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Nucleophilic fluorination of alkynyliodonium salts by alkali metal fluorides: access to fluorovinylic compounds

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ABSTRACT

Fluorovinylic compounds were synthesized by a one-pot procedure from the corresponding alkynyliodonium salts and alkali metal fluorides. Different reaction parameters, such as the temperature, the solvent and the reaction time were examined, and interestingly CsF was chosen for regio- and stereoselective reactions leading to different alkenyliodonium salts in good yields. Their reduction using $NaBH_4$ provided the corresponding 2-fluorovinylic products quantitatively.

1. Introduction

Selective methods to introduce a fluorine atom in organic compounds have found a large interest in organic synthesis, particularly for the preparation of pharmacologically active compounds. These methods were also required to prepare fluorine-18 (F-18) labelled radiopharmaceuticals for molecular imaging techniques, such as Positron Emission Tomography (PET). The use of radiofluoride anion limits the preparation of aromatic[1] or alkyl[2] radiofluorinated tracers. Furthermore, many radiofluorinated molecules, which contain a C(sp^3)–F bond, could be unstable in vivo leading to a defluorination, reducing the efficacy of the PET analysis. The objective of this work is to achieve a facile preparation of fluoroalkenyl moieties with a comparable stability to fluoroaryl groups, and almost the same steric bulkiness as fluoroalkyl groups, through nucleophilic substitution using a fluoride anion.

We focused on the fluorination of alkynyliodonium salts as potential precursors to fluoroolefins. Iodo hypervalent compounds, such as IBX, the Dess–Martin periodinane (DMP), $PhI(OAc)_2$, PhIO or PhI(OH)OTf, are often used as mild and selective oxidizing reagents or to form carbon–carbon bonds, whereas iodonium salts provide many by-products due to their very strong electron-withdrawing properties.[3,4] Iodonium salts or iodine(III) compounds are represented by the ionic form $R_2I^+X^-$ and classified according to the nature of R, such as alkyliodonium, aryliodonium, alkenyliodonium, or alkynyliodonium salts. Alkynyliodonium salts[5–8] can react with several nucleophiles as well as with Michael-type derivatives.[9] They can be used as electrophilic acetylene equivalents,[6] in coupling reaction[8,10] or to form five-membered carbocycles or heterocycle rings via a 1,5-carbene insertion.[6] Recent studies showed that HF and its derivatives can be added to the triple bond of 1-alkynyl(aryl) iodonium salts leading to (*Z*)-2-fluoro-1-alkenyl(aryl)iodonium salts in good yields.[11] However, the reaction between an excess of alkali metal fluorides (LiF, CsF) and different alkynyliodonium tetrafluoroborate salts resulted in the recovery of the starting products or very low yields of the fluorinated products.[9,12]

In this paper, we report the fluorination of alkynyl(phenyl) iodonium salts using different fluoride sources, especially alkali metal fluorides. The optimized conditions were suitable for the synthesis of different alkenyl(phenyl)iodonium salts in good yield, which could afford fluoroolefin compounds by subsequent reduction. Furthermore, we propose a novel access to fluorovinylic compounds from 1-alkynyl(phenyl)iodonium salts **1** in a one step fashion, corresponding to a one-pot nucleophilic addition of a fluoride anion to the triple bond followed by the reduction of the iodonium function by $NaBH_4$.

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2. Results and discussion

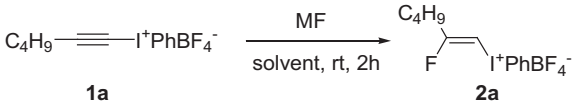
1-Alkynyl(phenyl)iodonium salts used in this study were synthesized using previously described methods with some modifications due to the instability of some of them.[13]

To optimize the fluorination of alkynyliodonium using fluoride anion, and also with default reactant, which could be similar to radiochemical processes, we decided to examine the influence of different reaction parameters, such as the fluoride source, the number of equivalents, the exposure time, the temperature and the solvent, on the fluorine incorporation.

2.1. Choice of the fluoride source and the appropriate solvent

To determinate the influence of the fluoride anion source and the nature of solvent used for the fluorination of alkynyliodoniums salts, we examined a variety of fluoride sources (CsF, KF, LiF, $^{n}Bu_4NF$ and HF) using the same number of equivalents [2.5 equiv, except for HF (5 equiv)] in a variety of aprotic or protic solvents, at room temperature during 2 h (compatible with the F-18 half-life) (Table 1). 1-Hexynyl(phenyl)iodonium tetrafluoroborate **1a** was used as a iodonium salt model for this reaction. The fluoride anion reacted with **1a** in a regio- and stereo-selective fashion, affording the (*Z*)-2-fluoro-1-hexenyl(phenyl)iodonium tetrafluoroborate salt **2a** as the unique product.

