EDGE ARTICLE

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Controllable double CF$_2$-insertion into sp^2 C–Cu bond using TMSCF$_3$: a facile access to tetrafluoroethylene-bridged structures†

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A highly efficient method for controllable double CF$_2$-insertion into pentafluorophenylcopper species using TMSCF$_3$ as difluoromethylene source has been developed. The newly generated fluoroalkylcopper(I) species, C$_6$F$_5$CF$_2$CF$_2$Cu, shows good reactivity towards a myriad of structurally diverse aryl, heteroaryl and alkenyl iodides. This protocol is easy to handle, ready to scale up and applicable for the synthesis of relative complex molecules, thus providing a convenient method for facile access to tetrafluoroethylene-bridged structures.

Introduction

Due to the unique physical, chemical and biological properties of organofluorine compounds, the introduction of fluorine atom(s) or fluorinated moieties into organic molecules has become a routine strategy in drug design and advanced material development.[1–4] Among various fluorinated functionalities, the tetrafluoroethylene motif (–CF$_2$CF$_2$–) has attracted considerable attention because of its applications in agrochemicals[5] and liquid-crystalline materials.[6–8] Moreover, the introduction of –CF$_2$CF$_2$– group into liquid crystals often results in highly advantageous properties such as high clearing temperature, broad nematic phase range, low rotational viscosity and high dielectric anisotropy.[6–8] Therefore, it is of strong demand to access tetrafluoroethylene-bridged molecules.

Current methods for the syntheses of tetrafluoroethylene-bridged structures are mainly based on (1) deoxofluorination of 1,2-dicarbonyl compounds with SF$_4$ and DeoxoFluor;[9–11] (2) fluorination of C–C triple bonds using F$_2$;[12–14] (3) 1,2-difunctionalization of tetrafluoroethylene (TFE);[15–23] (4) difluoromethylene insertion using CF$_2$Br$_2$ as the CF$_2$ source;[24,25] and (5) using RCF$_2$CF$_2$Br as the build block.[5] However, these methods suffer from several drawbacks such as (1) using toxic, highly reactive or hazardous reagents; (2) low functional group tolerance and/or (3) using explosive gaseous reagents or ozone-depleting substances (ODS). As such, developing a new method to incorporate –CF$_2$CF$_2$– structure motif into organic

molecules with readily available, easy to handle and environmentally benign reagents under mild conditions is highly desired.

(Trifluoromethyl)trimethylsilane (TMSCF$_3$), often called Ruppet–Prakash reagent, is arguably the most widely used trifluoromethylating agent.[26–30] In 2011, our group, in collaboration with the Prakash group, revealed that TMSCF$_3$ is a good difluorocarbene precursor, which can be used in the [2 + 1] cycloaddition reaction with alkenes and alkynes.[31] Recently, our group reported that difluorocarbene generated from TMSCF$_3$ could undergo dimerization to give tetrafluoroethene (TFE),[32,33] which can be used for a variety of transformations.[33] Very recently, our group demonstrated that, by using TMSCF$_3$ as the difluoromethylene source, controllable CF$_2$-insertion into CuCF$_3$ to generate CuCF$_2$CF$_3$ could be realized.[34] Inspired by this C$_1$ to C$_2$ process, we envisioned that it might be possible to insert CF$_2$ into other C–M bonds. Herein, we report our latest progress in the fluorocarbon homologation reaction using TMSCF$_3$ as the difluoromethylene source. By carefully tuning the reaction conditions, controllable double insertion of CF$_2$ into C$_6$F$_5$–Cu gives rise to C$_6$F$_5$CF$_2$CF$_2$Cu, which can be applied to the preparation of a diverse range of tetrafluoroethylene-bridged compounds (Scheme 1).

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a) Previous work: single CF$_2$ insertion into CF$_3$Cu with TMSCF$_3$

CuCl + KF + TMSCF$_3$ ⟶ CuCF$_3$ ⟶ CuCF$_2$CF$_3$

b) **This work**: double CF$_2$ insertion into C$_6$F$_5$Cu with TMSCF$_3$

CuCl + KF + TMSC$_6$F$_5$ ⟶ CuC$_6$F$_5$ ⟶[TMSCF$_3$] CuCF$_2$CF$_2$C$_6$F$_5$

Scheme 1 Fluorocarbon homologation with TMSCF$_3$. TMS = trimethylsilyl.

