Journal of Fluorine Chemistry 129 (2008) 695–700

Contents lists available at ScienceDirect

Journal of Fluorine Chemistry

journal homepage: www.elsevier.com/locate/fluor

One-pot preparation of fluorinated propargylamines under microwave irradiation and solvent-free conditions

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ARTICLE INFO

Article history:
Received 14 February 2008
Received in revised form 4 June 2008
Accepted 6 June 2008
Available online 24 June 2008

Keywords:
Fluorinated propargylamines
Microwave
Solvent free
One-pot reaction
Three-component coupling

ABSTRACT

A facile one-pot method has been developed for the synthesis of fluorine-containing propargylamines by a three-component coupling of fluorinated aldehydes, amines, and alkynes, in the presence of copper (I) chloride under microwave irradiation and solvent-free condition. This process is an efficient alternative to traditional thermal reaction. All new compounds are fully characterized by spectral methods.

1. Introduction

The increasing environmental consciousness of the chemical community has led to the search for more efficient and environmentally friendly methods for chemical synthesis. Microwave-promoted reactions, especially those run in water or solvent-free conditions have been attracting increasing research interest from chemists in recent years, not only because these reactions exhibit some particular or unexpected reactivities in some cases but also because they are significantly useful for green chemistry [1]. Since the first report on the use of microwave heating to accelerate organic chemical transformations by the groups of Gedye and Giguere/Majetich [2], thousands of articles have been published in the area of microwave assisted organic synthesis. In our corresponding investigations, we have reported a microwave-promoted synthesis of 2-pentafluorophenylquinoline derivatives [3] and α-aminoalkyl phosphonates [4].

More recently, one-pot multi-component reactions (MCR) as an versatile strategy in organic synthesis have received much attention, for example, the three-component coupling of the aldehyde, the alkyne and the amine (A^3 coupling) [5] gave propargylamines, which are important synthetic intermediates for potential therapeutic agents and polyfunctional amino derivatives [6]. This A^3 coupling reaction can be catalyzed by several transition metal catalysts via C–H activation. such as, silver salts [7], gold salts [8], and copper salts [9]. Also a variety of chiral ligands have been used in this reaction to gain high asymmetric induction [10]. However, these procedures require a long reaction time (4–24 h), and some of these catalysts are expensive. Recently, an ultrasound-promoted three-component reaction for the preparation of propargylamines using CuI as the catalyst was reported by Sreedhar [11b], the reaction time was shorted to 45–75 min. To our best knowledge, the preparation of fluorine-containing propargylamines has been studied rarely.

As a part of our work on the microwave-promoted reactions in organic synthesis, we describe a fast and efficient one-pot procedure for the synthesis of fluorinated propargylamines under microwave irradiation and solvent-free conditions.

2. Results and discussion

The microwave-promoted three components coupling experiment was performed by irradiation of a mixture of aldehydes, amines, and alkynes in the presence of CuCl (30 mol%) in a sealed tube to afford the desired propargylamines in 2–15 min (Scheme 1).

Initially, different reaction conditions were screened and the coupling of pentafluorophenylaldehyde (**1d**), *p*-fluoroaniline (**2e**) and phenylacetylene (**3**) was selected as model reaction (Table 1).

It was found that the molar ratio of aldehyde:amine:alkyne = 1:1.2:1.5 was the best reaction ratio. Even when 2 equiv. of

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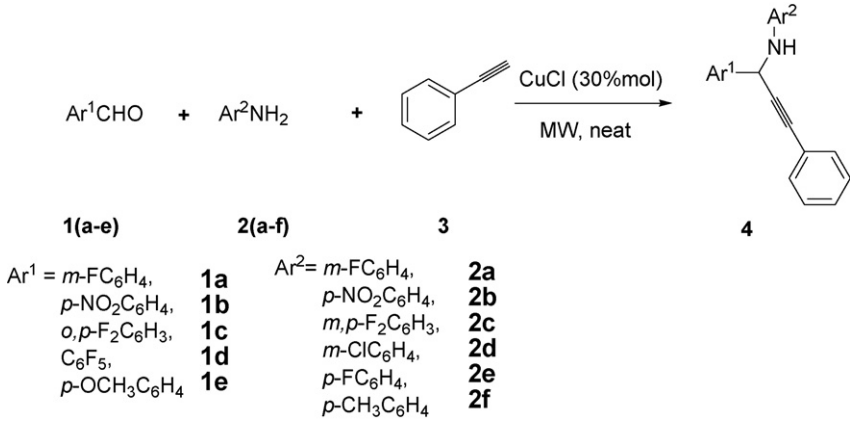
doi:10.1016/j.jfluchem.2008.06.015



Scheme 1. Synthesis of the fluorinated propargylamines.