Table 1
Yields of the fluorination of the 1-hexynyl(phenyl)iodonium tetrafluoroborate salt **1a** by fluoride anion in different solvents

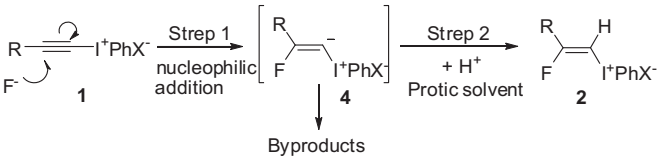


1a **2a**

Entry[a,b]	Solvent	MF				
		CsF I	KF II	LiF III	$^{n}Bu_4NF$ IV	HF V
1	H_2O	30 (24)[c]	36	18	22	9
2	CH_2Cl_2	11	20	15	<5	0
3	CH_3CN	10	13	5	<5	0
4	CH_3CN/H_2O	31 (25)[c]	22	9	27	0
5	CH_2Cl_2/H_2O	28 (25)[c]	26	24	10	9
6	$CH_2Cl_2/H_2O/CH_3COCH_3$	24	17	< 5	18	0
7	MeOH	25	27	9	15	9
8	CH_2Cl_2/AcOH	31	<5	<5	<5	0
9	DMSO	0	0	0	—	—

[a] The structure of **2a** was confirmed by ^{1}H-, ^{19}F and ^{13}C NMR spectroscopy.
[b] The percentage of conversion was calculated by ^{1}H NMR.
[c] Isolated yield.

As shown in Table 1, CsF and KF showed a higher reactivity compared to LiF, $^{n}Bu_4NF$ or HF. Except in aprotic solvents, all other fluorinations using CsF afforded **2a** in reasonable isolated yields (25%, entries 1, 4 and 5, column I, Table 1). Likewise, KF afforded **2a** in reasonable yields, in protic solvents, such as H_2O, MeOH, CH_3CN/H_2O and CH_2Cl_2/H_2O (entries 1, 4, 5 and 7, column II, Table 1). LiF gave a correct conversion of **1a** especially in H_2O and in a mixture of CH_2Cl_2/H_2O (entries 1 and 5, column III, Table 1). Thus, the relative reactivity of these alkali metal fluorides was strongly dependent on the solvent used, however, their nucleophilic activity towards **1a** followed the following order: CsF≥KF>LiF. When the $^{n}Bu_4NF$ was used, the best results were obtained in water and in a mixture of CH_3CN/H_2O (entries 1 and 4, column 4, Table 1). The low yields obtained with $^{n}Bu_4NF$ in aprotic solvents could be explained by the relative instability of the intermediate anion **4** under these conditions (Scheme 1) as suggested in the literature.[6] Furthermore, using a large excess of HF (45–50% in water), none of the desired product was observed (column V, Table 1).



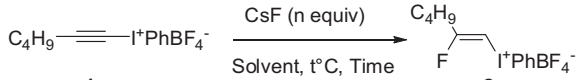
Scheme 1.

We concluded that the presence of a proton source was essential to ensure the incorporation of fluorine, since the fluorination of **1a** using CsF gave similar yields in CH_3CN/H_2O, CH_2Cl_2/H_2O, MeOH or CH_2Cl_2/CH_3COOH.

2.2. Influence of the stoichiometry, the temperature, the reaction time and concentration

Using CsF as the fluoride source, in conjunction with protic solvents, we elected to optimize the fluorination of 1-hexynyl(phenyl) iodonium tetrafluoroborate salt **1a** by examining the effect of parameters such as the reaction stoichiometry, its temperature, length of time and concentration. Salt **1a** was reacted with a limited amount of CsF [0.5 (to use a default quantity of fluorine source as for radiolabelling) to 1.2 equiv], in protic solvents, such as H_2O, CH_3CO_2H in acetonitrile or MeOH, with reaction temperatures ranging between room temperature (rt) and reflux during a 2 h period (Table 2). The reaction yield is calculated according to the default reactant (CsF, if 0.5 equiv, or **1a**). The conversion of **1a** was monitored every 15–30 min, and was reported in Table 2 and in Figs. 1–3.

Table 2
Influence of the reaction stoichiometry and temperature over a 2 h period, in different solvent systems[a]



1a **2a**

Entry	Conditions[b]	Time (h)				
		0.25	0.5	1	1.5	2
1	CsF 1.2 equiv, H_2O (50 equiv), CH_3CN, rt	5	10	14	17	20
2	CsF 1.2 equiv, H_2O (50 equiv), CH_3CN, 40 °C	12	24	46	49	43
3	CsF 1.2 equiv, H_2O (50 equiv), CH_3CN, 60 °C	25	59	56	43	39
4	CsF 1.2 equiv, H_2O (50 equiv), CH_3CN, reflux	31	45	27	9	0
5	CsF 0.5 equiv, H_2O (50 equiv), CH_3CN, 60 °C	—	84	100	98	94
6	CsF 0.5 equiv, H_2O (2.2 equiv), CH_3CN, 60 °C	—	60	100	74	66
7	CsF 0.5 equiv, CH_3CO_2H (2.2 equiv), CH_3CN, 60 °C	—	24	28	26	10
8	CsF 0.5 equiv, MeOH	—	58	100	94	86

[a] The conversion of **1a** was calculated from ^{1}H NMR. Yields are calculated from the limiting reagent (CsF or **1a**).
[b] The volume of CH_3CN or MeOH was 4 mL/(mmol of **1a**).

