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# Direct nucleophilic fluorination of carbonyl groups of benzophenones and benzils with Deoxofluor

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ABSTRACT

The carbonyl groups of diaryl ketones and diaryl diketones were directly fluorinated with bis(2-methoxyethyl)aminosulfur trifluoride (Deoxofluor) under neat conditions to give the corresponding *gem*-difluorides and tetrafluorinated derivatives in moderate to high yields.



## 1. Introduction

A combination of different properties of fluorine substituent or fluorinated substituents, such as electronegativity, size, bond polarizibility, brings in significant changes in the physical, chemical, and biological properties of fluorinated compounds, which have a broad range of applications in materials science, pharmaceuticals, and agrochemicals. Therefore, the development of new and efficient synthetic methods of organofluorine compounds has become an area of increasing interest.[1]

A particularly useful transformation is the selective fluorination of carbonyl functional groups to *gem*-difluorides. The classic conversion method uses sulfur tetrafluoride.[2] Although the yields are generally acceptable, the drawbacks of this method are the toxicity of the reagent and the high-pressure reaction conditions.

The commercial availability of diethylaminosulfur trifluoride (DAST) has allowed its broader applications in organic compound fluorination,[3] but the thermal instability of DAST above 80 °C has prevented its use in large-scale applications. Bis(2-methoxyethyl)aminosulfur trifluoride (Deoxofluor) is more thermally stable than DAST and is being used increasingly for the selective fluorination of organic molecules.[3,4] Deoxofluor can convert alcohols to alkyl fluorides,[4,5] aldehydes/ketones to *gem*-difluorides,[5,6] and carboxylic acids to trifluoromethyl derivatives.[5] The fluorination reactions are generally carried out with a suitable inert solvent such as methylene chloride.[7] Although the direct fluorination of ketones using Deoxofluor has appeared in the literature,[5a] the substrates have been confined mostly to simple and reactive ketones.

While investigating the preparation of partially fluorinated aromatic polymers, we became interested in the fluorination of the carbonyl groups of substituted benzophenones and benzils, which are relatively unreactive under general fluorination conditions. The direct conversion of benzophenone to the *gem*-difluorinated product with sulfur tetrafluoride in the presence of hydrogen fluoride catalyst has been reported,[2b] but it required harsh conditions (180 °C) and pressure equipment. Thus, for the *gem*-difluorination of benzophenone, two-step synthetic pathways that involve preparation of carbonyl derivatives (such as thioketone and thiolane), which need to be isolated, followed by fluorination have been developed.[6a,8] Although benzophenone can be *gem*-fluorinated via this indirect route, some of the resulting unstable intermediates could decompose to the starting ketones.[9] For example, when thioketone **1**, prepared from Lawesson reagent, was reacted with 2.3 equiv of Deoxofluor in methylene chloride in the presence of antimony trichloride (14 mol %) at room temperature for 7 h, the desired *gem*-difluoride product **2** as well as the decomposed product, 3,3′-dibromobenzophenone **3**, were obtained in 45% and 55% yield, respectively (Scheme 1).

Diaryltetrafluoroethanes have generally been prepared through fluorination of diarylacetylenes with $F_2$,[10] $XeF_2$/anhydrous HF,[11] or IF prepared directly from $I_2$ and $F_2$,[12] all of which require extreme caution because of the toxicity, reactivity, and volatility of the fluorinating reagents. To overcome the drawbacks of these fluorination reactions, tetrafluorination of diarylacetylenes with nitrosonium tetrafluoride/pyridinium polyhydrogen fluoride has been developed.[13] Only recently the preparation of diaryltetrafluoroethanes by direct fluorination of benzils using Deoxofluor has been reported,[6d] but the reaction scope was rather limited to certain types of benzil substrates. For example, we found that 4,4′-dibromobenzil was sparely soluble in dichloromethane under Shreeve's condition, and the desired tetrafluoride product was formed only in 13% yield together with *gem*-difluoride product in 7% yield.

A few cases of carbonyl compound fluorination with Deoxofluor under neat conditions have been reported independently by Lal[4,5a] and Shreeve.[6c] The substrates were limited mostly to simple

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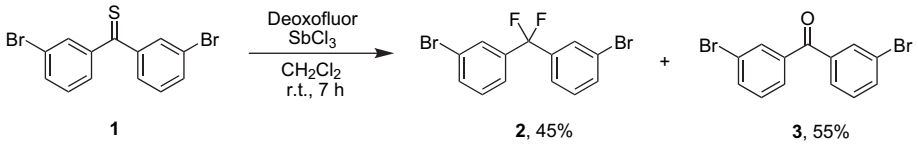



**Scheme 1.** *gem*-Difluorination of thioketone of benzophenone.

aromatic aldehydes, acetophenone, and carboxylic acid halides, however. Herein, we describe a direct, one-step fluorination of carbonyl groups of various substituted benzophenones and benzils with Deoxofluor under neat conditions. The reaction generates the corresponding *gem*-difluorides and tetrafluorides in moderate to high yields.[14]

## 2. Results and discussions

### 2.1. *gem*-Difluorination of benzophenone

Lal and co-workers reported that no reaction was observed when benzophenone was reacted with Deoxofluor under neat condition at 90 °C.[6a] However, we found that the reaction of benzophenone with 1.4 equiv of Deoxofluor at 90 °C for 24 h could produce the corresponding *gem*-difluoride compound in 27% isolated yield, and the yield improved to 63% with 3 equiv of Deoxofluor (Table 1, entry 1). Increasing the temperature to 100 °C and the reaction time to 48 h did not improve the yield significantly. Considering the thermal stability of Deoxofluor,[5a] we selected 90 °C and 24 h as the standard reaction conditions.

