluorotoluene-d<sub>5</sub>. Similar, only traces of α,α,α-trifluorotoluene-d<sub>5</sub> were observed when 10-phenylphenothiazine (Scheme 1) was used to activate SF<sub>5</sub>CF<sub>3</sub>. However, irradiation of SF<sub>5</sub>CF<sub>3</sub> in the presence of the photoredox catalyst [Ir(dtbbpy)(ppy)<sub>2</sub>]PF<sub>6</sub> (Scheme 1), triethylamine and cesium carbonate with a 456 nm LED lamp for 16 h in C<sub>6</sub>D<sub>6</sub> yielded α,α,α-trifluorotoluene-d<sub>5</sub> with a turnover number (TON) of 410 (TON are based on the concentration of the catalyst on using 1,4-difluorobenzene as internal standard) (Scheme 2). Note

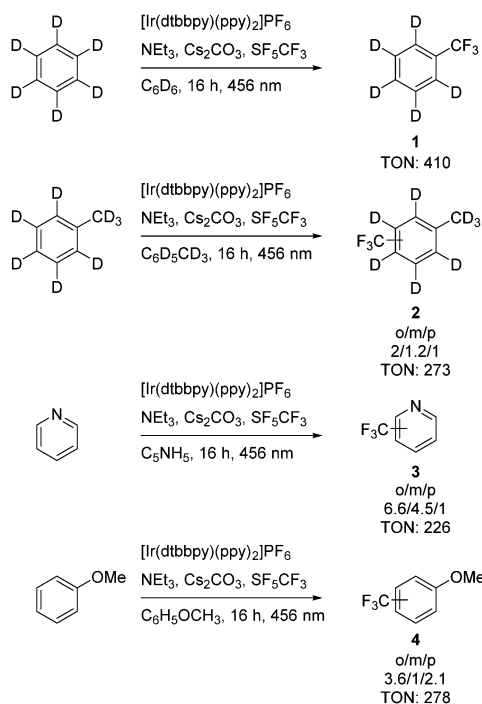
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Scheme 1 Catalysts studied for the reduction of  $\text{SF}_5\text{CF}_3$ .

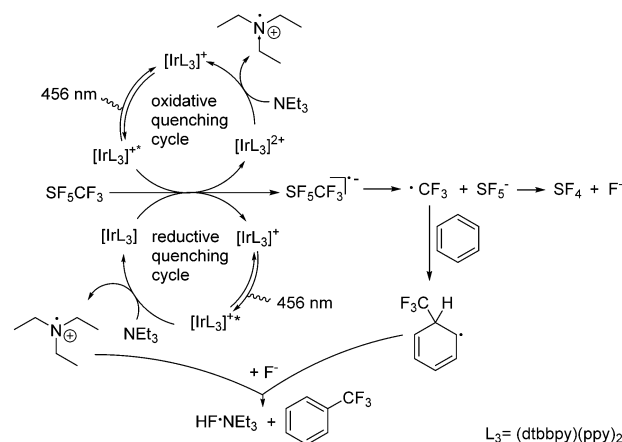
that without the presence of  $\text{Et}_3\text{N}$  the conversion does not proceed. Attempts to use  $\text{K}_2\text{HPO}_4$  as an alternative base failed. Triethylamine and cesium carbonate in a ratio of 1:1 led to the highest turnover numbers.  $^{19}\text{F}$  NMR experiments revealed the presence of DF when no  $\text{Cs}_2\text{CO}_3$  was present. Using 4-methoxydiphenylamine and  $\text{Cs}_2\text{CO}_3$  as bases in a ratio of 1:1 led to a decrease of the TON to 26. Note that with the photoredox catalyst  $[\text{Ru}(\text{bpy})_3](\text{PF}_6)_2$  or  $[\text{Ir}(\text{dFppy})_3]$  lower TONs of 28 and 46, respectively, were observed in the presence of  $\text{NEt}_3$  and  $\text{Cs}_2\text{CO}_3$  in a ratio of 1:1. Reactions with  $[\text{Ir}(\text{dtbbpy})(\text{ppy})_2]\text{PF}_6$  as catalyst with only stoichiometric amounts of benzene in acetonitrile or dichloroethane as solvents gave  $\alpha,\alpha,\alpha$ -trifluorotoluene- $\text{d}_5$  only in very low yield. Mainly the generation of trifluoromethane and other minor unidentified products was observed (ratio  $\text{CF}_3\text{H}$  to  $\text{PhCF}_3$ : 71:1 in acetonitrile, 52:1 in dichloroethane). With dichloromethane and tetrahydrofuran as