Results and discussion

Our investigation commenced with the preparation of C_6F_5-CF_2CF_2Cu from $TMSC_6F_5$ and $TMSCF_3$. Initially, we used 1 equivalent of $TMSC_6F_5$ as the C_6F_5Cu precursor, 1 equivalent of $TMSCF_3$ as the difluorocarbene precursor, 2 equivalents of KF as the desilylating reagent and 2.5 equivalents of CuCl as the copper source. All these components were added simultaneously with DMF as the solvent, and the resulting mixture was stirred at room temperature for 12 hours. Analysis of the mixture by ^{19}F NMR spectroscopy revealed that $C_6F_5CF_2CF_2Cu$ (21%), C_6F_5Cu (57%) and $CuCF_3$ (37%) were formed; no single CF_2-insertion product $C_6F_5CF_2Cu$ could be detected (Table 1, entry 1). When adding 2 equivalents of difluorocarbene source $TMSCF_3$, we found that the desired product $C_6F_5CF_2CF_2Cu$ was formed in 79% yield, in conjunction with C_6F_5Cu (3%), $CuCF_3$ (10%) and CuC_2F_5 (5%) (entry 2).[35] If 3 equivalents of $TMSCF_3$ was used, $C_6F_5CF_2CF_2Cu$ was formed in 83% yield, along with $CuCF_3$ (16%) and CuC_2F_5 (12%) being formed; neither C_6F_5Cu nor triple CF_2-insertion product $C_6F_5CF_2CF_2CF_2Cu$ could be detected (entry 3). These results (entries 1–3) clearly indicate that the $TMSCF_3$-derived difluorocoppercarbene ($Cu=CF_2$) species[34] could selectively undergo double CF_2-insertion into C_6F_5Cu, regardless of the amount of $TMSCF_3$ used. This behaviour is in accord with previous reports.[24] The high selectivity may be attributed to the intrinsic reactivity of different fluoroalkylcopper species toward $Cu=CF_2$ (Scheme 2). As to the possible intermediate, $C_6F_5CF_2Cu$, its benzylic C–Cu bond is highly reactive and tended to insert another CF_2 unit to give $C_6F_5CF_2CF_2Cu$;[24,25] the resulting $C_6F_5CF_2CF_2Cu$ has lower reactivity than $CuCF_3$ because of its longer fluoroalkyl chain.[24,25] Therefore, even in the presence of excess of $TMSCF_3$, triple CF_2-

Scheme 2 Proposed reaction mechanism.

insertion into C_6F_5Cu could not be observed; in that case, the CF_2-insertion into $CuCF_3$ to generate CuC_2F_5 would be favoured. Altogether, the relative reaction rate of each step is $k_3 > k_2 > k_1 > k_4$.

With this understanding in mind, we went on to optimize the reaction conditions in order to increase the yield of C_6F_5-CF_2CF_2Cu and minimize those of $CuCF_3$ and CuC_2F_5. By using 2 equivalents of $TMSCF_3$ and prolonging reaction time to 20 hours, $C_6F_5CF_2CF_2Cu$ was formed in 87% yield (entry 4). When we decreased the amount of CuCl from 4 equivalents to 3 equivalents, only trace of $C_6F_5CF_2CF_2Cu$ was observed, with >80% C_6F_5Cu and $CuCF_3$ being recovered (entry 5). This result revealed that the presence of excess amount of CuCl is crucial for the $Cu=CF_2$ generation, which is consistent with our previous report.[34] As $CuCF_3$ was always observed, we tried to speed up the decomposition of $CuCF_3$ at elevated temperatures. However, when the reaction was carried out at 50 °C, although no $CuCF_3$ was observed, a larger amount of CuC_2F_5 was detected, and $C_6F_5CF_2CF_2Cu$ was obtained in relatively lower yield (entry 6 vs. entry 4). Next, we attempted to add $TMSCF_3$ into the reaction mixture after the preparation of C_6F_5Cu. Gratifyingly, the yield of $C_6F_5CF_2CF_2Cu$ was increased slightly (entry 7). In light of the decomposition of $CuCF_3$ to $Cu=CF_2$ would release

Table 1 Optimization of reaction conditions for the double CF_2 insertion into C_6F_5Cu with $TMSCF_3{}^a$

$$TMSC_6F_5 + CuCl + KF \xrightarrow[\text{RT, 0.5 h}]{\text{DMF}} C_6F_5Cu \xrightarrow[t,\ T]{TMSCF_3} C_6F_5CF_2CF_2Cu$$