Table 1
The reaction of *m*-fluorobenzaldehyde (**1a**), *p*-fluoroaniline (**2e**) and phenylacetylene

Entry	Mole ratio			Catalyst	Atmosphere	Microwave power (W)	Time (min)	Solvent	Yield (%)
	1a	**2e**	**3**						
1	1	1	1	CuCl	–	800	14	–	Trace
2	1	1	1	CuI	N_2	800	14	–	20
3	1	1.2	1	CuCl	N_2	800	14	–	30
4	1	1.2	1.5	CuCl	N_2	800	14	–	56
5	1	1.2	2	CuCl	N_2	800	14	–	50
6	1	1.2	1.5	CuI	N_2	800	14	–	55
7	1	1.2	1.5	CuCl	N_2	300	30	–	Trace
8	1	1.2	1.5	CuCl	N_2	400	30	–	10
9	1	1.2	1.5	CuCl	N_2	450	30	–	30
10	1	1.2	1.5	CuCl	N_2	800	30	Toluene	30
11	1	1.2	1.5	CuCl	N_2	800	30	DMF	25
12	1	1.2	1.5	CuCl	N_2	800	30	H_2O	Trace

the alkynes were used in the reaction, the reaction intermediate product imines ($Ar^1CH{=}NAr^2$) were not completely consumed (as monitored by TLC). On the basis of some literature reports, alkynes could come into small amount of oligomerization in the presence of metal catalyst [12]. Thus, more excess alkynes did not increase the yield of product (Table 1 entry 5). Additionally, in our experiment a sealed tube was necessary for this reaction; Otherwise, a low conversion and more by-products were observed. Some A^3 coupling reactions proceeded very well either in water [11b] or in an organic solvent such as toluene [9d] and DMF [7]. However, in our case when the reaction was carried out in toluene (30%), DMF (25%) or in water (trace) gave low yield product. We found a solvent-free condition offered a fine outcome. The catalyze effect of CuCl is the same as CuI.

Having identified the optimum reaction conditions, the substrate scope of this method was examined (Table 2). A study on the aniline substrates revealed that the reactions with the anilines with electron-withdrawing groups, such as –F and NO_2, gave much higher yields than those with electron-donating groups. For the substituents of the aromatic aldehydes, good yields were obtained with electron-withdrawing groups, while poor yields were given with electron-donating groups.

Subsequently, we could afford the desired yield in 2–15 min under microwave-promoted conditions, while very low yield could be gained in traditional thermal reactions. For example, only trace product was achieved after heating in toluene at 60 °C for 10 h.

All products (**4ae**–**4dd**) are fully characterized by standard spectroscopic methods. The IR shows single acutely middle intension signal at 3454–3319 cm^{-1} for vibration of –NH. The ^1H NMR shows signals at 5.83–5.41 and 5.26–4.07 ppm, these denote the hydrogen of –CH– and the active hydrogen of –NH–. The ^{19}F NMR spectrum is very similar to the starting aldehyde and amine. The ^{13}C NMR shows signals at 88.7–84.8 and 85.9–84.3 ppm for two sp^1 carbon atoms of C≡C. In this spectrum, the fluorine contiguous carbons always show first-order and second-order coupling. For example, in the ^{13}C NMR of compound **4ac**, 162.2 and 164.1 represent the first-order coupling of the carbon of $–Ar^1–F$ (δ = 163.3, d, J = 246 Hz). 151.8, 151.7, 149.9 and 159.8 represent the first-order and second-order coupling of $–Ar^2–F$ (δ = 150.8, dd, ^1J = 244 Hz, ^2J = 14 Hz). The EI-MS shows a weak molecular ion peak M^+ and the basic peak M^+–ArNH or M^+–$C_6H_5C{\equiv}CH$.

The molecular structure of **4de** was further determined by X-ray crystal diffraction analysis. Its molecule structure and the packing map was shown in Figs. 1 and 2. The selected bond lengths (Å) and band angles (°) for compound **4de** was listed in Table 3.

This compound shows strong intermolecular hydrogen bonding between N–H...N ($d_{N–H...N}$ = 2.307 Å; $\angle_{N–H...N}$ = 158.3°), and the intramolecular weak hydrogen bonding between C–H...F. ($d_{C–H...F}$ = 2.352, 2.480 and 2.580 Å; $\angle_{C–H...F}$ = 110.1°, 148.8° and 149.9°).