To investigate the scope of the fluorination method, we examined various substituted benzophenones; the results are shown in Table 1. In most cases, moderate to high yields could be obtained. Generally, the fluorination of *meta*- and *para*-substituted benzophenones proceeded smoothly, regardless of whether the substituent(s) was located on one or both sides of the aromatic rings. The fluorination of *ortho*-substituted benzophenone gave a poor yield owing to steric factors (Table 1, entry 2). All benzophenone substrates shown in Table 1 gave clean reactions; after aqueous workup at the end of the reaction, only the product and the remaining starting material were observed on gas chromatography/mass spectroscopy (GC/MS).

The electronic effect of the substituent exerted a significant influence on the reactivities of benzophenones. The presence of an electron-withdrawing group is believed to facilitate the nucleophilic attack of the fluoride anion to the carbonyl group, causing more facile cleavage of the carbon–oxygen double bond. Among the benzophenone substrates examined, 4-nitrobenzophenone exhibited the highest reactivity and the corresponding *gem*-difluorinated product was obtained in 91% yield (Table 1, entry 8). 3,3′-Bis(trifluoromethyl)benzophenone was also fluorinated in high yield (86%; Table 1, entry 15). By contrast, lower yields were obtained for benzophenones bearing electron-donating groups such as 4-methoxy (27%; Table 1, entry 6), 4-methyl (24%; Table 1, entry 7), and 4,4′-dimethyl (9%; Table 1, entry 13). No desired fluorinated product was obtained with 4,4′-dimethoxybenzophenone (Table 1, entry 14); only the starting material was recovered after the attempted fluorination.

When dicyclohexyl ketone was used under standard conditions, only 10% conversion was obtained, and no further enhancement in yield could be achieved even after prolonged reaction time (i.e., 3 days). The lower reactivity may be attributed to a combination of electronic and steric effects of the cyclohexyl group. When the reactivities of *gem*-fluorinations of various substituted benzophenones were compared in Table 1, benzophenones bearing an electron-donating group were much less reactive toward the fluorination. However, when *gem*-fluorinations of benzophenone and acetophenone were compared, the latter containing more electron-donating alkyl group was more reactive than the former. Thus, we speculate that for the *gem*-fluorination of dialkyl or alkyl aryl ketone, the steric effect plays a more important role than the electronic effect.

The mechanism of the fluorination is still obscure at this stage because we have not yet identified the fluorine-containing by-product(s).[15] After completion of the reaction, however, we noticed a small amount of solid at the bottom of the reaction mixture, which was isolated as a yellowish powder using column chromatography (mp 119–120 °C, 15% yield based on the amount of Deoxofluor used). $^{1}H$ and $^{19}F$ NMR spectroscopies and GC/MS detected no signal for this solid. We believe it to be elemental sulfur based on the melting point. To the best of our knowledge, no similar finding has appeared in the literature.

### 2.2. Tetrafluorination of benzil

We also discovered that the standard fluorination conditions worked well for tetrafluorination of the carbonyl groups of benzil. The fluorination yields of benzils were comparable to those of benzophenones (Table 2). In contrast to the *gem*-fluorination of benzophenones, the electronic effect of the substituent was not observed in the case of benzils. Thus, 4,4′-dimethoxybenzil could be fluorinated in 61% isolated yield (Table 2, entry 9). When benzils containing the same substituent at a different position were compared, however, slightly lower yields were observed for those with a substituent at the *meta* position (Table 2, entries 2 and 5) compared to *para*-substituted benzils (Table 2, entries 3 and 6). 2,2′-Dichlorobenzil was fluorinated in only 22% isolated yield, which again indicated that the reaction was affected by steric hindrance. The fluorination of 4,4′-difluorobenzil afforded the corresponding tetrafluoroethane product in the highest yield (92%; Table 2, entry 7). Similar to the observation of Shreeve and co-workers,[6d] our GC/MS analysis of the fluorination of benzil substrates indicated the presence of a mixture of tetrafluoride and *gem*-difluoride products in a ratio ranging from 13:1 to 8:1.

## 3. Summary

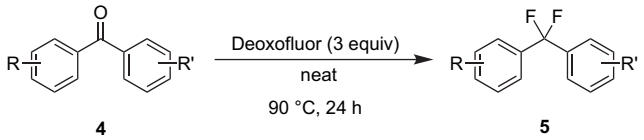
In summary, we have described a direct, one-step fluorination of various substituted benzophenones and benzils with Deoxofluor under neat conditions. The carbonyl groups of benzophenones and benzils are efficiently fluorinated under the standard conditions. This new procedure provides a convenient method for synthesizing diaryl-*gem*-difluoromethanes and diaryltetrafluoroethanes from the corresponding benzophenones and benzils.