2.3. Effect of the temperature and reaction time on the conversion of (1a)

When reacting **1a** with CsF (1.2 equiv) in an CH_3CN/H_2O mixture, at different temperatures (room temperature, 40 °C, 60 °C and reflux) (entries 1–4, Table 2), we observed that the fluorination was strongly dependent on the reaction temperature and length of time. While the fluorination at room temperature gave only 20% of **2a** after 2 h, at 40 °C, the conversion to **2a** was doubled after 1 h. This conversion reached 59% when the reaction was carried out at 60 °C in only 30 min. Refluxing the mixture did not increase the yield of **2a** and the undesired decompositions of iodonium salts were observed.[14–16] These results suggested that the formation of

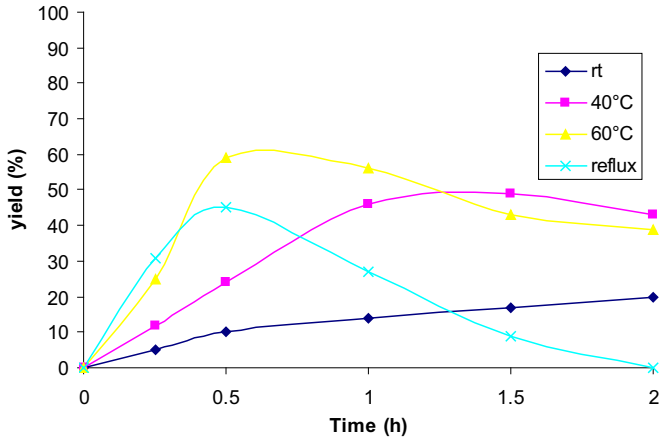


Fig. 1. Influence of the temperature and the reaction time on the fluorination of **1a** using CsF.

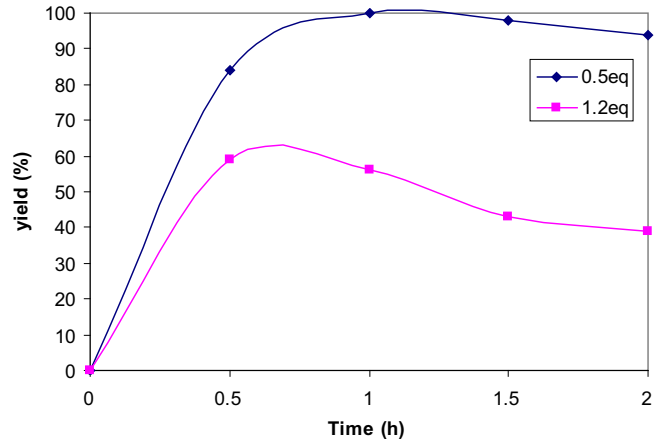


Fig. 2. Influence of CsF stoichiometry and the reaction time on the fluorination of **1a**.

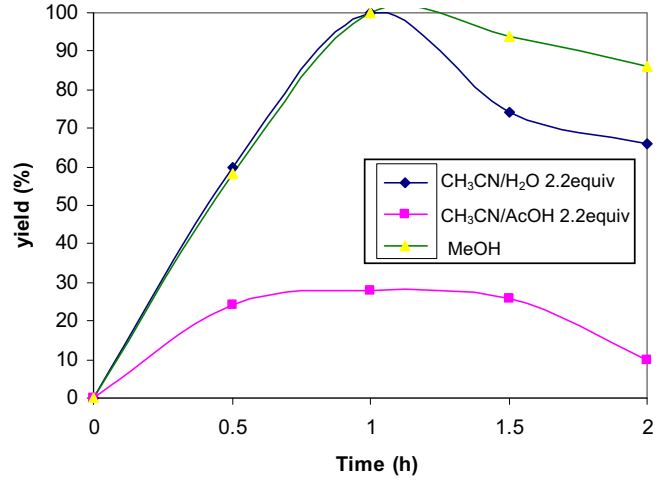


Fig. 3. Solvent and reaction time influences on the fluorination of **1a**.

2a was generally increased at higher temperatures over a longer period of time as shown in Fig. 1.

2.4. Influence of CsF stoichiometry and the reaction time

As shown in Fig. 2, a higher concentration of CsF did not increase the reaction yield. Indeed, when the amount of CsF was increased from 1.2 to 2.5 equiv the fluorination of **1a** decreased (entry 4, Table 1 and entry 1, Table 2), maybe due to by-products as previously described.[7,17] Surprisingly, the use of 0.5 equiv of CsF resulted in a higher conversion of **1a** regardless of the reaction time (entries 4 and 5, Table 2). We found that this optimal condition concerning the number of fluoride equivalents is different from those optimized for general chemistry of F-19 (generally an excess of fluoride is suggested). This could be rationalized by the fact that the use of a limited quantity of CsF will avoid the occurrence of side-reactions, making the fluoride addition to the triple bond the predominant reaction, which is a best for radiolabelling (where the fluoride anion is in default).