Entry	$TMSC_6F_5$: CuCl : KF : $TMSCF_3$	t (h)	T (°C)	Yield (%)	
				$C_6F_5C_2F_4Cu$	$C_6F_5Cu/CuCF_3/CuC_2F_5$
1^b	1 : 2.5 : 2 : 1	12	rt	21	57/37/n.d.
2^b	1 : 4 : 3 : 2	12	rt	79	3/10/5
3^b	1 : 5.5 : 4 : 3	12	rt	83	n.d./16/12
4^b	1 : 4 : 3 : 2	20	rt	87	4/2/4
5^b	1 : 3 : 3 : 2	20	rt	1	87/82/n.d.
6^b	1 : 4 : 3 : 2	10	50	75	1/n.d./23
7	1 : 4 : 3 : 2	28	rt	91	<1/<1/4
8	1 : 4 : 2 : 2	28	rt	76	n.d./2/5
9^c	1 : 4 : 3 : 2	28	rt	91	n.d./6/2
10^d	1 : 4 : 3 : 2	28	rt	93	n.d./8/2
11^e	1 : 4 : 3 : 1.9	28	rt	92	2/4/2
12^e	1 : 4 : 3 : 1.9	36	rt	86	3/4/2
$13^{e,f}$	1 : 4 : 3 : 1.9	28	rt	89	n.d./1/2

^{a} Reactions were performed on 0.2 mmol $TMSC_6F_5$ (1.0 equiv.) scale. Yields were determined by ^{19}F NMR spectroscopy using $PhOCF_3$ as an internal standard. n.d. = not detected. ^{b} $TMSC_6F_5$ and $TMSCF_3$ were added simultaneously without the pre-preparation of C_6F_5Cu. ^{c} $TMSCF_3$ was added in three portions for every 4 hours. ^{d} $TMSCF_3$ was added in three portions for every 6 hours. ^{e} $TMSCF_3$ was added in two portions for every 6 hours. ^{f} After reacted at rt for 28 hours, the reaction mixture was stirred at 60 °C for another 2 hours.

fluoride ions, we surmised that the amount of externally added KF could be reduced. However, lowering down KF to 2 equivalents gave inferior result (entry 8). To further decrease the yield

of CuC_2F_5, we envisaged that adding $TMSCF_3$ in batches to decrease the concentration of $CuCF_3$ might be helpful. After some brief optimizations and decreasing the amount of $TMSCF_3$ to 1.9 equivalents (entries 9–11), $C_6F_5CF_2CF_2Cu$ was formed in 92% yield, together with 2% of C_6F_5Cu and 4% of $CuCF_3$ being formed (entry 11). Prolonging the reaction time to 36 hours did not have any beneficial effect (entry 12). Finally, when the reaction was conducted at room temperature for 28 hours, then stirred at 60 °C for 2 hours, no C_6F_5Cu and little amounts of $CuCF_3$ (1%) and CuC_2F_5 (2%) could be detected, with $C_6F_5CF_2CF_2Cu$ being formed in 89% yield (entry 13).

With the optimized conditions (Table 1, entry 13) in hand, the reactivity of this $TMSCF_3$-derived $C_6F_5CF_2CF_2Cu$ towards aryl iodides was studied. A variety of structurally diverse (hetero)aryl and alkenyl iodides are all viable substrate, giving the desired tetrafluoroethylene-bridged products in moderate to good yields (Scheme 3). The electronic character of aryl iodides do not have obvious influence on the reaction efficiency, and both electron-deficient (**2a–i**) and electron-rich (**2k–p**, **2r–s**) substrates were readily transformed to the desired products in good yields. Common functional groups such as nitro (**2a–c**, in *ortho*, *meta* and *para* positions), acetyl (**2d**), ester (**2e**), cyano (**2f**), sulfonamide (**2h**) and sulfone (**2i**) were compatible with the reaction conditions, and good yields of products were observed. Notably, because of the mildness of the reaction conditions, some sensitive functionalities including aldehyde (**2g**, **2ab–ac**), alcohol (**2m**) and unprotected NH group (**2u**, **2ab**), were also tolerated. Heterocycles, such as pyrazole (**2p**), coumarin (**2q**), carbazole (**2r**), benzothiophene (**2s**), quinoline (**2t**) and indole (**2u**) were competent under the reaction conditions, as demonstrated by the formation of tetrafluoroethylene-bridged products in high yields. Moreover, heteroaryl iodides, including iodopyridine (**2w–x**), iodoimidazole (**2y**), iodoisoxazole (**2z**), iodothiophene (**2aa**), iodopyrrole (**2ab**) and iodofuran (**2ac**), participated in this perfluorophenylethylation to afford corresponding products in moderate to good yields (54–84%). Iodoalkene **1ad** also showed good reactivity towards $C_6F_5CF_2CF_2Cu$, furnishing the desired product **2ad** in 88% yield. This protocol is also