## 4. Experimental section

### 4.1. General

$^{1}H$ (400 MHz), $^{19}F$ (376 MHz), and $^{13}C$ (100 MHz) NMR spectra were obtained using a Varian NMR spectrometer at room temperature and chemical shifts were referenced to TMS for $^{1}H$ and $^{13}C$ NMR and $CFCl_3$ for $^{19}F$ NMR. GC/MS analysis was conducted using

**Table 1**
*gem*-Difluorination of benzophenones with Deoxofluor under neat conditions




**4** **5**

| Entry | Substrate | | Product | | Isolated yield (%) |
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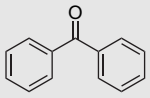
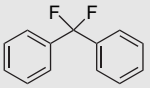
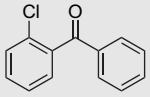
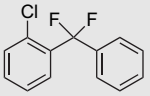
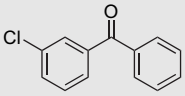
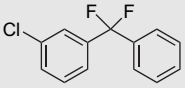
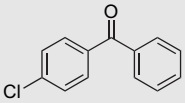
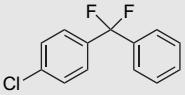
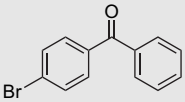
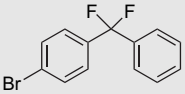
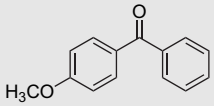
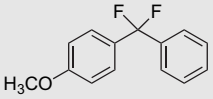
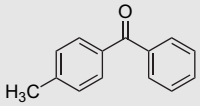
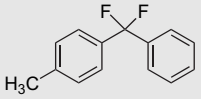
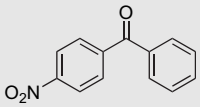
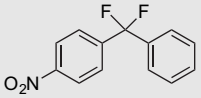
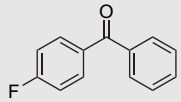
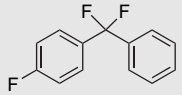
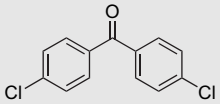
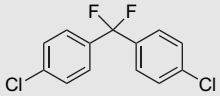
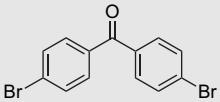
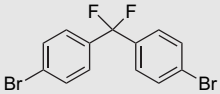
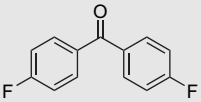
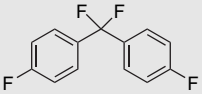
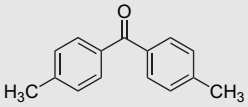
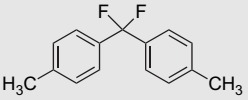
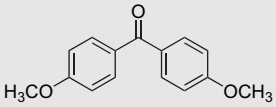
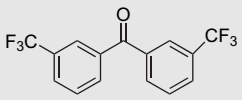
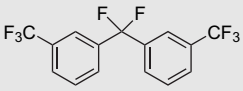
| 1 |  | **4a** |  | **5a** | 63 |
| 2 |  | **4b** |  | **5b** | 20 |
| 3 |  | **4c** |  | **5c** | 82 |
| 4 |  | **4d** |  | **5d** | 64 |
| 5 |  | **4e** |  | **5e** | 74 |
| 6 |  | **4f** |  | **5f** | 27 |
| 7 |  | **4g** |  | **5g** | 24 |
| 8 |  | **4h** |  | **5h** | 91 |
| 9 |  | **4i** |  | **5i** | 50 |
| 10 |  | **4j** |  | **5j** | 65 |
| 11 |  | **4k** |  | **5k** | 62 |
| 12 |  | **4l** |  | **5l** | 76 |
| 13 |  | **4m** |  | **5m** | 9 |
| 14 |  | **4n** | — | | nr[a] |
| 15 |  | **4o** |  | **5o** | 86 |

(*continued on next page*)

**Table 1** (*continued*)

| Entry | Substrate | | Product | | Isolated yield (%) |
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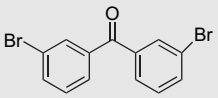
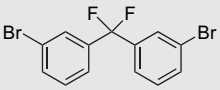
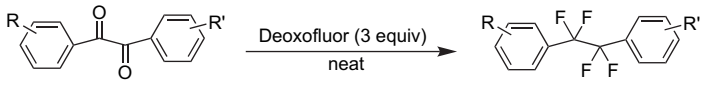
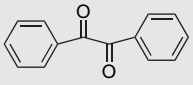
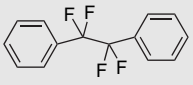
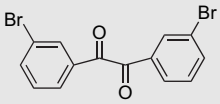
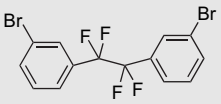
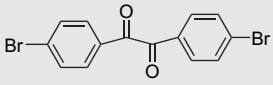
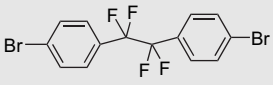
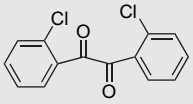
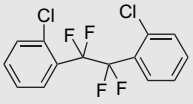
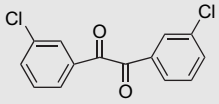
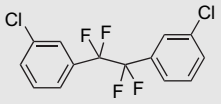
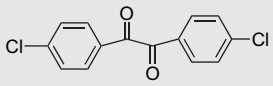
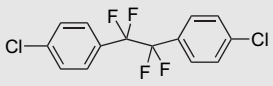
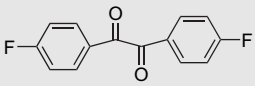
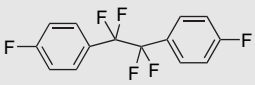
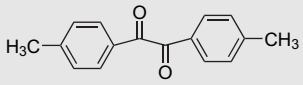
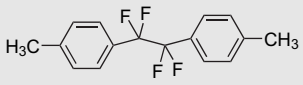
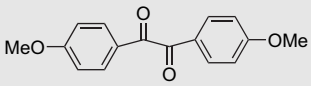
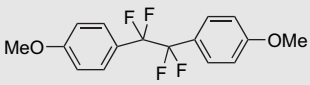
| 16 |  | **4p** (**3**) |  | **5p** (**2**) | 85 |

[a] No reaction.

