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Cu(I)-catalyzed coupling reactions of fluorinated imidoyl halides with terminal alkynes: Convenient synthesis of fluorinated alkynyl imines

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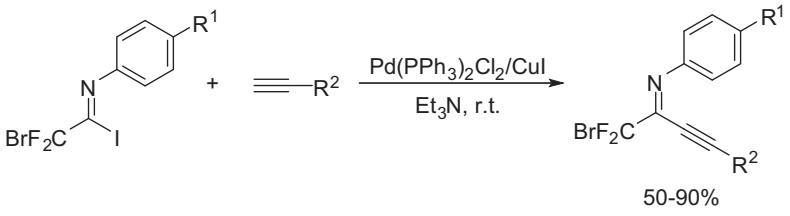
ABSTRACT

The first example of coupling reactions of fluorinated imidoyl halides with terminal alkynes catalyzed by CuI is presented. Each reaction needed no ligand, and fluorinated alkynyl imines were obtained with excellent yields.

1. Introduction

Alkynyl imines are versatile intermediates, which are used to synthesize many different kinds of heterocycles, such as pyrroles [1], quinolines [2], pyridines [3], and others [4]. Furthermore, they can also react with conjugated diene to give bicyclic compounds [5] (Scheme 1).

Up to now, many procedures have been developed to construct the skeleton of alkynyl imines, such as the reactions of alkynes with isonitriles, amides, or others [6]. Among them, the most useful method is the cross coupling reaction of imidoyl halides with terminal alkynes catalyzed by $Pd(PPh_3)_2Cl_2$ and CuI system [7]. Recently, synthetic and medicinal chemists have been paying more and more attention to fluorinated compounds because of the unique physical and biological properties imparted by fluorine [8]. In search for new CF_2-containing reactive synthetic intermediates, our group has focused developing new methods for the synthesis of $BrCF_2$-containing compounds from bromodifluoroacetimidoyl halides [9]. Several years ago, we reported a method for synthesis of fluorinated alkynyl imines via coupling reaction of bromodifluoroacetimidoyl iodide with terminal alkynes catalyzed by Pd/Cu system (Eq. (1)) [10]. Herein, we wish to present the result of our further study on this reaction which shows that the transformation can be completed by Cu(I) salt catalyst only.



(1)

2. Results and discussion

It is reported that terminal alkynes can react with aryl halides in the presence of some Lewis acids [11–13]. Therefore, $ZnBr_2$, and CuI were tested in this transformation. Extensive research indicated that when CuI was used as catalyst, K_3PO_4 as base,

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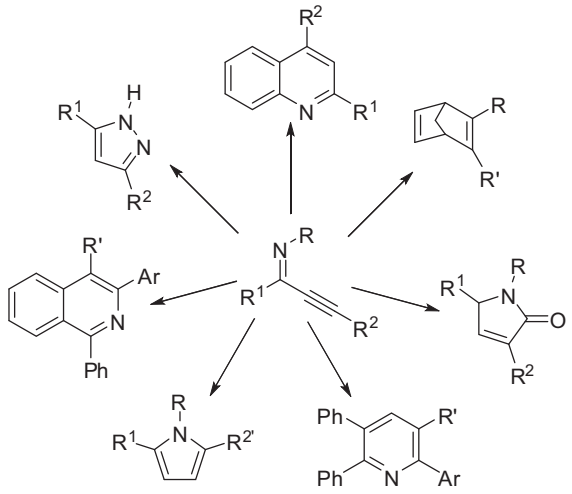


Scheme 1. Heterocycles that synthesized from alkynyl imines.

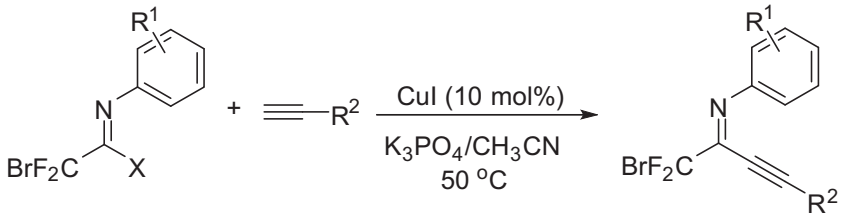
and CH_3CN as solvent, fluorinated alkynyl imines could be obtained with excellent yields at 50 °C.