On the basis of the above experimental results, together with some literature reports [7,11a], a tentative mechanism was proposed as shown in Scheme 2. The MW irradiation first promoted CuCl catalyzed activation of the C–H bond of alkyne to give the copper acetylide **A** as well as the formation of iminie from the condisation of aldehyde and aniline. Then, the copper acetylide intermediate **A** attacked iminium **B** which is protonated by HCl to give the final propargylamine with releasing the Cu (I) catalyst for further cycle of reactions.

Table 2
One-pot preparation of fluorinated propargylamines **4** under microwave irradiation[a]

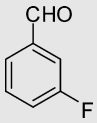
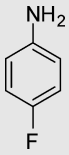
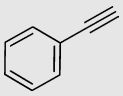
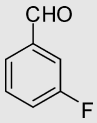
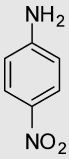
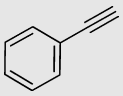
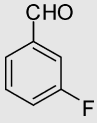
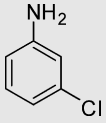
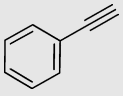
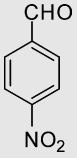
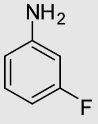
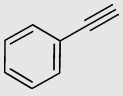
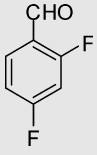
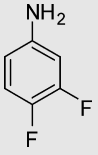
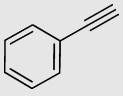
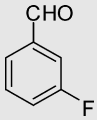
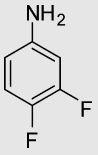
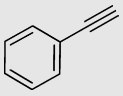
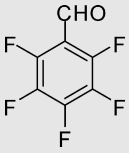
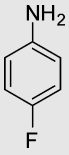
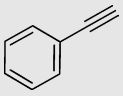
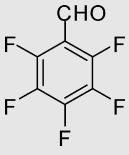
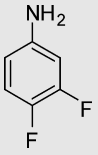
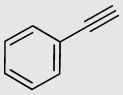
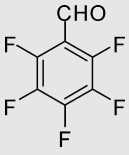
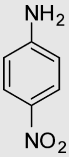
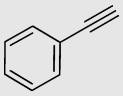
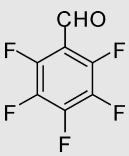
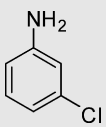
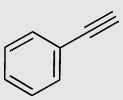
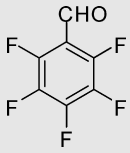
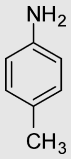
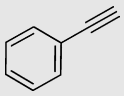
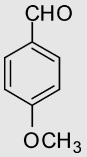
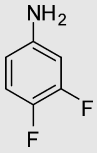
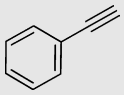
Entry	Aldehyde	Amine	Alkyne	Product	Time (min)	Yield (%)[b]
1				**4ae**	6	91
2				**4ab**	2	89
3				**4ad**	16	51
4				**4ba**	3	90
5				**4cc**	5	43
6				**4ac**	4	70
7				**4de**	14	56
8				**4dc**	13	90
9				**4db**	7	70
10				**4dd**	11	76

Table 2 (*Continued*)

Entry	Aldehyde	Amine	Alkyne	Product	Time (min)	Yield (%)[b]
11				**4df**	15	Trace
12				**4ec**	15	Trace

[a] Power 800 W.
[b] Isolated yield based on aldehyde 1.

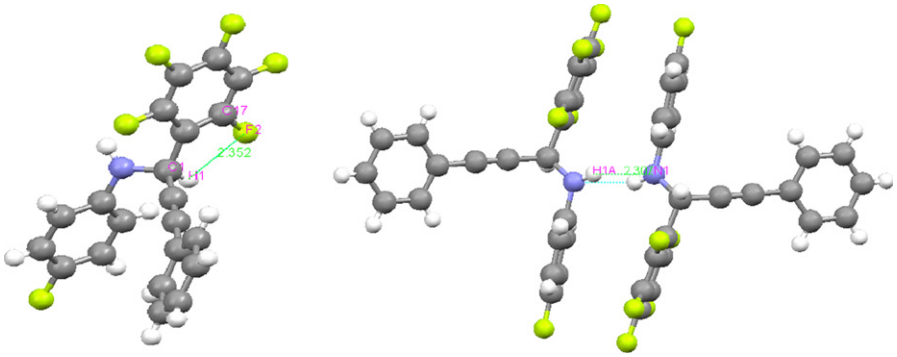


Fig. 1. The crystal structure of compound **4de** shows the inter- and intramolecular hydrogen bonds.