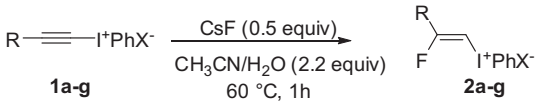
2.5. Solvent and reaction time influence on the reaction

As shown in Table 2, the use of a protic solvent increased the formation of **2a**. We subsequently attempted to minimize the amount of solvent used in the reaction mixture (Fig. 3). The reaction between **1a** and 0.5 equiv of CsF in acetonitrile, in presence of only 2.2 equiv of water, gave the alkenyliodonium salt **2a** quantitatively after 1 h (entry 6, Table 2), while the use of 2.2 equiv of acetic acid led to a poor fluorination yield (≤28%, entry 7, Table 2). However, excess of methanol (10 mL/mmol of substrate) gave an excellent conversion yield of **1a**. Thus, the optimal conditions for the fluorination the 1-hexynyl(phenyl)iodonium tetrafluoroborate **1a** were: 0.5 equiv of CsF, 60 °C, in CH_3CN/H_2O for 1 h or 0.5 equiv of CsF, in MeOH at reflux for 1 h. Finally, for a radiolabelling process to ensure that the fluoride anion was provided by CsF and not the counter ion BF_4^-, 1-dodecynyl(phenyl)iodonium tetrafluoroborate salt **1d** was refluxed in methanol during 1 h in absence of CsF, and derivative **2d** was not detected by ^1H NMR in the crude reaction mixture. We thus proposed that the BF_4^- ion was not involved as a fluorine source in this fluorination process. Our choice of alkynyliodonium tetrafluoroborate salts compare to alkynyliodonium tosylate salts seemed obvious as they gave higher yields.

2.6. Fluorination of different alkynyliodonium salts

To extend the scope of the method, we attempted to use the optimized conditions [CsF 0.5 equiv, H_2O (2.2 equiv), CH_3CN, 60 °C, 1 h] to fluorinate several salts **1a**–**g** containing aliphatic, alicyclic and aromatic groups (C_4H_9, $C_{10}H_{21}$, cyclohexyl-CH_2, phenyl) with tetrafluoroborate or tosylate counter ion (Table 3). The yields of the resulting fluorinated substrates **2a**–**g** were good to excellent (31–87%, Table 3).

Table 3
Fluorination of alkynyliodonium salts **1a**–**g** using CsF



1a-g **2a-g**

Entry	Compound	R	X	Yield[a] (%)
1	**1a**	C_4H_9	BF_4	**2a** (87)
2	**1b**	C_4H_9	OTs	**2b** (43)
3	**1c**	Cyclohexyl-CH_2	BF_4	**2c** (71)
4	**1d**	$C_{10}H_{21}$	BF_4	**2d** (65)
5	**1e**	Ph	BF_4	**2e** (70)
6	**1f**	$PhCH_2CH_2$	BF_4	**2f** (61)
7	**1g**	Ph	OTs	**2g** (31)

[a] Isolated yield.

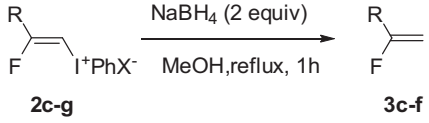
As shown in Table 3, the fluorination of compounds **1a**–**g** depended on the R group size and the counter ion nature. The fluorine incorporation was rather successful with a small R group, as shown with substrate **2a** (87%) compared to 31–71% for

substrates **2c**–**f** (entries 1 and 3–7, Table 3). The nature of the counter ion significantly influenced the fluorination yield of **1**. The tetrafluoroborate salts **2a**,**c**–**f** were obtained in better yields than their analogue tosylate salts **2b** and **2g** (61–87% and 31–43%, respectively). These results led us to believe that the optimal conditions previously studied were suitable for several substrates regardless of their structure.

2.7. Preparation of fluorovinyl compounds by reduction of iodonium salts (2)

To our knowledge several S_N2 and coupling reactions allow for the displacement of the iodonium function with different nucleophiles. However, the hydrolysis of the iodonium group has yet to be described. In our hands, the reduction of the iodonium group using $NaBH_4$, yielded chemioselectively the fluorovinyl compounds **3c**–**f** from the parent alkenyliodonium salts **2c**–**g** (Table 4). This reaction probably proceeds by a S_N2 substitution. When the reaction between the salts **2c**–**g** with an excess of $NaBH_4$ (2 equiv) in refluxing methanol was carried out for 1 h, the conversion to fluorovinyl **3c**–**f** was almost quantitative. Furthermore, the nature of the R group and the counter ion did not seem to alter the formation of the fluorovinyl compounds, which were obtained in good to excellent yields (Table 4).

Table 4
Formation of fluorovinyl compounds **3c**–**f** by reduction of alkenyliodonium salts **2c**–**g**



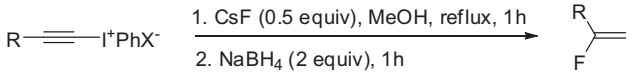
2c-g **3c-f**

Entry	Compound	R	X	Yield[a] (%)
1	**2c**	Cyclohexyl-CH_2	BF_4	**3c** (51)
2	**2d**	$C_{10}H_{21}$	BF_4	**3d** (86)
3	**2e**	Ph	BF_4	**3e** (61)
4	**2f**	$PhCH_2CH_2$	BF_4	**3f** (87)
5	**2g**	Ph	OTs	**3e** (67)

[a] Isolated yield.