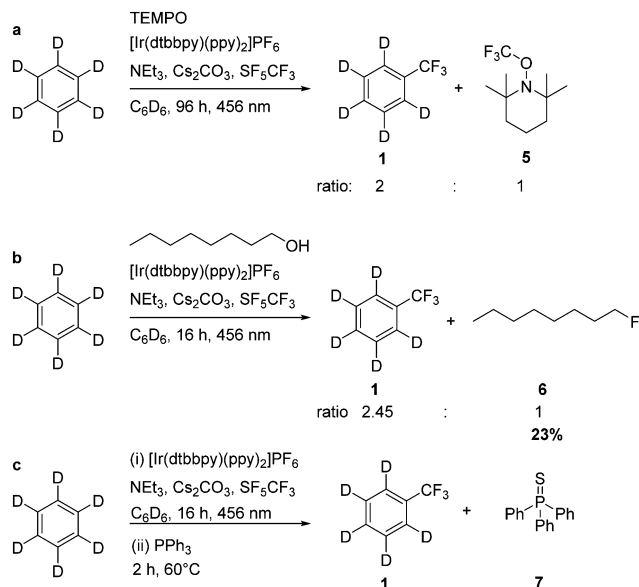
Scheme 2 Trifluoromethylation of arenes on using  $[\text{Ir}(\text{dtbbpy})(\text{ppy})_2]\text{PF}_6$  as photoredox catalyst.

solvents in the presence of stoichiometric amounts of benzene did not lead to any product formation.

To expand the scope of the conversions, pyridine, anisole, 1,2,3,4-tetrafluorobenzene and deuterated toluene (Scheme 2) were studied towards a photochemical trifluoromethylation on using a stock solution of  $[\text{Ir}(\text{dtbbpy})(\text{ppy})_2]\text{PF}_6$  as photocatalyst. All the conversions were run with the substrate as solvent. Selectivities can be explained when considering that the  $\text{CF}_3$  radical shows an electrophilic character.<sup>2,6</sup> Transformations of toluene- $\text{d}_8$  and anisole resulted mainly in the formation of isomers with the  $\text{CF}_3$  group in the *ortho* or *para* position. Pyridine gives mainly the *ortho*-product, but also considerable amounts of *meta*-trifluoromethylpyridine. Minor amounts of trifluoromethane were also detected. 1,2,3,4-Tetrafluorobenzene however did not show any reactivity under the standard conditions. The trifluoromethylated aromatics were characterized by their signals in the  $^{19}\text{F}$  NMR spectra for the  $\text{CF}_3$  groups in the *para*, *meta* or *ortho* positions as well as by GC-MS.

Mechanistically, it can be presumed that after irradiation at 456 nm a single electron transfer SET from the photocatalytic system to  $\text{SF}_5\text{CF}_3$  leads to the  $\text{SF}_5\text{CF}_3^{\cdot-}$  radical anion (Scheme 3). As mentioned above, the subsequent trifluoromethylation does not proceed without the presence of  $\text{NEt}_3$  as reductant. Thus,  $\text{NEt}_3$  can reduce the photoexcited species  $[\text{Ir}(\text{dtbbpy})(\text{ppy})_2]^{\cdot+}$  generated after excitation of  $[\text{Ir}(\text{dtbbpy})(\text{ppy})_2]^+$  in a reductive quenching cycle (Scheme 3). This step is followed by the SET from the reduced  $[\text{Ir}(\text{dtbbpy})(\text{ppy})_2]$  ( $E_{\text{pc}} = -1.51 \text{ V vs. SCE}$ )<sup>23,24</sup> to  $\text{SF}_5\text{CF}_3$ . Alternatively,  $[\text{Ir}(\text{dtbbpy})(\text{ppy})_2]^{\cdot+}$  ( $E_{\text{pc}} = -0.96 \text{ V vs. SCE}$ )<sup>23,24</sup> reduces  $\text{SF}_5\text{CF}_3$  and the generated  $[\text{Ir}(\text{dtbbpy})(\text{ppy})_2]^{2+}$  is then reduced by  $\text{NEt}_3$  in an oxidative quenching cycle. Note that photocatalytic conversions of  $[\text{Ir}(\text{dtbbpy})(\text{ppy})_2]^+$  have a tendency to proceed *via* a reductive quenching cycle.<sup>10,25</sup> However, the  $\text{SF}_5\text{CF}_3^{\cdot-}$  radical anion then decomposes to give a  $\text{CF}_3$  radical and  $\text{SF}_5^-$ .<sup>22,26</sup> The  $\text{SF}_5^-$  anion is not very stable and furnishes  $\text{SF}_4$  and fluoride.<sup>16,27</sup> The  $\text{CF}_3$  radical reacts then with benzene forming a cyclohexadienyl radical. The generation of the latter in trifluoromethylation reactions has been proposed by Kamigata *et al.*<sup>5</sup> and others.<sup>6,9,28</sup> Oxidation of the cyclohexadienyl