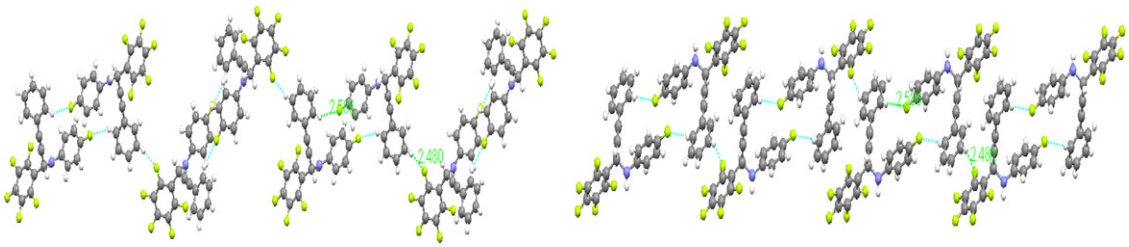
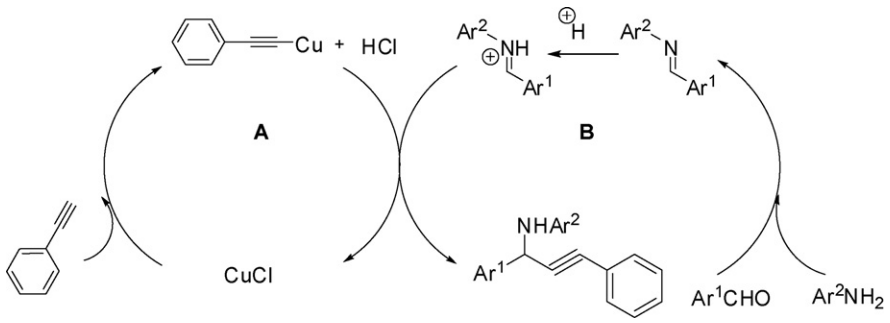


Fig. 2. The packing map of **4de**.



Scheme 2. Tentative reaction mechanism of three-component coupling reaction.

Table 3
Selected bond lengths (Å) and band angles (°) for compound **4de**

Bond	Length (Å)	Bond	Angle (°)
C(1)–N(1)	1.449(6)	N(1)–C(1)–C(16)	109.9(3)
C(1)–C(16)	1.516(6)	C(2)–C(1)–C(16)	110.4(4)
C(5)–C(6)	1.374(7)	N(1)–C(1)–H(1)	107.1
C(5)–H(5)	0.9300	C(10)–N(1)–H(1A)	121.5
C(13)–F(1)	1.366(6)	F(6)–C(21)–C(20)	118.3(4)
N(1)–H(1A)	0.8600	C(3)–C(2)–C(1)	178.4(5)

3. Conclusion

In summary, a microwave-promoted, rapid and efficient three-component reaction for the preparation of fluorinated propargylamines using CuCl as the catalyst in solvent-free condition has been developed. The notable advantages of this procedure, such as short reaction time, environmental friendly, cheap catalyst and simple workup, make this method an attractive and useful in organic synthesis. A further chemical transformation of the title products is under investigation.

4. Experimental

4.1. General experimental techniques and apparatus

All reactions were performed in an improved domestic Sanyo, EM-551S/550S, microwave oven (2450 MHz, 80–800 W). TLC was performed on precoated silica gel F-254 plates (0.25 mm; E. Merck), and product (s) and starting material(s) were detected by viewing under UV light. Column chromatography was performed on silica gel (300–400 mesh). Infrared spectra were recorded on an AVATAR370 FT spectrophotometer (PerkinElmer, USA). NMR spectra were determined with DRX500MHz spectrometer (Bruker, USA), using solutions in deuterated chloroform with tetramethylsilane as the internal standard for 1H and 13C nuclei, respectively. Low resolution mass spectrum or high resolution mass spectra were obtained on Finnigan MAT-8430 instrument using the electron impact ionization technique (70 eV). X-ray diffraction crystal structure analyses was obtained on Bruker SMART Apex II CCD diffractometer Mo Kα (λ = 0.71073 Å).