2.8. Preparation of fluorovinyl compounds in a one-pot reaction

We succeed in one-pot preparation of fluorovinyl derivatives **3d**–**f** from the corresponding alkynyliodonium salts: the reaction of alkynyliodoniums salts **1d**–**f** with CsF (0.5 equiv) in methanol followed by the $NaBH_4$ reduction (2 equiv) yielded **3d**–**f** in 76%, 44% and 77% yield, respectively (Scheme 2).



1d: R = $C_{10}H_{21}$, X = BF_4
1e: R = Ph, X = BF_4
1f: R = $PhCH_2CH_2$, X = BF_4

3d (76%)
3e (44%)
3f (77%)

Scheme 2. Formation of fluorovinyl compounds **3d**–**f** in one-pot reaction.

3. Conclusion

Fluorinated derivatives with a stable C(sp^2)–F bond can be obtained by a nucleophilic fluorination of alkynyliodonium salts. Optimization of the experimental conditions provided new insights on this reaction, mainly on the regio- and stereo-selective reaction between alkynyliodonium salts **1** and fluoride metal salts, such as CsF, KF, LiF and $^nBu_4NF$ affording (*Z*)-2-fluoro-1-(phenyl)alkenyl salts **2**. CsF (0.5 equiv) proved to have the highest reactivity towards alkynyliodonium salts **1**.

Finally, the displacement of the alkenyliodonium group using CsF as fluorine source, with $NaBH_4$ yielded fluorovinyl derivatives **3d**–**f**, either after isolation of intermediates **2d**–**f** or directly from alkynyliodonium salts **1d**–**f** in a one-pot fashion.

4. Experimental section

4.1. General

^1H, ^{13}C and ^{19}F NMR spectra were recorded on a 200 or 500 MHz Bruker spectrometer. Chemical shifts (δ) are given in parts per million relative to the internal standard tetramethylsilane. IR spectra were obtained on an Alpha-E FT-IR spectrometer (Bruker) with ATR crystal. All fluoride reagents (CsF, LiF, KF, $^nBu_4NF$, HF) were commercially available. Alkynyliodonium tosylates **1b** and **1g** were prepared from the corresponding terminal alkynes and the PhI(OH)OTs at room temperature, according to the Koser's method.[18,19] Alkynyliodonium tetrafluoroborate salts **1a**,**c**–**f** were synthesized from terminal alkynes and PhIO at 0 °C or at room temperature as the procedure of Yoshida et al.[20] The spectral data of **1a** [*n*-hexynyl(phenyl)iodonium tetrafluoroborate],[21,22] **1b** [*n*-hexynyl(phenyl)iodonium tosylate],[23] **1c** [phenyl(3-cyclohexylprop-1-ynyl)iodonium tetrafluoroborate],[24] **1d** [1-dodecynyl(phenyl)iodonium tetrafluoroborate],[20] **1e** [phenyl (phenylethynyl)iodonium tetrafluoroborate][25] and **1g** [phenyl(phenylethynyl)iodonium tosylate][19] have been previously reported in the literature. Products were characterized by comparison with these data. All alkynyliodonium salts were stored at −20 °C while the phenyl(phenylethynyl)iodonium tetrafluoroborate salt **1e** was used immediately after its synthesis.

*4.1.1. Phenyl(4-phenylbut-1-ynyl)iodonium tetrafluoroborate (**1f**).* Yield, 78%; ^1H NMR (200 MHz, $CDCl_3$): δ=2.90–3.02 (m, 4H), 7.11–7.33 (m, 7H), 7.51–7.56 (m, 1H), 7.63–7.67 (m, 1H), 7.95 ppm (d, *J*=7.8 Hz, 1H).

4.2. General procedure for the fluorination of the *n*-hexynyl (phenyl)iodonium tetrafluoroborate salt (1a) with different fluoride sources

4.2.1. Fluorination with alkaline fluorides. A mixture of the *n*-hexynyl(phenyl)iodonium tetrafluoroborate salt **1a** (372 mg, 1 mmol, 1 equiv) and an alkaline fluoride salt (CsF, KF or LiF, 2.5 equiv) was dissolved in the appropriate solvent (H_2O; CH_2Cl_2; CH_3CN; CH_3CN/H_2O: 3/1; CH_2Cl_2/H_2O: 3/1; $CH_2Cl_2/H_2O/CH_3COCH_3$: 2/1/1; MeOH; CH_2Cl_2/AcOH: 3/1; DMSO; THF; or $CHCl_3$; 4 mL) and stirred for 2 h, at room temperature. A solution of $NaBF_4$ (5% in water, 10 mL) was then added and the mixture was stirred for an additional 15 min. The resulting mixture was extracted with dichloromethane (3×20 mL), and the combined organic layers were dried over $MgSO_4$ and concentrated under reduce pressure. The conversion of the (*Z*)-2-fluorohex-1-enyl(phenyl)iodonium tetrafluoroborate salt **2a** was established by ^1H NMR of the crude product. The compound **2a** was purified by column chromatography on silica gel (CH_2Cl_2/MeOH: 90/10).