Next the scope and generality of this reaction are surveyed with different bromodifluoroacetimidoyl halides and terminal alkynes, and the results are listed in Table 1. Most of the imidoyl halides reacted with terminal alkynes smoothly to give the desired products in good to excellent yields. A variety of imidoyl halides with different substituents on the benzene ring were employed in this transformation. Electron-donating groups (Table 1, Entries 2, 4, 5, 7, 9, 15, 16, 19, and 21) or weak electron-withdrawing groups (Table 1, Entries 3, 6, 8, 10, 11, 12, 14, 17, 18, 19, 20, and 22) on the benzene ring of imidoyl halides were compatible with the former giving better yields. But in the case of imidoyl halides with strong electron-withdrawing groups (NO_2, F, and CF_3) on the benzene ring, the imidoyl chlorides shall be used as starting materials, since the corresponding imidoyl iodides is not stable in this reaction system, in such case, stoichiometric amount of CuI is needed (Table 1, Entries 3, 6, 8, 12, 18, and 20). The effect of terminal alkynes was also examined. It was found that phenylacetylene had the strongest reactivity, while 1-hexyne had less in this transformation. It is interesting to note that when ethylnyltrimethylsilane was used as alkyne substrate, N,N′-(1,6-dibromo-1,1,6,6-tetrafluorhex-3-yne-2,5-diylidene) dianiline was obtained as sole product. In this case, the trimethylsilyl group in the preliminary product of alkynyl imine was desilylated by K_3PO_4 and formed a new terminal alkyne which was subjected to the reaction with another equivalent of imidoyl halide.

The reaction was applied to the synthesis of trifluoromethylated alkynyl imines. Compared with bromodifluoromethylated imidoyl halides, the corresponding trifluoromethylated imidoyl halides showed weaker reactivity, and stoichiometric amount of CuI was needed (Table 2).

There are two possible routes to form alkynyl imines from imidoyl halides and terminal alkynes. The first one is the so-called addition–elimination pathway. In such case, copper alkynide attacks imidoyl halides followed by elimination of chloride anion to form the final product. A controlled experiment indicated that, complex results were obtained when NaH was used as base to produce alkynide which was allowed to react with imidoyl halides

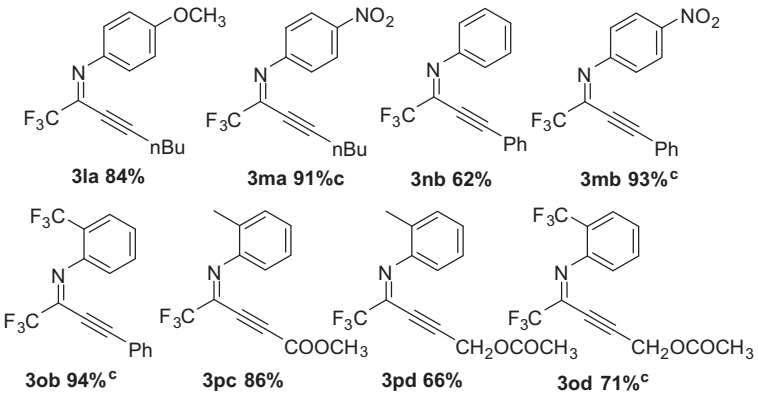
Table 1
The CuI-catalyzed coupling reaction of fluorinated imidoyl halides with terminal alkynes[a].



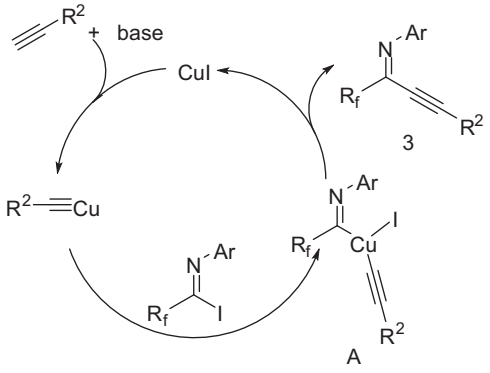
Entry	R^1	R^2	X	Product/yield (%)[b]
1	H	n-Bu	I	**3aa**/90.9
2	*p*-CH_3		I	**3ba**/93.1
3	*p*-NO_2		Cl[c]	**3ca**/86.4
4	*o*-CH_3		I	**3da**/73.1
5	*m*-CH_3		I	**3ea**/75.3
6	3,4-2F		Cl[c]	**3fa**/71.6
7	*p*-OCH_3	Ph	I	**3gb**/100.0
8	P–NO_2		Cl[c]	**3cb**/90.6
9	*m*-CH_3		I	**3eb**/98.1
10	*o*-Br		I	**3hb**/96.5
11	*m*-Cl		I	**3ib**/98.4
12	*p*-CF_3		Cl[c]	**3jb**/98.2
13	H	$COOCH_3$	I	**3ac**/87.6
14	P–Cl		I	**3kc**/90.7
15	*m*-CH_3		I	**3ec**/93.2
16	*p*-CH_3	CH_2OCOCH_3	I	**3bd**/93.4
17	*p*-Cl		I	**3kd**/85.5
18	P–NO_2		Cl[c]	**3cd**/80.1
19	*m*-Cl		I	**3id**/61.4
20	*p*-CF_3		Cl[c]	**3jd**/73.8
21	*p*-CH_3	$Si(CH_3)_3$	I	**3be**/83.1[d]
22	*p*-Cl		I	**3ke**/90.4[d]

[a] Reaction conditions: fluorinated imidoyl halides (1.0 mmol), alkynes (1.2 mmol), CuI (10 mol%), K_3PO_4 (1.2 mmol), CH_3CN (3.0 ml), T = 50 °C.
[b] Isolated yields.
[c] CuI (1.0 equiv).
[d] The production is N,N′-(1,1′-dibromo-1,1′,6,6′-tetrafluorhex-3-yne-2,5-diylidene)dianiline.