Scheme 3 Perfluorophenylethylation of (hetero)aryl iodides with $TMSCF_3$-derived $C_6F_5CF_2CF_2Cu$. [a] Unless otherwise noted, reactions were performed on 0.5 mmol of **1** (1.0 equiv.) scale, and $TMSCF_3$ was added in two portions every 6 h; 1.5 equivalents of $TMSC_6F_5$ was used; the molar ratio of $TMSC_6F_5 : CuCl : KF : TMSCF_3 = 1 : 4 : 3 : 1.9$. [b] 1.6 equivalent of $TMSC_6F_5$ was used. [c] 1.8 equivalent of $TMSC_6F_5$ was used.

Scheme 4 Gram-scale synthesis.

Fig. 1 (a) The single crystal structure and (b) packing diagram of **2n**.[36]

effective for the perfluorophenylethylation of relatively complex compounds and pharmaceutical intermediates **1ae** and **1af**, giving the corresponding products **2ae** and **2af** in 96% and 88% yields, respectively. The broad scope of this reaction underscores the great potential of its application in the synthesis of a raft of valuable $-CF_2CF_2-$ bridged molecules.

The inherent value of our controllable double CF_2-insertion strategy with $TMSCF_3$ for the introduction of tetrafluoroethylene bridge is further demonstrated by its applicability to gram-scale synthesis. For example, when iodoisoxazole **1z** was scaled up to 5 mmol (1.12 g), the desired product **2z** was obtained in 83% yield (1.50 g). Analogously, pharmaceutical intermediates **1ae** and **1af** were also successfully scaled up to 5 mmol, with the yields comparable to that on 0.5 mmol scale (Scheme 4).

It is worthwhile to note that the tetrafluoroethylene-bridged product **2n** possesses interesting conformation and intermolecular interaction. As shown in Fig. 1,[36] the single crystal structure of product **2n** shows that the dihedral angle of C10–C11–C12–C13 is 174.1°, and two aromatic (the naphthalenyl and pentafluorophenyl) rings in **2n** are almost parallel to each other (see Fig. 1a, also see ESI†). The packing diagram shows there are extensive intermolecular π–π stackings between naphthalenyl and pentafluorophenyl rings of **2n** (Fig. 1b), which might find useful applications in crystal engineering and materials science.

Conclusions

In conclusion, a controllable double CF_2-insertion into C_6F_5Cu was realized using $TMSCF_3$ as the difluoromethylene source. The resulting $C_6F_5CF_2CF_2Cu$ species showed high reactivity towards various (hetero)aryl iodides and alkenyl iodides,

providing an easy access to a variety of $-CF_2CF_2-$ bridged molecules. Compared with previous methods for the construction of $-CF_2CF_2-$ unit, this approach owns several merits such as utilizing commercially available and environmentally benign reagents as the CF_2 source, easy to handle, broad substrate scope and mild conditions. This double CF_2-insertion strategy represents the second generation of fluorocarbon homologation reactions *via* difluoromethylene insertion using $TMSCF_3$ (the first generation is single CF_2-insertion into $CuCF_3$). Further efforts to seek after novel CF_2-insertion reactions using $TMSCF_3$ are currently underway in our laboratory.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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35 The chemical shifts of these fluoroalkylcopper/fluoroarylcopper species were assigned as follows (in ppm): $C_6F_5CF_2CF_2Cu$, −101.1 (t, 2F), −106.6 (s, 2F), −139.4 (m, 2F), −153.1 (t, 1F), −163.9 (t, 2F); C_6F_5Cu, −111.0 (d, 2F), −163.3 (t, 1F), −164.3 (t, 2F); $CuCF_3$, −26.7 (s, 3F); CuC_2F_5, −84.0 (s, 3F), −112.4 (s, 2F).

36 CCDC 1957757† contains the supplementary crystallographic data for compound **2n**.