4.2.2. Fluorination with $^nBu_4NF$ or HF solution. To a stirred solution of the *n*-hexynyl(phenyl)iodonium tetrafluoroborate salt **1a** (372 mg, 1 mmol, 1 equiv) in the appropriate solvent (4 mL) was added a solution of $^nBu_4NF$ (1 M in THF, 2.5 mL, 2.5 equiv) or HF (48–50% in water, 0.2 mL, 5 equiv). The reaction mixture was stirred for 2 h at room temperature when a solution of $NaBF_4$ (5% in water, 10 mL) was added. The mixture was further stirred for 15 min and was extracted by CH_2Cl_2 (3×10 mL). The combined organic layers

were dried over $MgSO_4$ and concentrated under reduce pressure to give the crude product, which was characterized by ^1H NMR.

4.3. General procedure for fluorination of the *n*-hexynyl (phenyl)iodonium tetrafluoroborate salt 1a using CsF

A mixture of the *n*-hexynyl(phenyl)iodonium tetrafluoroborate salt **1a** (372 mg, 1 mmol, 1 equiv) and CsF (0.5–1.2 equiv), in the appropriate solvent (CH_3CN/H_2O: 3 mL/1 mL; CH_3CN/H_2O: 4 mL/40 μL; CH_3CN/CH_3COOH: 96% 4 mL/135 μL or MeOH: 10 mL) was stirred at desired temperature for 2 h. Small aliquots from the reaction solution were collected using a syringe after 15 min, 30 min, 1 h, 1 h 30 min and 2 h, extracted with CH_2Cl_2 as described above, and analyzed by ^1H NMR.

4.4. General procedure for the preparation of alkenyliodonium salts (2a–g)

Alkynyliodonium salt **1a**–**g** (1 mmol, 1 equiv) and CsF (76 mg, 0.5 equiv) were dissolved in a mixture of acetonitrile (4 mL) and water (40 μL). The reaction solution was stirred at 60 °C for 1 h, cooled at room temperature and was poured onto a solution of $NaBF_4$ (for **1a**,**c**–**f**) or NaOTs (for **1b**,**g**) (5% in water, 10 mL). The resulting mixture was stirred for additional 10 min and extracted with CH_2Cl_2 (3×10 mL). The combined organic layers were dried over $MgSO_4$ and concentrated under reduced pressure to give the corresponding fluoroalkenyliodonium salts **2a**–**g**, which were purified by column chromatography on silica gel (CH_2Cl_2/MeOH: 90/10).

^1H and ^{13}C NMR spectral data of isolated compounds (*Z*)-(3-cyclohexyl-2-fluoroprop-1-enyl)(phenyl)iodonium tetrafluoroborate **2c**, (*Z*)-2-fluoro-dodec-1-enyl(phenyl)iodonium tetrafluoroborate **2d** and (*Z*)-(2-fluoro-2-phenylvinyl)(phenyl)iodonium tetrafluoroborate **2e** were identical to the one described previously in the literature.[11,24]

*4.4.1. (Z)-2-Fluorohex-1-enyl(phenyl)iodonium tetrafluoroborate (**2a**).* The title compound was prepared according to the general procedure from hexynyl(phenyl)iodonium tetrafluoroborate **1a** (372 mg, 1 mmol). Compound **2a** was obtained as an oil, which crystallized upon treatment with Et_2O as a yellow solid (170 mg, 87%). ^1H NMR (500 MHz, $CDCl_3$): δ=0.89 (t, *J*=7.2 Hz, 3H), 1.28–1.35 (m, 2H), 1.53–1.38 (m, 2,), 2.55–2.61 (m, 2H), 6.54 (d, *J*=33.5 Hz, 1H), 7.45–7.48 (m, 2H), 7.61–7.64 (m, 1H), 8.01 ppm (d, *J*=8.0 Hz, 2H); ^{13}C NMR (50 MHz, $CDCl_3$): δ=14.0, 22.2, 28.0, 32.4 (d, *J*=23 Hz), 75.0 (d, *J*=22 Hz), 112.2, 132.8, 133.2, 135.8, 174.6 ppm (d, *J*=277 Hz); ^{19}F NMR (470 MHz, $CDCl_3$): δ=−63.7 ppm (dt, $^3J_{F-H(olefin)}$=31.5 Hz, $^3J_{F-H}$=18.8 Hz, 1F); HRMS *m*/*z* calcd for $C_{12}H_{15}FI$ 305.0197, found 305.0197.