**Table 2**
Tetrafluorination of benzils with Deoxofluor under neat conditions




**6** **7**

| Entry | Substrate | | Product | | Isolated yield (%) |
|---|---|---|---|---|---|
| 1 |  | **6a** |  | **7a** | 64 |
| 2 |  | **6b** |  | **7b** | 45 |
| 3 |  | **6c** |  | **7c** | 71 |
| 4 |  | **6d** |  | **7d** | 22 |
| 5 |  | **6e** |  | **7e** | 48 |
| 6 |  | **6f** |  | **7f** | 67 |
| 7 |  | **6g** |  | **7g** | 92 |
| 8 |  | **6h** |  | **7h** | 86 |
| 9 |  | **6i** |  | **7i** | 61 |

a Shimadzu QP2010S equipped with a 30 m×0.25 mm SHR-XLB GC column and an EI ionization MS detector. The melting point was uncorrected. Deoxofluor was purchased from Aldrich and used as-received.

## 4.2. General procedure for the preparation of *gem*-difluorides and tetrafluorides

*Caution*. Deoxofluor reacts rapidly and exothermally with water-generating HF. It should be handled in a well-ventilated hood.

Benzophenone or benzil (1.65 mmol) was added to a sealed tube and Deoxofluor (1.09 g, 4.94 mmol, 3 equiv) was added via a syringe. The tube was sealed and stirred at 90 °C for 24 h. The reaction mixture was cooled to room temperature, diluted with methylene chloride (40 mL), washed with water (20 mL×2), saturated aqueous sodium bicarbonate (20 mL×2), and brine (20 mL), dried over magnesium sulfate, filtered, and concentrated under reduced pressure. The crude product was purified using column chromatography with 2% ethyl acetate in hexane to afford the desired pure product.

### *4.2.1. Difluorodiphenylmethane (**5a**)*[8f]

Colorless oil (63% yield). $^{1}$H NMR ($CDCl_3$) $\delta$: 7.49–7.52 (m, 4H), 7.41–7.43 (m, 6H). $^{19}$F NMR ($CDCl_3$) $\delta$: −89.32 (s, $CF_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 137.9 (t, $^{2}J_{CF}$=28.3 Hz), 130.1 (t, $^{4}J_{CF}$=1.9 Hz), 128.6, 126.0 (t, $^{3}J_{CF}$=5.6 Hz), 121.0 (t, $^{1}J_{CF}$=240.4 Hz). MS (EI) *m*/*z*: 204 ($M^+$, 56%), 183 (26), 127 (100), 77 (36), 51 (28).

### *4.2.2. 2-Chlorophenyldifluorophenylmethane (**5b**)*

Colorless oil (20% yield). $^{1}$H NMR ($CDCl_3$) $\delta$: 7.79–7.81 (m, 1H), 7.45–7.47 (m, 2H), 7.36–7.41 (m, 6H). $^{19}$F NMR ($CDCl_3$) $\delta$: −89.00 (s, $CF_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 136.7 (t, $^{2}J_{CF}$=26.8 Hz), 134.7 (t,

$^{2}J_{CF}$=27.2 Hz), 132.8 (t, $^{3}J_{CF}$=3.4 Hz), 131.6, 130.2 (t, $^{4}J_{CF}$=1.9 Hz), 128.5, 128.0 (t, $^{3}J_{CF}$=8.2 Hz), 126.8, 126.3 (t, $^{3}J_{CF}$=5.2 Hz), 119.9 (t, $^{1}J_{CF}$=241.1 Hz). MS (EI) *m*/*z*: 238 ($M^{+}$, 55%), 203 (41), 183 (66), 161 (27), 127 (100), 77 (27), 51 (28). HRMS (EI) calcd for $C_{13}H_9ClF_2$ ($M^{+}$) 238.0361, found 238.0363.

#### 4.2.3. 3-Chlorophenyldifluorophenylmethane (**5c**)

Colorless oil (82% yield). $^{1}$H NMR ($CDCl_3$) $\delta$: 7.48–7.50 (m, 3H), 7.33–7.45 (m, 6H). $^{19}$F NMR ($CDCl_3$) $\delta$: −89.78 (s, *CF*$_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 139.8 (t, $^{2}J_{CF}$=29.1 Hz), 137.2 (t, $^{2}J_{CF}$=27.9 Hz), 134.7, 130.3, 130.2, 130.0, 128.7, 126.3 (t, $^{3}J_{CF}$=5.6 Hz), 125.9 (t, $^{3}J_{CF}$=5.6 Hz), 124.3 (t, $^{3}J_{CF}$=5.6 Hz), 120.2 (t, $^{1}J_{CF}$=241.5 Hz). MS (EI) *m*/*z*: 238 ($M^{+}$, 76%), 219 (7), 203 (43), 183 (45), 161 (23), 127 (100), 91 (15), 77 (25), 51 (26). HRMS (EI) calcd for $C_{13}H_9ClF_2$ ($M^{+}$) 238.0361, found 238.0359.

#### 4.2.4. 4-Chlorophenyldifluorophenylmethane (**5d**)[8f]

Colorless oil (64% yield). $^{1}$H NMR ($CDCl_3$) $\delta$: 7.47–7.50 (m, 2H), 7.38–7.45 (m, 7H). $^{19}$F NMR ($CDCl_3$) $\delta$: −89.24 (s, *CF*$_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 137.4 (t, $^{2}J_{CF}$=27.9 Hz), 136.4 (t, $^{2}J_{CF}$=28.7 Hz), 136.2 (t, $^{4}J_{CF}$=2.2 Hz), 130.3 (t, $^{4}J_{CF}$=1.9 Hz), 128.9, 128.7, 127.6 (t, $^{3}J_{CF}$=5.6 Hz), 125.9 (t, $^{3}J_{CF}$=5.6 Hz), 120.5 (t, $^{1}J_{CF}$=240.7 Hz). MS (EI) *m*/*z*: 240 ($M^{+}$, 32%), 238 ($M^{+}$, 98), 203 (100), 183 (64), 161 (87), 127 (98), 107 (20), 77 (35), 51 (32).