Scheme 3 Proposed mechanism for the trifluoromethylation of arenes by  $\text{SF}_5\text{CF}_3$ .



**Scheme 4** Quenching of the photocatalytic trifluoromethylation with TEMPO or 1-octanol (a and b); generation of  $\text{PPh}_3 = \text{S}$  after addition of  $\text{PPh}_3$  to the reaction mixture (c).

radical by the  $\text{NEt}_3^{*+}$  radical cation and subsequent deprotonation of the cyclohexadienyl cation by fluoride yields the trifluoromethylated aromatic product and  $\text{NEt}_3 \cdot \text{HF}$ .<sup>2,6,9,29</sup> Alternatively, hydrogen atom abstraction HAT from the cyclohexadienyl radical would give the intermediate  $\text{Et}_3\text{NH}^+$ , and in the presence of fluoride the same products.<sup>23</sup> Cesium carbonate acts as an HF scavenger. There is no indication for the formation of HD or  $\text{H}_2$  along with an iminium ion from the  $\text{NEt}_3$  radical. However, the observed generation of trifluoromethane in acetonitrile or dichloromethane can involve HAT from the solvent or the  $\text{NEt}_3^{*+}$  radical. The latter is consistent with the fact that higher  $\text{NEt}_3$  concentrations deliver more  $\text{CF}_3\text{H}$ .

Furthermore, to confirm the intermediate formation of a  $\text{CF}_3$  radical, TEMPO (2,2,6,6-tetramethylpiperidinyloxy) was added to the photocatalytic trifluoromethylation reaction of  $\text{C}_6\text{D}_6$ , and indeed TEMPO inhibited the conversion (Scheme 3). However, after 96 h TEMPO- $\text{CF}_3$  as well as the  $\alpha,\alpha,\alpha$ -trifluorotoluene- $\text{d}_5$  were observed in a ratio of 1:2. The formation of  $\text{SF}_4$  was not observed by low temperature NMR experiments, presumably because of the presence of  $\text{Cs}_2\text{CO}_3$ . Nevertheless, when the trifluoromethylation of  $\text{C}_6\text{D}_6$  was run in the presence of 1-octanol in the generation of 1-fluorooctane was observed, which was identified by GC-MS and  $^{19}\text{F}$  NMR spectroscopy (Scheme 4). The experiment suggests the deoxyfluorination of the alcohol by intermediate  $\text{SF}_4$ .<sup>30</sup> Hence, trifluoromethylation steps can be coupled with the fluorination of an alcohol. However, under the UV irradiation  $\text{SF}_4$  might also be further reduced yielding elemental sulfur, as it was also proposed by Nagorny *et al.* for the activation of  $\text{SF}_6$  in the presence of the organophotocatalyst 4,4-dimethoxybenzophenone.<sup>15</sup> Indeed, when  $\text{PPh}_3$  was added to the reaction mixture after the photolytic formation of  $\text{C}_6\text{D}_5\text{CF}_3$ , the generation of small amounts of  $\text{SPPH}_3$  (7) was observed after heating the reaction mixture for two hours at 60 °C, which might be due to the presence of sulfur (Scheme 4).

In conclusion, a catalytic photoredox process for the activation of the greenhouse gas  $\text{SF}_5\text{CF}_3$  and a concomitant trifluoromethylation of aromatics were reported.  $\text{SF}_5\text{CF}_3$  acts as source for  $\text{CF}_3$  radicals and at the same time  $\text{SF}_4$  and sulfur can be furnished. The former can be used for fluorination to couple the trifluoromethylation of aromatics with a fluorination of an alcohol. Note also that iridium photocatalyzed processes were applied for the defluorination of fluorinated organic substrates,<sup>31</sup> which was not observed for the described transformations.