Table 2
Synthesis of trifluoromethylated alkynyl imines[a,b].



[a]Reaction conditions: fluorinated imidoyl halides (1.0 mmol), alkynes (1.2 mmol), CuI (10 mol%), K_3PO_4 (1.2 mmol), CH_3CN (3.0 ml), $T = 50\ ^\circ C$.
[b]Isolated yields.
[c]CuI (1.0 equiv).



Scheme 2. Proposed mechanism for the coupling reaction.

under the same conditions. Only after cooling the mixture to 0 °C, the alkynyl imine was obtained in low yield. This result rules out the possibility of the addition-elimination mechanism. The other route is an oxidative addition-reductive elimination process as shown in Scheme 2. Copper alkynide firstly inserted to C–I bond of imidoyl iodide by oxidant addition to form intermediate A. After reductive elimination, alkynyl imine 3 was formed (Scheme 2).

3. Conclusion

In conclusion, we have demonstrated that CuI is able to catalyze the coupling reaction of fluorinated imidoyl halides with terminal alkynes in the absence of Pd complex [14]. A novel, general, and efficient method for the synthesis of fluorinated alkynyl imines has been developed, which offers a new way for the synthesis of fluorinated compounds.

4. Experimental

4.1. General

^1H NMR spectra were recorded in $CDCl_3$ on a Bruker AM-300 spectrometer (300 MHz) with TMS as internal standard. ^{19}F NMR spectra were taken on a Bruker AM-300 (282 MHz) spectrometer using $CFCl_3$ as external standard. ^{13}C NMR spectra were taken a Bruker AM-400 (100 MHz) spectrometer. IR spectra were obtained with a Nicolet AV-360 spectrophotometer. Elemental analysis was performed by the Analytical Laboratory of Shanghai Institute of Organic Chemistry. Mass spectra were recorded by EI methods. Solvents were purchased from commercial sources and purified before used by standard procedures. Unless otherwise specified, all reactions were carried out under nitrogen in a Schlenk tube and magnetic stirring. TLC analysis was performed on silica gel plates, Flash column chromatography was carried out using 300–400 mesh silica gel at increased pressure and petroleum ether/ethyl acetate combination was used as the eluent.

4.2. Typical procedure for the synthesis of fluorinated alkynyl imines

Under N_2, CuI (20 mg, 0.1 mmol), K_3PO_4 (254 mg, 1.2 mmol), CH_3CN (3.5 mL), imidoyl halides (1.0 mmol), and terminal alkynes (1.2 mmol) were added to a Schenk tube successively. Then the mixture was stirred at 50 °C. The reaction was monitored by TLC until the corresponding spot of imidoyl halide was no longer observable. When the reaction completed, the solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica gel to give the desired products.

4.3. Spectroscopic data of fluorinated alkynyl imines

N-(1-bromo-1,1-difluorooct-3-yn-2-ylidene) aniline (**3aa**) [10]. Yellow oil; ^1H NMR (300 Hz, $CDCl_3$): δ 7.41–7.36 (m, 3H), 7.26–7.17 (m, 2H), 2.35 (t, J = 6.9 Hz, 2H), 1.50–1.43 (m, 2H), 1.34–1.27 (m, 2H), 0.89–0.84 (t, J = 7.2 Hz, 3H). ^{19}F NMR (282 Hz, $CDCl_3$): δ −55.10 (s). MS (EI) m/z (%): 313 (M^+, 10.28), 184 (100).

N-(1-bromo-1,1-difluorooct-3-yn-2-ylidene)-4-methylaniline (**3ba**) [10]. Yellow oil; ^1H NMR (300 Hz, $CDCl_3$): δ 7.11 (s, 4H), 2.32–2.27 (m, 5H), 1.46–1.41 (m, 2H), 1.31–1.23 (m, 2H), 0.88 (t, J = 7.2 Hz, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −54.26 (s); MS (EI) m/z (%): 327 (M^+, 10), 198 (100).

N-(1-bromo-1,1-difluorooct-3-yn-2-ylidene)-4-nitroaniline (**3ca**) [10]. Brown oil; ^1H NMR (300 Hz, $CDCl_3$): δ 8.20 (d, J = 9.0 Hz, 2H), 7.09 (d, J = 9.0 Hz, 2H), 2.30–2.25 (t, J = 6.8 Hz, 2H), 1.40–1.35 (m, 2H), 1.22–1.14 (m, 2H), 0.76 (t, J = 7.4 Hz, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −56.16 (s); MS (EI) m/z (%): 358 (M^+, 3), 229 (100).