#### 4.2.5. 4-Bromophenyldifluorophenylmethane (**5e**)[8f]

Colorless oil (74% yield). $^{1}$H NMR ($CDCl_3$) $\delta$: 7.54 (d, *J*=8.4 Hz, 2H), 7.47–7.49 (m, 2H), 7.41–7.44 (m, 3H), 7.37 (d, *J*=8.4 Hz, 2H). $^{19}$F NMR ($CDCl_3$) $\delta$: −89.50 (s, *CF*$_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 137.3 (t, $^{2}J_{CF}$=27.9 Hz), 136.9 (t, $^{2}J_{CF}$=28.7 Hz), 131.8, 130.3 (t, $^{4}J_{CF}$=1.9 Hz), 128.7, 127.8 (t, $^{3}J_{CF}$=5.3 Hz), 125.9 (t, $^{3}J_{CF}$=5.6 Hz), 124.5 (t, $^{4}J_{CF}$=2.2 Hz), 120.5 (t, $^{1}J_{CF}$=240.7 Hz). MS (EI) *m*/*z*: 284 ($M^{+}$+1, 71), 282 ($M^{+}$, 73%), 263 (9), 203 (83), 183 (81), 127 (100), 107 (20), 91 (19), 77 (37), 51 (32).

#### 4.2.6. Difluoro(4-methoxyphenyl)phenylmethane (**5f**)[8f]

Colorless oil (27% yield). $^{1}$H NMR ($CDCl_3$) $\delta$: 7.50–7.51 (m, 2H), 7.39–7.43 (m, 5H), 6.91 (d, *J*=8.8 Hz, 2H), 3.82 (s, $CH_3$). $^{19}$F NMR ($CDCl_3$) $\delta$: −87.32 (s, *CF*$_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 160.9, 138.1 (t, $^{2}J_{CF}$=28.7 Hz), 130.2 (t, $^{2}J_{CF}$=28.7 Hz), 130.0 (t, $^{4}J_{CF}$=1.9 Hz), 128.5, 127.7 (t, $^{3}J_{CF}$=5.2 Hz), 126.1 (t, $^{3}J_{CF}$=5.6 Hz), 121.1 (t, $^{1}J_{CF}$=239.6 Hz), 113.9, 55.5. MS (EI) *m*/*z*: 234 ($M^{+}$, 68%), 203 (12), 170 (14), 157 (100), 127 (27), 77 (22), 51 (16).

#### 4.2.7. Difluoro(4-methylphenyl)phenylmethane (**5g**)

Colorless oil (24% yield). $^{1}$H NMR ($CDCl_3$) $\delta$: 7.50–7.51 (m, 2H), 7.37–7.41 (m, 5H), 7.20 (d, *J*=8.0 Hz, 2H), 2.36 (s, 3H). $^{19}$F NMR ($CDCl_3$) $\delta$: −88.68 (s, *CF*$_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 140.1, 138.1 (t, $^{2}J_{CF}$=28.3 Hz), 135.1 (t, $^{2}J_{CF}$=28.3 Hz), 130.0 (t, $^{4}J_{CF}$=1.9 Hz), 129.2, 128.5, 126.0 (td, $^{3}J_{CF}$=5.6, 3.0 Hz), 121.1 (t, $^{3}J_{CF}$=240.0 Hz), 21.5. MS (EI) *m*/*z*: 218 ($M^{+}$, 88%), 203 (67), 183 (31), 141 (100), 127 (65), 91 (33), 77 (28), 65 (10), 51 (23). HRMS (EI) calcd for $C_{14}H_{12}F_2$ ($M^{+}$) 218.0908, found 218.0920.

#### 4.2.8. Difluoro(4-nitrophenyl)phenylmethane (**5h**)

Yellowish solid (91% yield). Mp: 55–57 °C. $^{1}$H NMR ($CDCl_3$) $\delta$: 8.28 (d, *J*=8.8 Hz, 2H), 7.71 (d, *J*=8.8 Hz, 2H), 7.45–7.51 (m, 5H). $^{19}$F NMR ($CDCl_3$) $\delta$: −90.82 (s, *CF*$_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 148.8, 143.8 (t, $^{2}J_{CF}$=29.0 Hz), 136.4 (t, $^{2}J_{CF}$=27.5 Hz), 130.5, 128.8, 127.0 (t, $^{3}J_{CF}$=5.6 Hz), 125.6 (t, $^{3}J_{CF}$=5.6 Hz), 123.8, 119.8 (t, $^{1}J_{CF}$=242.6 Hz). MS (EI) *m*/*z*: 249 ($M^{+}$, 77%), 183 (69), 127 (100), 77 (31), 51 (15). HRMS (EI) calcd for $C_{13}H_9F_2NO_2$ ($M^{+}$) 249.0602, found 249.0658.