*4.4.2. (Z)-2-Fluorohex-1-enyl(phenyl)iodonium tosylate (**2b**).* The title compound was prepared according to the general procedure from hexynyl(phenyl)iodonium tosylate **1b** (456 mg, 1 mmol). Purification by chromatography on silica gel yielded compound **2b** as a white solid (102 mg, 43%). ^1H NMR (500 MHz, $CDCl_3$): δ=0.84 (t, *J*=7.2 Hz, 3H), 1.21–1.43 (m, 4H), 2.33 (s, 3H), 2.34–2.48 (m, 2H), 6.50 (d, *J*=35.0 Hz, 1H), 7.08 (d, *J*=8.0 Hz, 2H), 7.30–7.38 (m, 2H), 7.48–7.58 (m, 3H), 8.00 ppm (d, *J*=8.0 Hz, 2H); ^{13}C NMR (50 MHz, $CDCl_3$): δ=14.0, 21.9, 22.4, 28.0, 32.4 (d, *J*=23 Hz), 77.2 (d, *J*=22 Hz), 115.2, 126.5, 129.2, 131.9, 132.0, 135.8, 140.3, 142.9, 174.6 ppm (d, *J*=277 Hz); ^{19}F NMR (470 MHz, $CDCl_3$): δ=−67.8 ppm (dt, $^3J_{F-H(olefin)}$=32.9 Hz, $^3J_{F-H}$=16.9 Hz, 1F); HRMS *m*/*z* calcd for $C_{12}H_{15}FI$ 305.0197, found 305.0198.

*4.4.3. (Z)-(2-Fluoro-4-phenylbut-1-enyl)(phenyl)iodonium tetrafluoroborate (**2f**).* The title compound was prepared according to the general procedure from phenyl(4-phenylbut-1-ynyl)iodonium tetrafluoroborate **1f** (424 mg, 1 mmol). Purification by chromatography on silica gel led to compound **2f** as a brown solid (134 mg, 61%). ^1H NMR (200 MHz, $CDCl_3$): δ=2.91–2.99 (m, 4H), 6.47 (d, $^1J_{H-F}$=37.0 Hz, 1H), 7.13–7.30 (m, 6H), 7.41–7.48 (m, 2H), 7.59–7.66 (m, 1H), 7.88 ppm (d, *J*=7.8 Hz, 1H); ^{13}C NMR (50 MHz, $CDCl_3$): δ=31.9, 34.3 (d, *J*=23 Hz), 79.0 (d, *J*=22 Hz), 111.8, 127.3, 129.1, 129.3, 132.8, 133.1, 135.6, 139.1, 173.2 ppm (d, *J*=278 Hz); ^{19}F NMR (470 MHz, $CDCl_3$): δ=−64.8 ppm (dt, $^3J_{F-H(olefin)}$=32.9 Hz, $^3J_{F-H}$=18.8 Hz, 1F); HRMS *m*/*z* calcd for $C_{16}H_{15}FI$ 353.0197, found 353.0195.

*4.4.4. (Z)-(2-Fluoro-2-phenylvinyl)(phenyl)iodonium tosylate (**2g**).* The title compound was prepared according to the general procedure from phenyl(phenylethynyl)iodonium tosylate **1g** (476 mg, 1 mmol). Purification by chromatography on silica gel led to compound **2g** as a white solid (77 mg, 31%). ^1H NMR (200 MHz, $CDCl_3$): δ=2.30 (s, 3H), 7.13 (d, *J*=8.0 Hz, 2H), 7.49 (d, *J*=8.0 Hz, 2H), 7.55–7.80 (m, 7H), 7.96 (d, $^1J_{H-F}$=37.0 Hz, 1H), 8.18 ppm (d, *J*=7.4 Hz, 2H); ^{13}C NMR (50 MHz, $CDCl_3$): δ=21.8, 79.0 (d, *J*=22 Hz), 115.6, 126.5, 126.8, 126.9, 128.6 (d, *J*=27 Hz), 129.2, 129.4, 132.0, 132.6, 135.9, 140.2, 142.8, 165.4 ppm (d, *J*=260.4 Hz); ^{19}F NMR (470 MHz, $CDCl_3$): δ=−82.4 ppm (d, $^3J_{F-H(olefin)}$=35.7 Hz, 1F); HRMS *m*/*z* calcd for $C_{14}H_{11}FI$ 324.9884, found 324.9883.

4.5. General procedure for the preparation of fluorovinyl products (3c–g)

*4.5.1. Reduction of isolated alkenyliodonium salts (**2a**–**g**) using $NaBH_4$.* To a stirred solution of the fluoroalkenyliodonium salt **2c**–**g** (1 mmol, 1 equiv) in MeOH (10 mL) at room temperature was added $NaBH_4$ (76 mg, 2 equiv) in small portions, and the mixture was reflux for 1 h. After cooling to room temperature, water was added (5 mL), and the mixture was further stirred 10 min, and extracted with CH_2Cl_2 (3×30 mL). The combined organic layers were dried over $MgSO_4$ and concentrated under reduced pressure to yield the corresponding fluorovinyl compound **3c**–**f**. Compounds **3c** and **3d** were revealed on TLC using a $KMnO_4$ solution and were purified by preparative TLC (petroleum ether 100%). ^1H and ^{13}C NMR of 1-(1-fluorovinyl)benzene **3e** matched the literature spectral data.[26]