N-(1-bromo-1,1-difluorooct-3-yn-2-ylidene)-2-methylaniline (**3da**). Yellow oil; ^1H NMR (300 Hz, $CDCl_3$): δ 7.23–7.10 (m, 3H), 6.98 (dd, J_1 = 7.8 Hz, J_2 = 1.5 Hz, 1H), 2.30 (t, J = 6.0 Hz, 2H), 2.19 (s,

J = 7.2 Hz, 3H), 1.45–1.37 (m, 2H), 1.29–1.21 (m, 2H), 0.83 (t, J = 7.4 Hz, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −54.52 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 147.5, 145.7 (t, $J_{C,F}$ = 27.9 Hz), 131.3, 130.7, 127.1, 126.7, 119.1, 116.0 (t, $J_{C,F}$ = 306.5 Hz), 104.9, 71.6, 30.3, 22.5, 20.0, 18.4, 14.3; MS (EI) m/z (%): 329 (M^+, 8), 198 (100); IR (neat, cm^{-1}): 2960, 2213, 1620, 1484, 1461, 1450, 1228, 1156, 1130, 888, 821, 764; HRMS: Calc. for $C_{15}H_{16}NF_2{}^{79}Br$: 327.0431. Found: 327.0434.

N-(1-bromo-1,1-difluorooct-3-yn-2-ylidene)-3-methylaniline (**3ea**). Yellow oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.26 (m, 1H), 7.03 (m, 3H), 2.40–2.32 (m, 5H), 1.50–1.43 (m, 2H), 1.35–1.27 (m, 2H), 0.86 (t, J = 7.1 Hz, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −54.54 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 148.2, 145.1 (t, $J_{C,F}$ = 27.7 Hz), 139.4, 129.4, 128.5, 122.5, 118.8, 116.2 (t, $J_{C,F}$ = 306.5 Hz), 104.8, 71.9, 30.3, 22.6, 22.2, 20.0, 14.3; MS (EI) m/z (%): 327 (M^+, 6), 198 (100); IR (neat, cm^{-1}): 2960, 2212, 1599, 1483, 1464, 1253, 1158, 1116, 835, 785; HRMS: Calc. for $C_{15}H_{16}NF_2{}^{81}Br$: 329.0418. Found: 3290414.

N-(1-bromo-1,1-difluorooct-3-yn-2-ylidene)-3,4-difluoroaniline (**3fa**) [10]. Yellow oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.23–7.12 (m, 2H), 7.01–7.69 (m, 1H), 2.41 (t, J = 7.2 Hz, 2H), 1.58–1.48 (m, 2H), 1.39–1.26 (m, 2H), 0.92–0.87 (t, J = 7.2 Hz, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −55.41 (s), −136.75–136.60 (m, 1F), −138.56–139.45 (m, 1F); MS (EI) m/z (%): 349 (M^+, 5), 220 (100).

N-(1-bromo-1,1-difluoro-4-phenylbut-3-yn-2-ylidene)-4-methoxyaniline (**3gb**) [10]. Yellow oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.56–7.48 (m, 4H), 7.46–7.26 (m, 3H), 6.96 (d, J = 8.70 Hz, 2H), 3.86 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −53.736 (s); MS (EI) m/z (%): 363 (M^+, 7), 234 (100); IR (neat, cm^{-1}): 3060, 2927, 2196, 1613, 1574, 1504, 1378, 1254, 1033, 839; Anal: Calc. for $C_{17}H_{12}BrF_2NO$: C, 56.07; H, 3.32; N, 3.84. Found: C, 50.17; H, 3.58; N, 3.71.

N-(1-bromo-1,1-difluoro-4-phenylbut-3-yn-2-ylidene)-4-nitroaniline (**3cb**) [10]. Yellow solid; ^{1}H NMR (300 Hz, $CDCl_3$): δ 8.26–8.23 (d, J = 8.7 Hz, 2H), 7.41–7.35 (m, 1H), 7.29–7.28 (m, 4H), 7.22–7.20 (d, J = 8.7 Hz, 2H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −55.22 (s); MS (EI) m/z (%): 378 (M^+, 1), 249(100).

N-(1-bromo-1,1-difluoro-4-phenylbut-3-yn-2-ylidene)-3-methylaniline (**3eb**). Yellow oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.42–7.31 (m, 6H), 7.14–7.09 (m, 3H), 2.39 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −54.14 (s). ^{13}C NMR (100 Hz, $CDCl_3$): δ 146.6, 144.5 (t, $J_{C,F}$ = 28.3 Hz), 132.7, 130.9, 130.8, 130.6, 128.6, 126.8, 125.9, 120.1, 118.5, 115.2 (t, $J_{C,F}$ = 306.7 Hz), 100.5, 78.7, 17.7; MS (EI) m/z (%): 349 (M^+, 7.5), 218 (100); IR (neat, cm^{-1}): 3061, 2923, 2195, 1593, 1488, 1444, 1137, 1062, 939, 891, 816, 756, 687; HRMS: Calc. for $C_{17}H_{12}NF_2Br$: 347.0118. Found: 347.0121.