4.2. Synthesis of propargylamines

Aldehyde (1 mmol), amine (1.5 mmol), and phenylacetylene (2 mmol) were mixed with copper chloride (0.3 mmol) and ground into a fine, homogeneous mixture; then the mixture was put in a 10-mL sealed tube flask and exposed to microwave irradiation at 800 W using a microwave oven for an appropriate time under nitrogen. After completion of the reaction (as monitored by TLC), the reaction mixture was diluted with ethyl acetate, the catalyst was filtered through Celite. After removal of the solvent under vacuum, the crude material was purified by flash column chromatography (using hexane:ethyl = 8:1 acetate as elute) to afford pure product.

4.2.1. N-(4-Fluorophenyl)-3-amino-3-(3-fluorophenyl)-1-phenylprop-1-yne (**4ae**)

IR (KBr, cm^{-1}): ν 3415, 3070, 2869, 2392, 1628, 1583, 1500, 1448, 1261, 1196, 835, 787, 682; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.01–7.43 (m, 9H), 6.89–6.93 (m, 2H), 6.67–6.70 (m, 2H), 5.41 (s, 1H), 4.07 (brs, 1H); ^{19}F NMR (470 MHz, $CDCl_3$): δ −112.2 to −112.1 (m, 1F), −125.9 (d, J = 3.8 Hz, 1F); ^{13}C NMR (125 MHz, $CDCl_3$): δ 163.4 (d, J = 207.5 Hz), 161.4 (d, J = 205 Hz), 158.6 (d, J = 3 Hz), 147.6 (s), 138.5 (d, J = 8 Hz), 131.9 (s), 130.4 (d, J = 8 Hz), 128.7 (s), 128.4 (s), 125.2 (d, J = 3 Hz), 122.5 (d, J = 8 Hz), 118.5 (d, J = 22 Hz), 116.1 (d, J = 22 Hz), 114.7 (d, J = 22 Hz), 87.7 (s), 85.7 (s), 51.0 (s); EI-MS: m/z (%): 319 (M^+, 1), 217 (M^+–$C_6H_5C{\equiv}CH$, 100), 209 (M^+–FC_6H_5NH, 28).

4.2.2. N-(4-Nitrophenyl)-3-amino-3-(3-fluorophenyl)-1-phenylprop-1-yne (**4ab**)

IR (KBr, cm^{-1}): ν 3349, 3059, 2917, 2224, 1598, 1483, 1321, 1295, 1109, 830, 753, 689; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.99 (d, J = 9.0 Hz, 2H), 7.18–7.34 (m, 8H), 6.94–6.98 (m, 1H), 6.61 (m, 2H), 5.50 (d, J = 7.0 Hz, 1H), 5.03 (d, J = 6.0 Hz, 1H); ^{19}F NMR (470 MHz, $CDCl_3$): δ −111.5 to −111.4 (m, 1F); ^{13}C NMR (125 MHz, $CDCl_3$): δ 163.1 (d, J = 246 Hz), 151.4 (d, J = 3 Hz), 140.7 (d, J = 6 Hz), 139.2 (s), 131.8 (s), 130.7 (d, J = 8 Hz), 129.0 (s), 128.5 (s), 126.2 (s), 122.9 (d, J = 4 Hz), 121.9 (s), 115.6 (d, J = 21 Hz), 114.3 (d, J = 22 Hz), 112.6 (s), 86.3 (s), 85.9 (s), 49.6 (s); EI-MS: m/z (%): 346 (M^+, 2), 209 (M^+–$NO_2C_6H_4NH$, 100); HRMS cacld. for $C_{21}H_{15}N_2O_2F$: 346.1118. Found: 346.1115.

4.2.3. N-(3-Chlorophenyl)-3-amino-3-(3-fluorophenyl)-1-phenylprop-1-yne (**4ad**)

IR (KBr, cm^{-1}): ν 3411, 3060, 2963, 1595, 1486, 1260, 1091, 1020, 798, 687; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.52–7.54 (m, 1H), 7.03–7.37 (m, 10H), 6.60–6.77 (m, 2H), 5.47 (d, J = 7.0 Hz, 1H), 4.26 (d, J = 7.0 Hz, 1H); ^{19}F NMR (470 MHz, $CDCl_3$): δ −112.1 to −112.0 (m, 1F); ^{13}C NMR (125 MHz, $CDCl_3$): δ 147.4 (s), 141.8 (d, J = 8 Hz), 135.0 (s), 131.8 (s), 130.4 (d, J = 8 Hz), 130.2 (s), 128.7 (s), 128.5 (s), 128.3 (s), 122.8 (d, J = 4 Hz), 122.3 (s), 118.8 (s), 115.2 (d, J = 21 Hz), 114.3 (d, J = 22 Hz), 114.0 (s), 112.3 (s), 87.1 (s), 85.7 (s), 50.1 (s); EI-MS: m/z (%): 335 (M^+, 4), 209 (M^+–ClC_6H_4NH, 100); HRMS cacld. for $C_{21}H_{15}NFCl$: 335.0877. Found: 335.0885.