*4.5.2. (2-Fluoroallyl)cyclohexane (**3c**).* Yield, 51%; ^1H NMR (200 MHz, $CDCl_3$): δ=0.74–1.33 (m, 6H), 1.47–1.56 (m, 5H), 2.03–2.16 (dd, $^2J_{H-F}$=20.0 Hz, *J*=7.0 Hz, 2H), 4.22 (dd, $^2J_{H-F}$=50.0 Hz, *J*=2.5 Hz, 1H), 4.55 ppm (dd, $^2J_{H-F}$=18.0 Hz, *J*=2.5 Hz, 1H); ^{13}C NMR (50 MHz, $CDCl_3$): δ=26.7, 26.9, 30.3, 33.5, 35.4, 41.3 (d, *J*=26 Hz), 91.0 (d, *J*=21 Hz), 167.9 ppm (d, *J*=255 Hz); ^{19}F NMR (470 MHz, $CDCl_3$): δ=−94.1 ppm (dtd, $^3J_{F-Htrans(olefin)}$=50.3 Hz, $^3J_{F-H}$=19.2 Hz, $^3J_{F-Hcis(olefin)}$=18.8 Hz, 1F); IR: ν=2921, 2852, 1460, 1012, 795 cm^{-1}; HRMS *m*/*z* calcd for $C_9H_{15}F$ 142.1158, found 142.1158.

*4.5.3. 2-Fluoro-dodec-1-ene (**3d**).* Yield, 86%; ^1H NMR (200 MHz, $CDCl_3$): δ=0.88 (t, *J*=7.1 Hz, 3H), 1.19–1.63 (m, 16H), 2.13–2.28 (m, 2H), 4.24 (dd, $^2J_{H-F}$=51.0 Hz, *J*=2.5 Hz, 1H), 4.52 ppm (dd, $^2J_{H-F}$=18.0 Hz, *J*=2.5 Hz, 1H); ^{13}C NMR (50 MHz, $CDCl_3$): δ=14.5, 23.0, 26.3, 26.4, 29.3, 29.7, 29.9, 30.0, 32.2 (d, *J*=27 Hz), 32.3, 89.6 (d, *J*=21 Hz), 167.5 ppm (d, *J*=256 Hz); ^{19}F NMR (470 MHz, $CDCl_3$): δ=−94.6 ppm (dq, $^3J_{F-Htrans(olefin)}$=50.6 Hz, $^3J_{F-H}$=$^3J_{F-Hcis(olefin)}$=16.6 Hz, 1F); IR: ν=2961, 2852, 1258, 1014, 793 cm^{-1}; HRMS *m*/*z* calcd for $C_{12}H_{23}F$ 186.0845, found 186.0847.

*4.5.4. 1-(1-Fluorovinyl)benzene (**3e**).* The title compound was prepared according to the general procedure described above. The purification of the crude product by chromatography on silica gel C-18 (gradient of CH_3CN/H_2O 1:1 to CH_3CN/H_2O 1:0) led to **3e** in 67% yield.

*4.5.5. 1-(3-Fluorobut-3-enyl)benzene (**3f**).* Yield, 87%; ^1H NMR (200 MHz, $CDCl_3$): δ=2.46–2.62 (m, 2H), 2.48–2.92 (m, 2H), 4.45 (dd, $^2J_{H-F}$=50.0 Hz, *J*=2.5 Hz, 1H), 4.61 (dd, $^2J_{H-F}$=18.0 Hz, *J*=2.5 Hz,

1H), 7.22–7.33 (m, 3H), 7.47–7.55 ppm (m, 2H); ^{13}C NMR (50 MHz, $CDCl_3$): δ=32.9, 34.4 (d, J=27 Hz), 90.4 (d, J=20 Hz), 126.8, 128.9, 129.1, 141.2, 166.5 ppm (d, J=255 Hz); ^{19}F NMR (470 MHz, $CDCl_3$): δ=−95.5 ppm (dq, $^3J_{F-H(olefin)}$=49.8 Hz, $^3J_{F-H}$=$^3J_{F-Hcis(olefin)}$=17.4 Hz, 1F,); IR: ν=2922, 2852,1460, 1258, 1017, 861, 795 cm^{-1}; HRMS m/z calcd for $C_{10}H_{11}F$ 150.0845, found 150.0844.

4.6. One-pot preparation of fluorovinyl products (3d–f)

Alkynyliodonium salt (**1d**, **1e** or **1f**) (1 mmol, 1 equiv) and CsF (0.5 equiv) were dissolved in MeOH (10 mL) and the mixture was refluxed for 1 h. $NaBH_4$ (2 equiv) was then added in small portions, and the solution was further reflux for an additional hour. The resulting solution was cooled at room temperature and hydrolyzed with water and was extracted with CH_2Cl_2 (3×30 mL). The combined organic layers were dried over $MgSO_4$, concentrated under reduced pressure to yield the corresponding compound **3d**–**f**, which were purified by preparative TLC (petroleum ether 100%).

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Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2011.03.043. These data include MOL files and InChiKeys of the most important compounds described in this article. These data include MOL files and InChIKeys of the most important compounds described in this article.

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