N-(1-bromo-1,1-difluoro-4-phenylbut-3-yn-2-ylidene)-2-bromoaniline (**3hb**). Yellow oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.57 (d, J = 8.7 Hz, 1H), 7.35–7.23 (m, 6H), 7.06–7.02 (m, 2H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −55.15 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 146.8, 147.0 (t, $J_{C,F}$ = 28.7 Hz), 133.2, 132.8, 131.1, 128.7, 127.6, 127.5, 120.2, 119.7, 115.7, 114.6 (t, $J_{C,F}$ = 306.7 Hz), 102.0, 78.3; MS (EI) m/z (%): 413 (M^+, 9.7), 282 (100); IR (neat, cm^{-1}): 3062, 2200, 1615, 1593, 1498, 1464, 1443, 1146, 1067, 916, 754; HRMS: Calc. for $C1_6H_9NF_2{}^{81}Br_2$: 414.9025. Found: 414.9029.

N-(1-bromo-1,1-difluoro-4-phenylbut-3-yn-2-ylidene)-3-chloroaniline (**3ib**). Yellow oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.37–7.06 (m, 9H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −54.97 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 148.6, 145.4 (t, $J_{C,F}$ = 28.6 Hz), 134.4, 132.8, 131.1, 130.6, 128.7, 127.1, 121.2, 119.9, 119.7, 114.9 (t, $J_{C,F}$ = 306.9 Hz), 101.7, 78.5; MS (EI) m/z (%): 367 (M^+, 3.2), 238 (100); IR (neat, cm^{-1}): 3064, 2202, 1614, 1585, 1489, 1469, 1145, 1063, 923, 756, 686; HRMS: Calc. for $C_{16}H_9NClF_2Br$: 366.9573. Found: 366. 9575.

N-(1-bromo-1,1-difluoro-4-phenylbut-3-yn-2-ylidene)-4-trifluoromethylaniline (**3jb**). Yellow oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.70 (d, J = 7.8 Hz, 2H), 7.46–7.41 (m, 2H), 7.36–7.34 (m, 3H), 7.30 (d, J = 7.8 Hz, 2H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −55.01 (s, 2F), −62.16 (s, 3F); ^{13}C NMR (100 Hz, $CDCl_3$): δ 146.5, 142.0 (t, $J_{C,F}$ = 28.3 Hz), 128.6, 127.0, 124.3, 121.9, 122.6 (q, $J_{C,F}$ = 270.4 Hz), 116.8, 115.3, 110.4 (t, $J_{C,F}$ = 306.5 Hz), 97.7, 74.0; MS (EI) m/z (%): 401 (M^+, 2.7), 272 (100); IR (neat, cm^{-1}): 2200, 1606, 1593, 1485, 1440, 1324, 1128, 1065, 918, 859, 757, 687; HRMS: Calc. for $C_{17}H_9NF_5{}^{81}Br$: 402.9822. Found: 402.9818.

Methyl 5-bromo-5,5-difluoro-4-(phenylimino)pent-2-ynoate (**3ac**) [10]. Brown oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.37–7.34 (m, 2H), 7.30–7.19 (m, 3H), 3.74 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −55.06 (s); MS (EI) m/z (%): 315 (M^+, 4), 77 (100).

Methyl 5-bromo-5,5-difluoro-4-(4-chlorophenylimino)pent-2-ynoate (**3kc**) [10]. Brown oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.36 (d, J = 9.0 Hz, 2H), 7.17 (d, J = 9.0 Hz, 2H), 3.77 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −55.22 (s); MS (EI) m/z (%): 349 (M^+, 9), 220 (100).

Methyl 5-bromo-5,5-difluoro-4-(m-tolylimino)pent-2-ynoate (**3ec**). Brown oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.21–7.13 (m, 3H), 7.02–6.99 (m, 1H), 3.72 (s, 3H), 2.18 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −54.37 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 152.2, 145.0, 140.9 (t, $J_{C,F}$ = 29.3 Hz), 131.8, 130.9, 128.3, 126.3, 117.9, 114.2 (t, $J_{C,F}$ = 306.6 Hz), 87.0, 72.4, 53.5, 17.7; MS (EI) m/z (%): 329 (M^+, 12.6), 200 (100); IR (neat, cm^{-1}): 2956, 1728, 1577, 1485, 1436, 1230, 1141, 1090, 754; HRMS: Calc. for $C_{13}H_{10}NF_2O_2Br$: 328.9868. Found: 328.9863.

5-Bromo-5,5-difluoro-4-(p-tolylimino)pent-2-ynyl acetate (**3bd**). Yellow oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.13 (s, 4H), 4.72 (s, 2H), 2.30 (s, 3H), 2.01 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −54.56 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 169.8, 143.9, 141.6 (t, $J_{C,F}$ = 28.3 Hz), 138.2, 129.5, 121.9, 114.5 (t, $J_{C,F}$ = 306.6 Hz), 94.5, 75.7, 51.7, 21.2, 20.4; MS (EI) m/z (%): 343 (M^+, 9.9), 214 (100); IR (neat, cm^{-1}): 2923, 2212, 1753, 1617, 1571, 1504, 1428, 1377, 1221, 1151, 1114, 1035, 881, 826; HRMS: Calc. for $C_{14}H_{12}NO_2F_2{}^{79}Br$: 343.0017. Found: 343.0019.