4.2.4. N-(3-Fluorophenyl)-3-amino-3-(4-nitrophenyl)-1-phenylprop-1-yne (**4ba**)

IR (KBr, cm^{-1}): ν 3405, 3075, 2962, 2204, 1618, 1519, 1346, 1149, 757, 689; ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.22 (d, J = 8.5 Hz, 2H), 7.79 (d, J = 8.5 Hz, 2H), 7.10–7.42 (m, 6H), 6.39–6.50 (m, 3H), 5.55 (d, J = 5.5 Hz, 1H), 4.47 (d, J = 5.5 Hz, 1H); ^{19}F NMR (470 MHz, $CDCl_3$): δ −112.1 to −112.0 (m, 1F); ^{13}C NMR (125 MHz, $CDCl_3$): δ 163.7 (d, J = 243 Hz), 146.6 (s), 142.3 (s), 132.6 (s), 131.8 (s), 128.5 (s), 128.1 (s), 124.1 (s), 123.7 (s), 122.0 (s), 116.9 (d, J = 4 Hz), 110.0 (d, J = 3 Hz), 105.7 (d, J = 29 Hz), 101.2 (d, J = 25 Hz), 86.5 (s), 82.2 (s), 50.1 (s); EI-MS: m/z (%): 346 (M^+, 2), 298 (M^+–NO_2, 100), 209 (M^+–$C_6H_5NO_2$, 74).

4.2.5. N-(3,4-Difluorophenyl)-3-amino-3-(2,4-difluorophenyl)-1-phenylprop-1-yne (**4cc**)

IR (KBr, cm^{-1}): ν 3418, 3080, 2926, 2229, 1609, 1521, 1428, 1272, 1219, 965, 851, 757, 691; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.66–7.70 (m, 1H), 7.28–7.42 (m, 5H), 6.85–7.01 (m, 3H), 6.42–6.44 (m, 1H), 5.60 (s, 1H), 4.30 (brs, 1H); ^{19}F NMR (470 MHz, $CDCl_3$): δ −109.3 (s, 1F), −114.0 (q, J = 8 Hz, 1F), −136.7 (t, J = 9 Hz, 1F), −150.6 (s, 1F); ^{13}C NMR (125 MHz, $CDCl_3$): δ 163.0 (dd, ^1J = 249 Hz, ^2J = 13 Hz), 160.4 (dd, ^1J = 249 Hz, ^2J = 13 Hz), 150.7 (dd, ^1J = 244 Hz, ^2J = 13 Hz), 144.0 (dd, ^1J = 238 Hz, ^2J = 13 Hz), 143.0 (s), 131.8 (s), 129.8 (q, J = 5 Hz), 128.8 (s), 128.4 (s), 122.6 (dd, ^1J = 13 Hz, ^2J = 4 Hz), 117.6 (dd, ^1J = 23 Hz, ^2J = 2 Hz), 111.8 (dd, ^1J = 21 Hz, ^2J = 4 Hz), 109.6 (q, J = 3 Hz), 104.4 (t, J = 25 Hz), 103.1 (d, J = 21 Hz), 86.5 (s), 85.4 (s), 45.0 (d, J = 4 Hz); EI-MS: m/z (%): 355 (M^+, 3), 227 (M^+–$F_2C_6H_4$, 84), 127 ($F_2C_6H_3N^+$, 100); HRMS cacld. for $C_{21}H_{13}NF_4$: 355.0984. Found: 355.0972.

4.2.6. N-(3,4-Difluorophenyl)-3-amino-3-(3-fluorophenyl)-1-phenylprop-1-yne (**4ac**)

IR (KBr, cm^{-1}): ν 3415, 3062, 2853, 2226, 1609, 1518, 1444, 1216, 755, 689; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.28–7.42 (m, 8H), 6.92–7.03 (m, 2H), 6.51–6.55 (m, 1H), 6.37–6.40 (m, 1H), 5.36 (s,