#### 4.2.9. Difluoro(4-fluorophenyl)phenylmethane (**5i**)[8b]

Colorless oil (50% yield). $^{1}$H NMR ($CDCl_3$) $\delta$: 7.47–7.50 (m, 4H), 7.40–7.44 (m, 3H), 7.10 (t, *J*=8.8 Hz, 2H). $^{19}$F NMR ($CDCl_3$) $\delta$: −88.10 (s, 2F, *CF*$_2$), −111.56 (m, 1F, *Ar–F*). $^{13}$C NMR ($CDCl_3$) $\delta$: 163.7 (d, $^{1}J_{CF}$=248.5 Hz), 137.6 (t, $^{2}J_{CF}$=28.0 Hz), 134.0 (td, $^{2}J_{CF}$=29.0 Hz, $^{4}J_{CF}$=3.0 Hz), 130.2, 128.7, 128.3 (dt, $^{3}J_{CF}$=5.6, 8.2 Hz), 126.0 (t, $^{3}J_{CF}$=5.3 Hz), 120.6 (t, $^{1}J_{CF}$=240.4 Hz), 115.6 (d, $^{2}J_{CF}$=21.6 Hz). MS (EI) *m*/*z*: 222 ($M^{+}$, 90%), 201 (30), 183 (12), 145 (100), 127 (64), 95 (17), 77 (25), 51 (27).

#### 4.2.10. Bis(4-chlorophenyl)difluoromethane (**5j**)[8f]

White solid (65% yield). Mp: 56–57 °C. $^{1}$H NMR ($CDCl_3$) $\delta$: 7.37–7.42 (m, 8H). $^{19}$F NMR ($CDCl_3$) $\delta$: −89.06 (s, *CF*$_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 136.6 (t, $^{4}J_{CF}$=2.2 Hz), 135.9 (t, $^{2}J_{CF}$=28.7 Hz), 129.0, 127.5 (t, $^{3}J_{CF}$=5.2 Hz), 120.2 (t, $^{1}J_{CF}$=241.1 Hz). MS (EI) *m*/*z*: 274($M^{+}$, 38%), 272 ($M^{+}$, 61), 237 (83), 161 (100), 125 (12), 107 (18), 75 (29), 50 (13).

#### 4.2.11. Bis(4-bromophenyl)difluoromethane (**5k**)

White solid (62% yield). Mp: 79–80 °C. $^{1}$H NMR ($CDCl_3$) $\delta$: 7.54 (d, *J*=8.0 Hz, 4H), 7.34 (d, *J*=8.0 Hz, 4H). $^{19}$F NMR ($CDCl_3$) $\delta$: −89.55 (s, *CF*$_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 136.3 (t, $^{2}J_{CF}$=28.7 Hz), 132.0, 127.7 (t, $^{3}J_{CF}$=5.2 Hz), 124.8, 120.2 (t, $^{1}J_{CF}$=241.5 Hz). MS (EI) *m*/*z*: 362 ($M^{+}$, 100%), 281 (60), 207 (62), 183 (28), 126 (84), 107 (34), 75 (51), 50 (45). HRMS (EI) calcd for $C_{13}H_8Br_2F_2$ ($M^{+}$) 359.8960, found 359.8984.

#### 4.2.12. Bis(4-fluorophenyl)difluoromethane (**5l**)[8f]

Colorless oil (76% yield). $^{1}$H NMR ($CDCl_3$) $\delta$: 7.46 (dd, $J_{HH}$=8.4 Hz, $J_{HF}$=5.2 Hz, 4H), 7.08 (t, $J_{HH}$=8.4 Hz, 4H). $^{19}$F NMR ($CDCl_3$) $\delta$: −86.79 (s, 2F, *CF*$_2$), −111.12 (m, 2F, *Ar–F*). $^{13}$C NMR ($CDCl_3$) $\delta$: 163.8 (dt, $^{1}J_{CF}$=248.5 Hz, $^{5}J_{CF}$=1.8 Hz), 133.7 (td, $^{2}J_{CF}$=28.3 Hz, $^{4}J_{CF}$=3.0 Hz), 128.3 (dt, $^{3}J_{CF}$=8.9, 5.2 Hz), 120.3 (t, $^{1}J_{CF}$=259.7 Hz), 115.7 (d, $^{2}J_{CF}$=22.4 Hz). MS (EI) *m*/*z*: 240 ($M^{+}$, 48%), 221 (16), 145 (100), 126 (16), 95 (18), 75 (17).

#### 4.2.13. Bis(4-methylphenyl)difluoromethane (**5m**)[6d]

Colorless oil (9% yield). $^{1}$H NMR ($CDCl_3$) $\delta$: 7.30–7.31 (m, 4H), 7.12–7.13 (m, 4H), 2.29 (s, 6H). $^{19}$F NMR ($CDCl_3$) $\delta$: −88.05 (s, *CF*$_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 140.0, 135.3 (t, $^{2}J_{CF}$=28.3 Hz), 129.2, 126.0 (t, $^{3}J_{CF}$=5.6 Hz), 121.2 (t, $^{1}J_{CF}$=239.6 Hz), 21.5. MS (EI) *m*/*z*: 232 ($M^{+}$, 94%), 217 (100), 197 (19), 141 (93), 101 (20), 91 (47), 65 (25), 51 (13).

#### 4.2.14. Bis(3-trifluoromethylphenyl)difluoromethane (**5o**)

Colorless oil (86% yield). $^{1}$H NMR ($CDCl_3$) $\delta$: 7.80 (s, 2H), 7.74 (d, *J*=8.4 Hz, 2H), 7.67 (d, *J*=7.6 Hz, 2H), 7.59 (t, *J*=7.8 Hz, 2H). $^{19}$F NMR ($CDCl_3$) $\delta$: −63.30 (s, 6F, 2*CF*$_3$), −90.05 (s, 2F, *CF*$_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 138.2 (t, $^{1}J_{CF}$=290.0 Hz), 131.6 (q, $^{2}J_{CF}$=32.7 Hz), 129.7, 129.5 (t, $^{3}J_{CF}$=6 Hz), 127.5 (m), 123.9 (q, $^{1}J_{CF}$=270.9 Hz), 122.8 (m), 119.6 (t, $^{1}J_{CF}$=242.3 Hz). MS (EI) *m*/*z*: 340 ($M^{+}$, 42%), 321 (19), 271 (27), 251 (12), 195 (100), 176 (8), 145 (23), 125 (10). HRMS (EI) calcd for $C_{15}H_8F_8$ ($M^{+}$) 340.0498, found 340.0517.