5-Bromo-5,5-difluoro-4-(4-chlorophenylimino)pent-2-ynyl acetate (**3kd**). Yellow oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.29 (d, J = 8.4 Hz, 2H), 7.11 (d, J = 8.4 Hz, 2H), 4.71 (s, 2H), 2.01 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −55.16 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 169.7, 145.1, 143.4 (t, $J_{C,F}$ = 28.7 Hz), 133.3, 129.1, 122.8, 114.6 (t, $J_{C,F}$ = 306.8 Hz), 95.7, 75.2, 51.5, 20.4; MS (EI) m/z (%): 365 (M^+, 10.7), 234 (100); IR (neat, cm^{-1}): 2936, 2218, 1751, 1617, 1485, 1377, 1220, 1156, 1116, 1092, 1035, 880, 835, 800; HRMS: Calc. for $C_{13}H_9NO_2ClF_2{}^{79}Br$: 362.9475. Found: 362.9473.

5-Bromo-5,5-difluoro-4-(4-nitrophenylimino)pent-2-ynyl acetate (**3cd**). Yellow solid; ^{1}H NMR (300 Hz, $CDCl_3$): δ 8.21 (d, J = 8.7 Hz, 2H), 7.13 (d, J = 8.7 Hz, 2H), 4.67 (s, 2H), 1.97 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −55.83 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 169.6, 152.6, 145.8 (t, $J_{C,F}$ = 29.0 Hz), 146.2, 124.8, 120.9, 114.2 (t, $J_{C,F}$ = 306.8 Hz), 97.4, 74.5, 51.4, 20.3; MS (EI) m/z (%): 374 (M^+), 43 (100); IR (neat, cm^{-1}): 3103, 2929, 2224, 1753, 1626, 1590, 1520, 1377, 1345, 1222, 1156, 1118, 1036, 884, 859; HRMS: Calc. for $C_{13}H_9N_2O_4F_2{}^{81}Br$: 375.9699. Found: 375.9693.

5-Bromo-5,5-difluoro-4-(3-chlorophenylimino)pent-2-ynyl acetate (**3id**). Yellow oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.29–7.24 (m, 1H), 7.19–7.13 (m, 2H), 7.01–6.98 (m, 1H), 4.71 (s, 2H), 2.01 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −55.17 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 169.7, 147.8, 144.1 (t, $J_{C,F}$ = 28.9 Hz), 134.5, 130.0, 127.3, 120.9, 119.5, 114.4 (t, $J_{C,F}$ = 306.7 Hz), 95.9, 75.0, 51.5, 20.4; MS (EI) m/z (%): 363 (M^+, 2.7), 43 (100); IR (neat, cm^{-1}): 2936, 2224, 1756, 1587, 1570, 1469, 1219, 1157, 1121, 907, 835; HRMS: Calc for $C_{13}H_9NO_2ClF_2{}^{81}Br$: 364.9455. Found: 364.9453.

5-Bromo-5,5-difluoro-4-(4-(trifluoromethyl)phenylimino)-pent-2-ynyl acetate (**3jd**). Yellow oil; ^{1}H NMR (300 Hz, $CDCl_3$): δ 7.67 (d, J = 7.8 Hz, 2H), 7.21 (d, J = 8.4 Hz, 2H), 4.75 (s, 2H), 2.03 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −55.27 (s, 2F), −62.29 (s, 3F); ^{13}C NMR (100 Hz, $CDCl_3$): δ 165.4, 145.8, 140.8 (t, $J_{C,F}$ = 28.2 Hz), 124.7 (q, $J_{C,F}$ = 32.3 Hz), 121.9, 120.0 (q, $J_{C,F}$ = 270.9 Hz), 116.5, 110.0 (t,

$J_{C,F}$ = 306.8 Hz), 92.1, 70.5, 47.2, 16.0; MS (EI) *m*/*z* (%): 397 (M^+, 2.05), 268 (100); IR (neat, cm^{-1}): 2936, 2223, 1754, 1609, 1580, 1325, 1223, 1164, 1125, 1067, 883, 847; HRMS: Calc. for $C_{14}H_9NO_2F_5{}^{81}Br$: 398.9713. Found: 398.9716.

N,N′-(1,6-dibromo-1,1,6,6-tetrafluorhex-3-yne-2,5-diylidene)di(4-methylaniline) (**3be**). Yellow solid; ^1H NMR (300 Hz, $CDCl_3$): δ 7.00 (m, 8H), 2.18 (s, 6H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −53.94 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 143.7, 140.0, 139.8 (t, $J_{C,F}$ = 28.3 Hz), 130.0, 122.6, 114.8 (t, $J_{C,F}$ = 306.6 Hz), 86.1, 21.7. MS (EI) *m*/*z* (%): 518 (M^+, 2.57), 91 (100); IR (neat, cm^{-1}): 2960, 1577, 1502, 1296, 1156, 1096, 929, 819; HRMS: Calc. for $C_{20}H_{14}N_2F_4Br_2$: 515.9464. Found: 515.9460.