1H), 4.13 (brs, 1H); ^{19}F NMR (470 MHz, $CDCl_3$): δ −111.9 to −111.8 (m, 1F), −136.8 to −136.7 (m, 1F), −150.9 to −150.8 (m, 1F); ^{13}C NMR (125 MHz, $CDCl_3$): δ 163.3 (d, J = 246 Hz), 150.8 (dd, ^1J = 244 Hz, ^2J = 14 Hz), 144.0 (dd, ^1J = 236 Hz, ^2J = 14 Hz), 143.2 (dd, ^1J = 9 Hz, ^2J = 3 Hz), 141.7 (d, J = 8 Hz), 131.9 (s), 130.6 (s), 128.8 (s), 128.5 (s), 122.8 (d, J = 3 Hz), 122.3 (s), 117.55 (d, J = 18 Hz), 115.4 (d, J = 21 Hz), 114.4 (d, J = 22 Hz), 109.7 (dd, ^1J = 5 Hz, ^2J = 3 Hz), 103.2 (d, J = 21), 87.1 (s), 85.9 (s), 50.7 (d, J = 1 Hz); EI-MS: m/z (%): 337 (M^+, 3), 209 (M^+–$F_2C_6H_4NH$, 100); HRMS cacld. for $C_{21}H_{14}NF_3$: 337.1078. Found: 337.1073.

4.2.7. N-(4-Fluorophenyl)-3-amino-3-(pentafluorophenyl)-1-phenylprop-1-yne (4de)

IR (KBr, cm^{-1}): ν 3441, 3043, 2962, 2223, 1506, 1219, 1125, 984, 756, 690; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.28–7.53 (m, 6H), 6.67–6.93 (m, 3H), 5.83 (d, J = 7.5 Hz, 1H), 4.35 (d, J = 8.0 Hz, 1H); ^{19}F NMR (470 MHz, $CDCl_3$): δ −124.5 to −124.6 (m, 1F), −143.7 (dd, ^1J = 22 Hz, ^2J = 8 Hz, 2F), −153.8 (t, J = 21 Hz, 1F), −160.8 to −160.9 (m, 2F); ^{13}C NMR (125 MHz, $CDCl_3$): δ 157.2 (d, J = 238 Hz), 145.8–145.9, 143.8–144.0 (dm, J = 245 Hz), 142.0–142.1, 140.0–140.2 (dm, J = 251Hz), 141.2 (d, J = 1 Hz), 138.6–138.9, 136.6–136.9 (dm, J = 252 Hz), 131.9 (s), 129.0 (s), 128.4 (s), 121.8 (s), 116.1 (d, J = 22Hz), 115.6 (d, J = 8 Hz), 114.0–114.2 (m), 84.8 (s), 84.8 (s), 41.8 (s); EI-MS: m/z (%): 391 (M^+, 9), 281 (M^+–FC_6H_4NH, 100); HRMS cacld. for $C_{21}H_{11}NF_6$: 391.0794. Found: 391.0796.

Crystal data for 3 g $C_{21}H_{11}NF_6$ (CCDC 669044): Mw = 391.31, monoclinic, space group $P2(1)/n$, a = 12.379(1) Å, b = 5.960(2) Å, c = 24.17(2) Å, beta = 101.869(14)°, V = 1745(3) A^3, Z = 4, Dc = 1.489 mg/m^3, F(0 0 0) = 792, crystal size 0.30 mm × 0.20 mm × 0.10 mm, Theta range for data collection 2.78–25.04°, limiting indices $-14 \le h \le 14$, $-7 \le k \le 7$, $-28 \le l \le 20$, Reflections collected/unique 8299/3065 [R(int) = 0.0525], completeness to theta = 25.04, 99.3%, max. and min. transmission 0.9869 and 0.9614, refinement method full-matrix least-squares on F^2, data/restraints/parameters = 3065/0/254, goodness-of-fit on F^2 = 0.998, final R indices [$I > 2$sigma(I)] $R1$ = 0.0876, $wR2$ = 0.2624, R indices (all data) $R1$ = 0.1373, $wR2$ = 0.3121, extinction coefficient = 0.017(5), largest diff. peak and hole = 0.335 and −0.307 e A^{-3}.