#### 4.2.15. Bis(3-bromophenyl)difluoromethane (**5p**)

White solid (85% yield). Mp: 34–35 °C. $^{1}$H NMR ($CDCl_3$) $\delta$: 7.65 (s, 2H), 7.56 (d, *J*=8.0 Hz, 2H), 7.40 (d, *J*=7.8 Hz, 2H), 7.29 (t, *J*=8.0 Hz, 2H). $^{19}$F NMR ($CDCl_3$) $\delta$: −90.11 (s, *CF*$_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 139.3 (t, $^{2}J_{CF}$=28.3 Hz), 133.6 (t, $^{4}J_{CF}$=1.0 Hz), 130.5, 129.1 (t, $^{3}J_{CF}$=6.0 Hz), 124.7 (t, $^{3}J_{CF}$=5.6 Hz), 122.9, 119.2 (t, $^{1}J_{CF}$=243.0 Hz). MS (EI) *m*/*z*: 362 ($M^{+}$, 100%), 281 (22), 202 (90), 183 (22), 126 (58), 101 (44), 91 (32), 75 (34), 50 (28). HRMS (EI) calcd for $C_{13}H_8Br_2F_2$ ($M^{+}$) 359.8960, found 359.8961.

#### 4.2.16. 1,1,2,2-Tetrafluoro-1,2-diphenylethane (**7a**)[6d]

White solid (64% yield). Mp: 125–127 °C. $^{1}$H NMR ($CDCl_3$) $\delta$: 7.39–7.51 (m, 10H). $^{19}$F NMR ($CDCl_3$) $\delta$: −112.37 (s, 4F, *CF*$_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 130.9, 130.9 (t, $^{2}J_{CF}$=25.8 Hz), 127.9, 126.8 (m), 116.6 (tt, $^{1}J_{CF}$=247.6 Hz, $^{2}J_{CF}$=35.8 Hz). MS (EI) *m*/*z*: 254 ($M^{+}$, 10%), 127 (100), 77 (15), 51 (5).

*4.2.17. 1,2-Bis(3-bromophenyl)-1,1,2,2-tetrafluoroethane (**7b**)*

White solid (45% yield). Mp: 105–107 °C. $^1$H NMR ($CDCl_3$) $\delta$: 7.63–7.68 (m, 4H), 7.41–7.43 (m, 2H), 7.30–7.34 (m, 2H). $^{19}$F NMR ($CDCl_3$) $\delta$: −111.79 (s, $CF_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 134.6, 132.6 (t, $^2J_{CF}$=25.3 Hz), 130.4 (t, $^3J_{CF}$=4.1 Hz), 130.1, 125.9 (t, $^3J_{CF}$=3.7 Hz), 122.6, 115.9 (tt, $^1J_{CF}$=253.0 Hz, $^2J_{CF}$=37.2 Hz). MS (EI) *m/z*: 412 ($M^+$, 17%), 205 (100), 126 (63), 107 (10), 75 (17), 50 (11). HRMS (EI) calcd for $C_{14}H_8Br_2F_4$ ($M^+$) 409.8928, found 409.8928.

*4.2.18. 1,2-Bis(4-bromophenyl)-1,1,2,2-tetrafluoroethane (**7c**)*

White solid (71% yield). Mp: 98–100 °C. $^1$H NMR ($CDCl_3$) $\delta$: 7.58 (d, *J*=8.6 Hz, 4H), 7.33 (d, *J*=8.6 Hz, 4H). $^{19}$F NMR ($CDCl_3$) $\delta$: −112.31 (s, $CF_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 131.8, 129.7 (t, $^2J_{CF}$=26.1 Hz), 128.9 (m), 126.2, 116.4 (tt, $^1J_{CF}$=252.3 Hz, $^2J_{CF}$=36.5 Hz). MS (EI) *m/z*: 412 ($M^+$, 10%), 205 (100), 126 (60), 107 (10), 75 (15), 50 (12). HRMS (EI) calcd for $C_{14}H_8Br_2F_4$ ($M^+$) 409.8928, found 409.8939.

*4.2.19. 1,2-Bis(2-chlorophenyl)-1,1,2,2-tetrafluoroethane (**7d**)*

White solid (22% yield). Mp: 104–106 °C. $^1$H NMR ($CDCl_3$) $\delta$: 7.54 (d, *J*=8.0 Hz, 2H), 7.38–7.44 (m, 4H), 7.29–7.33 (m, 2H). $^{19}$F NMR ($CDCl_3$) $\delta$: −107.34 (s, $CF_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 133.7, 132.4, 132.0, 130.7 (m), 128.4 (t, $^2J_{CF}$=26.1 Hz), 126.6, 117.0 (tt, $^1J_{CF}$=255.7 Hz, $^2J_{CF}$=37.2 Hz). MS (EI) *m/z*: 322 ($M^+$, 8%), 161 (100), 111 (6), 75 (23), 50 (5). HRMS (EI) calcd for $C_{14}H_8Cl_2F_4$ ($M^+$) 321.9940, found 321.9932.