N,N′-(1,1-dibromo-1,1,6,6-tetrafluorhex-3-yne-2,5-diylidene)di(4-chloroaniline) (**3ke**). Yellow solid; ^1H NMR (300 Hz, $CDCl_3$): δ 7.28 (d, J = 9.0 Hz, 4H), 7.10 (d, J = 9.0 Hz, 4H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −54.77 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 144.6, 141.4 (t, $J_{C,F}$ = 29.3 Hz), 135.1, 129.7, 123.3, 114.2 (t, $J_{C,F}$ = 307.4 Hz), 85.7; MS (EI) *m*/*z* (%): 558 (M^+, 6.0), 111 (100); IR (neat, cm^{-1}): 1895, 1607, 1574, 1482, 1304, 1175, 1155, 1102, 926, 844; HRMS: Calc. for $C_{18}H_8N_2Cl_2F_4{}^{81}Br_2$: 559.8332. Found: 559.8326.

N-(1,1,1-trifluorooct-3-yn-2-ylidene)-4-methoxylaniline (**3la**). Yellow oil; ^1H NMR (300 Hz, $CDCl_3$): δ 7.43 (d, J = 8.7 Hz, 2H), 6.91 (d, J = 8.7 Hz, 2H), 3.83 (s, 3H), 2.41 (t, J = 7.1 Hz, 2H), 1.57–1.50 (m, 2H), 1.42–1.35 (m, 2H), 0.90 (t, J = 7.4 Hz, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −71.37 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 159.3, 140.0, 136.6 (q, $J_{C,F}$ = 37.2 Hz), 124.3, 118.5 (q, $J_{C,F}$ = 275.4 Hz), 113.8, 103.2, 72.1, 55.4, 29.5, 21.8, 19.2, 13.4; MS (EI) *m*/*z* (%): 283 (M^+, 49.8), 214 (100); IR (neat, cm^{-1}): 2961, 2936, 2211, 1615, 1579, 1504, 1466, 1252, 1195, 1138, 1034, 835; HRMS: Calc. for $C_{15}H_{16}NOF_3$: 283.1182. Found: 283.1184.

N-(1,1,1-trifluorooct-3-yn-2-ylidene)-4-nitroaniline (**3ma**). Yellow oil; ^1H NMR (300 Hz, $CDCl_3$): δ 8.29 (d, J = 8.7 Hz, 2H), 7.19 (d, J = 8.7 Hz, 2H), 2.35 (t, J = 7.1 Hz, 2H), 1.47–1.42 (m, 2H), 1.28–1.21 (m, 2H), 0.83 (t, J = 7.2 Hz, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −72.19 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 147.6, 140.1 (q, $J_{C,F}$ = 38.0 Hz), 128.7, 127.0, 120.9, 118.5 (q, $J_{C,F}$ = 276.2 Hz), 103.8, 71.4, 29.4, 21.7, 19.1, 13.4; MS (EI) *m*/*z* (%): 298 (M^+, 24.2), 229 (100); IR (neat, cm^{-1}): 2962, 2865, 2215, 1626, 1604, 1591, 1523, 1486, 1345, 1202, 1149, 862, 730; HRMS: Calc. for $C_{14}H_{13}N_2O_2F_3$: 298.0917. Found: 298.0929.

N-(1,1,1-trifluoro-4-phenylbut-3-yn-2-ylidene) aniline (**3nb**). Yellow oil; ^1H NMR (300 Hz, $CDCl_3$): δ 7.47–7.30 (m, 10H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −71.44 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 147.6, 139.6 (q, $J_{C,F}$ = 38.7 Hz), 132.7, 130.9, 128.8, 128.7, 127.5, 121.4, 118.5 (q, $J_{C,F}$ = 276.2 Hz), 119.9, 100.0, 79.2; MS (EI) *m*/*z* (%): 273 (M^+, 38.6), 204 (100); IR (neat, cm^{-1}): 3065, 2927, 2209, 1614, 1584, 1489, 1444, 1346, 1258, 1145, 1062, 757, 688; HRMS: Calc. for $C_{16}H_{10}NF_3$: 273.0767. Found: 273.0765.

N-(1,1,1-trifluoro-4-phenylbut-3-yn-2-ylidene)-4-nitroaniline (**3mb**). Yellow oil; ^1H NMR (300 Hz, $CDCl_3$): δ 8.34 (d, J = 8.7 Hz, 2H), 7.49–7.44 (m, 1H), 7.37–7.36 (m, 4H), 7.30 (d, J = 8.7 Hz, 2H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −71.65 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 153.4, 146.0, 142.5 (q, $J_{C,F}$ = 39.4 Hz), 132.9, 131.6, 128.8, 124.8, 121.1, 119.0, 118.0 (q, $J_{C,F}$ = 276.2 Hz), 102.7, 78.3; MS (EI) *m*/*z* (%): 318 (M^+, 36.8), 249 (100); IR (neat, cm^{-1}): 3104, 2201, 1614, 1592, 1508, 1489, 1195, 1145, 1065, 872, 762, 687; HRMS: Calc. for $C_{16}H_9N_2O_2F_3$: 318.0617. Found: 318.0616.