4.2.8. N-(3,4-Fluorophenyl)-3-amino-3-(pentafluorophenyl)-1-phenylprop-1-yne (4dc)

IR (KBr, cm^{-1}): ν 3439, 3081, 2924, 2224, 1612, 1523, 1507, 1264, 1128, 988, 756, 688; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.28–7.52 (m, 5H), 6.95–7.01 (m, 1H), 6.51–6.54 (m, 1H), 6.38–6.40 (m, 1H), 5.78 (s, 1H), 4.42 (brs, 1H); ^{19}F NMR (470 MHz, $CDCl_3$): δ −136.0 to −135.9 (m, 1F), −143.6 (dd, ^1J = 22 Hz, ^2J = 8 Hz, 2F), −149.6 to −149.5 (m, 1F), −153.4 (t, J = 21 Hz, 1F), −160.6 to −160.5 (m, 2F); ^{13}C NMR (125 MHz, $CDCl_3$): δ 150. 9 (dd, ^1J = 245 Hz, ^2J = 14 Hz), 144.4 (dd, ^1J = 239 Hz, ^2J = 13 Hz), 145.8–145.9, 143. 8–143.9 (dm, J = 251 Hz), 141.9 (dd, ^1J = 9 Hz, ^2J = 3 Hz), 142.1–142.4, 140.1–140.2 (dm, J = 254 Hz), 138.7–138.9, 136.7–136.9 (dm, J = 253 Hz), 131.9 (s), 129.1 (s), 128.4 (s), 121.6 (s), 117.9 (d, J = 19 Hz), 113.6–113.9 (m), 109.4 (dd, ^1J = 5 Hz, ^2J = 1 Hz), 103.3 (d, J = 21 Hz), 85.0 (s), 84.3 (s), 41.4 (s); EI-MS: m/z (%): 409 (M^+, 5), 281 (M^+–$F_2C_6H_4NH$, 100); HRMS cacld. for $C_{21}H_{10}NF_7$: 409.0701. Found: 409.0686.

4.2.9. N-(4-Nitrophenyl)-3-amino-3-(pentafluorophenyl)-1-phenylprop-1-yne (4db)

IR (KBr, cm^{-1}): ν 3454, 3092, 2922, 2233, 1599, 1503, 1317, 1113, 992, 756, 692; ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.12 (d, J = 9.0 Hz, 2H), 7.31–7.44 (m, 5H), 6.68 (d, J = 9.0 Hz, 2H), 6.0 (d, J = 8.5 Hz, 1H), 5.26 (d, J = 8.5 Hz, 1H); ^{19}F NMR (470 MHz, $CDCl_3$): δ −143.3 (dd, ^1J = 21 Hz, ^2J = 6 Hz, 2F), −152.5 (t, J = 21 Hz, 1F), −161.0 to −160.1 (m, 2F); ^{13}C NMR (125 MHz, $CDCl_3$): δ 150.3 (s), 145.7–145.9, 143.7–144.2 (dm, J = 253 Hz), 142.3–142.7, 140.4–140.7 (dm, J = 253 Hz), 139.7 (s), 138.7–139.0, 136.6–137.0 (dm, J = 250 Hz), 131.9 (s), 129.3 (s), 128.5 (s), 126.3 (s), 121.3 (s), 113.0–113.3 (m), 112.0 (s), 85.6 (s), 83.3 (s), 40.1 (s); EI-MS: m/z (%): 418 (M^+, 3), 281 (M^+–$NO_2C_6H_4NH$, 100); HRMS cacld. for $C_{21}H_{11}N_2O_2F_5$: 418.0741. Found: 418.0725.

4.2.10. N-(3-Chlorophenyl)-3-amino-3-(pentafluorophenyl)-1-phenylprop-1-yne (4dd)

IR (KBr, cm^{-1}): ν 3419, 3061, 2926, 2233, 1596, 1501, 1121, 992, 757, 686; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.08–7.51 (m, 7H), 6.56–6.76 (m, 2H), 5.87 (d, J = 6.0 Hz, 1H), 4.55 (d, J = 5.0 Hz, 1H); ^{19}F NMR (470 MHz, $CDCl_3$): −143.6 (dd, ^1J = 22 Hz, ^2J = 7 Hz, 2F), −153.6 (t, J = 21 Hz, 1F), −160.8 to −160.6 (m, 2F); ^{13}C NMR (125 MHz, $CDCl_3$): δ 146.1 (s), 145.8–146.1, 143.7–144.0 (dm, J = 263 Hz), 142.1–143.4, 140.0–140.3 (dm, J = 256 Hz), 138.6–139.0, 136.6–137.0 (dm, J = 256 Hz), 135.3 (s), 131.9 (s), 129.1 (s), 128.4 (s), 121.7 (s), 120.9 (s), 119.6 (s), 113.9 (s), 111.8 (s), 110.9–111.1 (m), 85.0 (s), 84.4 (s), 40.7 (s); EI-MS: m/z (%): 407 (M^+, 6), 281 (M^+–ClC_6H_4NH, 100); HRMS cacld. for $C_{21}H_{11}NF_5Cl$: 407.0500. Found: 407.0493.

Acknowledgment

This work was supported by the National Science Foundation of China (No. 20772078).

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