*4.2.20. 1,2-Bis(3-chlorophenyl)-1,1,2,2-tetrafluoroethane (**7e**)*

White solid (48% yield). Mp: 93–95 °C. $^1$H NMR ($CDCl_3$) $\delta$: 7.48–7.51 (m, 4H), 7.36–7.40 (m, 4H). $^{19}$F NMR ($CDCl_3$) $\delta$: −118.81 (s, $CF_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 134.7, 132.5 (t, $^2J_{CF}$=25.3 Hz), 131.6, 129.8, 127.5 (m), 125.5 (m), 116.0 (tt, $^1J_{CF}$=252.7 Hz, $^2J_{CF}$=37.2 Hz). MS (EI) *m/z*: 322 ($M^+$, 7%), 161 (100), 111 (9), 75 (11). HRMS (EI) calcd for $C_{14}H_8Cl_2F_4$ ($M^+$) 321.9940, found 321.9928.

*4.2.21. 1,2-Bis(4-chlorophenyl)-1,1,2,2-tetrafluoroethane (**7f**)*

White solid (67% yield). Mp: 93–94 °C. $^1$H NMR ($CDCl_3$) $\delta$: 7.38–7.43 (m, 8H). $^{19}$F NMR ($CDCl_3$) $\delta$: −112.15 (s, $CF_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 137.8, 129.2 (t, $^2J_{CF}$=25.7 Hz), 128.8, 128.6 (m), 116.8 (tt, $^1J_{CF}$=252.9 Hz, $^2J_{CF}$=36.6 Hz). MS (EI) *m/z*: 322 ($M^+$, 6%), 161 (100), 111 (8), 75 (9). HRMS (EI) calcd for $C_{14}H_8Cl_2F_4$ ($M^+$) 321.9940, found 321.9949.

*4.2.22. 1,2-Bis(4-fluorophenyl)-1,1,2,2-tetrafluoroethane (**7g**)*[8b]

White solid (92% yield). Mp: 99–100 °C. $^1$H NMR ($CDCl_3$) $\delta$: 7.43–7.46 (m, 4H), 7.11 (t, *J*=8.6 Hz, 4H). $^{19}$F NMR ($CDCl_3$) $\delta$: −109.46 (s, 2F, *Ar–F*), −111.61 (s, 4F, $CF_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 164.6 (d, $^1J_{CF}$=250.1 Hz), 129.4 (m), 127.5 (t, $^2J_{CF}$=26.9 Hz), 116.5 (tt, $^1J_{CF}$=251.9 Hz, $^2J_{CF}$=36.8 Hz), 115.7 (d, $^2J_{CF}$=21.6 Hz). MS (EI) *m/z*: 290 ($M^+$, 5%), 145 (100), 125 (3), 95 (10), 75 (6).

*4.2.23. 1,2-Bis(4-methylphenyl)-1,1,2,2-tetrafluoroethane (**7h**)*[6d]

White solid (86% yield). Mp: 137–140 °C. $^1$H NMR ($CDCl_3$) $\delta$: 7.26 (d, *J*=7.6 Hz, 4H), 7.11 (d, *J*=7.6 Hz, 4H), 2.29 (s, 6H). $^{19}$F NMR ($CDCl_3$) $\delta$: −111.84 (s, 2$CF_2$). $^{13}$C NMR ($CDCl_3$) $\delta$: 141.3, 129.0, 128.3–128.6 (m), 127.1 (m), 117.1 (tt, $^1J_{CF}$=251.5 Hz, $^2J_{CF}$=36.5 Hz), 21.5. MS (EI) *m/z*: 282 ($M^+$, 10%), 141 (100), 101 (7), 91 (14).

*4.2.24. 1,2-Bis(4-methoxyphenyl)-1,1,2,2-tetrafluoroethane (**7i**)*

White solid (61% yield). Mp: 201–203 °C. $^1$H NMR ($CDCl_3$) $\delta$: 7.34 (d, *J*=8.8 Hz, 4H), 6.90 (d, *J*=8.8 Hz, 4H), 3.84 (s, 6H). $^{19}$F NMR ($CDCl_3$) $\delta$: −111.49 (s, $CF_2$). $^{13}$C NMR ($CDCl_3$): low solubility, only four kinds of carbons were observed $\delta$: 161.6, 128.7 (m), 113.6, 55.6. MS (EI) *m/z*: 314 ($M^+$, 8%), 157 (100), 114 (17), 109 (8). HRMS (EI) calcd for $C_{16}H_{14}F_4O_2$ ($M^+$) 314.0930, found 314.0929.

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## Supplementary data

Supplementary spectra ($^1$H, $^{19}$F, and $^{13}$C NMR and MS) of all products. Supplementary data associated with this article can be found in the online version, at doi:doi:10.1016/j.tet.2008.08.009.

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14. During the course of our study, we found a patent that described a direct fluorination of benzophenone using 2,2-difluoro-1,3-dimethylimidazolidine (U.S. Patent 6,329,529 B1, 2001). This reagent did not work for the fluorination of benzil in our investigation, however.
15. When the crude reaction mixture from fluorination of 4,4′-dichlorobenzophenone (**4j**) was checked using $^{19}$F NMR, two major signals in addition to the signal of **5j** were observed: −132.1 ppm (br s) and −152.6 ppm (s) in the integration ratio of 5:1. After aqueous workup, however, the fluorine signals from the two by-products disappeared, and only the signal of **5j** at −89.1 ppm (s) remained. Based on this observation, we speculate that the fluorine-containing by-products are hydrogen fluoride complexes of bis(methoxyethyl)amine.