N-(1,1,1-trifluoro-4-phenylbut-3-yn-2-ylidene)-2-(trifluoromethyl) aniline (**3ob**). Yellow oil; ^1H NMR (300 Hz, $CDCl_3$): δ 7.73 (d, J = 7.8 Hz, 1H), 7.59 (t, J = 7.4 Hz, 1H), 7.44–7.27 (m, 6H), 7.13 (d, J = 8.7 Hz, 1H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −60.84 (s, 3F), −71.69 (s, 3F); ^{13}C NMR (100 Hz, $CDCl_3$): δ 142.4, 138.4 (q, $J_{C,F}$ = 39.7 Hz), 128.6, 128.1, 127.0, 124.5, 122.4, 122.0, 118.5 (q, $J_{C,F}$ = 272.2 Hz), 117.3 (q, $J_{C,F}$ = 31.0 Hz), 115.4, 115.1, 112.6, 97.8, 74.3; MS (EI) *m*/*z* (%): 341 (M^+, 27.9), 272 (100); IR (neat, cm^{-1}): 3064, 2194, 1621, 1603, 1582, 1489, 1452, 1319, 1258, 1224, 1155, 1069, 758, 687; HRMS: Calc. for $C_{17}H_9NF_6$: 341.0646. Found: 341.0639.

Methyl 5,5,5-trifluoro-4-(o-tolylimino)pent-2-ynoate (**3pc**). Yellow oil; ^1H NMR (300 Hz, $CDCl_3$): δ 7.26–7.20 (m, 3H), 7.13–7.11 (m, 2H), 3.78 (s, 3H), 2.25 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −70.78 (s); ^{13}C NMR (100 Hz, $CDCl_3$): δ 152.9, 146.1, 137.0 (q, $J_{C,F}$ = 39.5 Hz), 132.8, 131.7, 129.5, 127.1, 118.5 (q, $J_{C,F}$ = 276.1 Hz), 118.8, 87.4, 73.5, 54.3, 18.4; MS (EI) *m*/*z* (%): 269 (M^+, 68.1), 91 (100); IR (neat, cm^{-1}): 3378, 2940, 1731, 1669, 1578, 1461, 1438, 1329, 1253, 1196, 1100, 755; HRMS: Calc. for $C_{13}H_{10}NO_2F_3$: 269.0669. Found: 269.0664.

5,5,5-Trifluoro-4-(o-tolylimino)pent-2-ynyl acetate (**3pd**). Yellow oil; ^1H NMR (300 Hz, $CDCl_3$): δ 7.23 (m, 1H), 7.19–7.16 (m, 2H), 7.05 (m, 1H), 4.72 (s, 2H), 2.21 (s, 3H), 2.04 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −71.33 (s, 3F); ^{13}C NMR (100 Hz, $CDCl_3$): δ 170.5, 146.8, 139.1 (q, $J_{C,F}$ = 38.4 Hz), 131.5, 131.4, 128.2, 126.8, 119.0, 119.5 (q, $J_{C,F}$ = 275.8 Hz), 95.0, 76.5, 52.3, 21.2, 18.3; MS (EI) *m*/*z* (%): 283 (M^+, 64.1), 223 (100); IR (neat, cm^{-1}): 2923, 2224, 1755, 1630, 1485, 1429, 1377, 1333, 1205, 1145, 1035, 951, 767; HRMS: Calc. for $C_{14}H_{12}NO_2F_3$: 283.0818. Found: 283.0820.

5,5,5-Trifluoro-4-(2-(trifluoromethyl)phenylimino)pent-2-ynyl acetate (**3od**). Yellow oil; ^1H NMR (300 Hz, $CDCl_3$): δ 7.71 (d, J = 7.8 Hz, 1H), 7.56 (t, J = 7.7 Hz, 1H), 7.35(t, J = 7.5 Hz, 1H), 7.03 (d, J = 8.1 Hz, 1H), 4.70 (s, 2H), 2.02 (s, 3H); ^{19}F NMR (282 Hz, $CDCl_3$): δ −60.93 (s, 3F), −71.95 (s, 3F); ^{13}C NMR (100 Hz, $CDCl_3$): δ 165.4, 141.5, 137.2 (q, $J_{C,F}$ = 39.3 Hz), 128.2, 122.4, 122.3, 118.5 (q, $J_{C,F}$ = 272.2 Hz), 117.0, 112.5 (q, $J_{C,F}$ = 31.0 Hz), 112.3, 92.0, 70.7, 47.0, 25.5; MS (EI) *m*/*z* (%): 337 (M^+, 15.4), 277 (100); IR (neat, cm^{-1}): 2936, 2226, 1757, 1633, 1603, 1452, 1320, 1208, 1142, 1036, 948, 774; HRMS: Calc. for $C_{14}H_9NO_2F_6$: 337.0536. Found: 337.0537.

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