Experiments, data collection (NMR and GC-MS) and analysing the data was performed by D. Herbstritt. The manuscript was drafted by D. Herbstritt. T. Braun supervised the work, designed the project and contributed to manuscript writing.

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## Conflicts of interest

There are no conflicts to declare.

## Notes and references

- (a) M. G. Perrone, P. Vitale, A. Panella, A. Tolomeo and A. Scilimati, ed., Current and emerging applications of fluorine in medicinal chemistry, *MedComm*, 2015, vol. 11; (b) K. Müller, C. Faeh and F. Diederich, *Science*, 2007, **317**, 1881–1886; (c) S. Purser, P. R. Moore, S. Swallow and V. Gouverneur, *Chem. Soc. Rev.*, 2008, **37**, 320–330.
- A. Studer, *Angew. Chem., Int. Ed.*, 2012, **124**, 9082–9090.
- E. S. Huyser and E. Bedard, *J. Org. Chem.*, 1964, **29**, 1588–1590.
- C. Lai and T. E. Mallouk, *J. Chem. Soc., Chem. Commun.*, 1993, 1359–1361.
- N. Kamigata, T. Ohtsuka, T. Fukushima, M. Yoshida and T. Shimizu, *J. Chem. Soc., Perkin Trans. 1*, 1994, 1339–1346.
- D. A. Nagib and D. W. C. MacMillan, *Nature*, 2011, **480**, 224–228.
- Z. Wei, Z. Lou, C. Ni, W. Zhang and J. Hu, *Chem. Commun.*, 2022, **58**, 10024–10027.
- C. Tian, Q. Wang, X. Wang, G. An and G. Li, *J. Org. Chem.*, 2019, **84**, 14241–14247.
- Y. Ouyang, X.-H. Xu and F.-L. Qing, *Angew. Chem., Int. Ed.*, 2018, **57**, 6926–6929.
- D. A. Nagib, M. E. Scott and D. W. C. MacMillan, *J. Am. Chem. Soc.*, 2009, **131**, 10875–10877.
- T. Koike and M. Akita, *Acc. Chem. Res.*, 2016, **49**, 1937–1945.
- (a) N. J. W. Straathof, S. E. Cramer, V. Hessel and T. Noël, *Angew. Chem., Int. Ed.*, 2016, **128**, 15778–15782; (b) C.-J. Wallentin, J. D. Nguyen, P. Finkbeiner and C. R. J. Stephenson, *J. Am. Chem. Soc.*, 2012, **134**, 8875–8884; (c) T. Liu, J. Liu, Y. Hong, H. Zhou, Y.-L. Liu and S. Tang, *Synthesis*, 2022, 1919–1938; (d) T. Chatterjee, N. Iqbal, Y. You and E. J. Cho, *Acc. Chem. Res.*, 2016, **49**, 2284–2294; (e) S. Barata-Vallejo, S. M. Bonesi and A. Postigo, *Org. Biomol. Chem.*, 2015, **13**, 11153–11183.
- (a) L. Zámotná and T. Braun, *Angew. Chem., Int. Ed.*, 2015, **127**, 10798–10802; (b) M. Wozniak, T. Braun, M. Ahrens, B. Braun-Cula, P. Wittwer, R. Herrmann and R. Laubenstein, *Organometallics*, 2018, **37**, 821–828; (c) M. Rueping, P. Nikolaenko, Y. Lebedev and A. Adams, *Green Chem.*, 2017, **19**, 2571–2575; (d) F. Buß, C. Mück-Lichtenfeld, P. Mehlmann and F. Dielmann, *Angew. Chem., Int. Ed.*, 2018, **130**, 5045–5049; (e) T. Eder, F. Buß, L. F. B. Wilm, M. Seidl, M. Podewitz and F. Dielmann, *Angew. Chem., Int. Ed.*, 2022, **61**, e202209067; (f) P. Tomar, T. Braun and E. Kemnitz, *Chem. Commun.*, 2018, **54**, 9753–9756; (g) P. Holze, B. Horn, C. Limberg, C. Matlachowski and S. Mebs, *Angew. Chem., Int. Ed.*, 2014, **126**, 2788–2791; (h) D. Rombach and H.-A. Wagenknecht, *ChemCatChem*,



- 2018, **10**, 2955–2961; (i) B. S. N. Huchenski and A. W. H. Speed, *Chem. Commun.*, 2021, **57**, 7128–7131; (j) R. F. Weitkamp, B. Neumann, H.-G. Stammer and B. Hoge, *Chem. – Eur. J.*, 2021, **27**, 6460–6464; (k) A. Taponard, T. Jarrosson, L. Khrouz, M. Médebielle, J. Broggi and A. Tlili, *Angew. Chem., Int. Ed.*, 2022, **61**, e202204623; (l) S. Kim and P. Nagorny, *Org. Lett.*, 2022, **24**, 2294–2298; (m) C. Berg, T. Braun, M. Ahrens, P. Wittwer and R. Herrmann, *Angew. Chem., Int. Ed.*, 2017, **56**, 4300–4304; (n) D. Dirican, M. Talavera and T. Braun, *Chem. – Eur. J.*, 2021, **27**, 17707–17712; (o) D. Dirican, N. Pfister, M. Wozniak and T. Braun, *Chem. – Eur. J.*, 2020, **26**, 6945–6963.
- 14 L. Zámotná, T. Braun and B. Braun, *Angew. Chem., Int. Ed.*, 2014, **53**, 2745–2749.
  - 15 S. Kim, Y. Khomutnyk, A. Bannykh and P. Nagorny, *Org. Lett.*, 2021, **23**, 190–194.
  - 16 G. Iakobson, M. Pošta and P. Beier, *J. Fluorine Chem.*, 2018, **213**, 51–55.
  - 17 D. Rombach and H.-A. Wagenknecht, *Angew. Chem., Int. Ed.*, 2020, **132**, 306–310.
  - 18 T. A. McTeague and T. F. Jamison, *Angew. Chem., Int. Ed.*, 2016, **55**, 15072–15075.
  - 19 A. Akhgarnusch, R. F. Höckendorf and M. K. Beyer, *J. Phys. Chem. A*, 2015, **119**, 9978–9985.
  - 20 W. T. Sturges, T. J. Wallington, M. D. Hurley, K. P. Shine, K. Sihra, A. Engel, D. E. Oram, S. A. Penkett, R. Mulvaney and C. A. M. Brenninkmeijer, *Science*, 2000, **289**, 611–613.
  - 21 C. M. R. A. Kennedy, *Int. J. Mass Spectrom.*, 2001, **206**, vii–x.
  - 22 W. Sailer, H. Drexel, A. Pelc, V. Grill, N. J. M. Eugen Illenberger, J. D. Skalny, T. Mikoviny, P. Scheier and T. D. Märk, *Chem. Phys. Lett.*, 2001, 71–78.
  - 23 L. Zhou, *Molecules*, 2021, **26**, 7051.
  - 24 M. S. Lowry, J. I. Goldsmith, J. D. Slinker, R. Rohl Jr., R. A. Pascal, G. G. Malliaras and S. Bernhard, *Chem. Mater.*, 2005, **17**, 5712–5719.
  - 25 J. W. Tucker and C. R. J. Stephenson, *J. Org. Chem.*, 2012, **77**, 1617–1622.
  - 26 (a) R. Chim, R. Kennedy and R. Tuckett, *Chem. Phys. Lett.*, 2003, **367**, 697–703; (b) S. Solovev, A. Palmentieri, N. D. Potekhina and T. E. Madey, *J. Phys. Chem. C*, 2007, **111**, 18271–18278.
  - 27 (a) J. T. Goettel, N. Kostiuk and M. Gerken, *Angew. Chem., Int. Ed.*, 2013, **125**, 8195–8198; (b) N. Kostiuk, J. T. Goettel and M. Gerken, *Inorg. Chem.*, 2020, **59**, 8620–8628.
  - 28 C. F. Harris, C. S. Kuehner, J. Bacsa and J. D. Soper, *Angew. Chem., Int. Ed.*, 2018, **57**, 1311–1315.
  - 29 J. Xie, X. Yuan, A. Abdukader, C. Zhu and J. Ma, *Org. Lett.*, 2014, **16**, 1768–1771.
  - 30 G. A. Boswell Jr., W. C. Ripka, R. M. Scribner and C. W. Tullock, ed., *Organic Reactions, Fluorination with Sulfur Tetrafluoride*, 21st edn, 1974.
  - 31 (a) S. M. Senaweera, A. Singh and J. D. Weaver, *J. Am. Chem. Soc.*, 2014, **136**, 3002–3005; (b) D. B. Vogt, C. P. Seath, H. Wang and N. T. Jui, *J. Am. Chem. Soc.*, 2019, **141**, 13203–13211.

