4-Halogeno-1,1,1-trifluorobut-3-yn-2-one [4+2] cycloadducts and their cross-coupling with organozinc compounds

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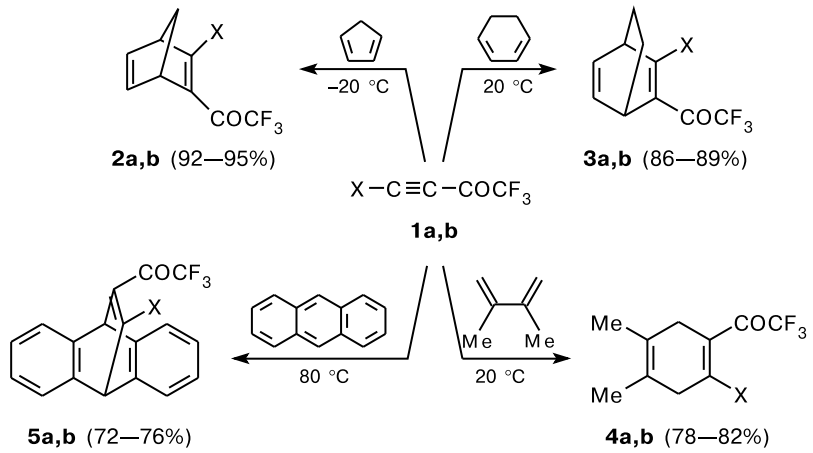
The reactions of 4-chloro-1,1,1-trifluorobut-3-yn-2-one and 4-bromo-1,1,1-trifluorobut-3-yn-2-one with conjugated dienes afford [4+2] cycloadducts in high yields. The halogen atom in the products is readily replaced by a (het)aryl residue in the cross-coupling with organozinc compounds.

Key words: halogenotrifluoroacetylacetylenes, diene, dienophile, [4+2] cycloaddition reaction, the Negishi reaction, organofluorine compounds.

Acetylenic dienophiles and enophiles that have two activating substituents, one of which is halogen, are of significant interest as polyfunctional substrates in the synthesis of biologically active compounds.[1] [4+2] Cycloaddition reactions of halogenoacetylenes activated by alkoxycarbonyl,[2] acyl,[3] and sulfonyl[1] groups, and further transformations of the obtained cycloadducts have been studied.[2] Recently,[4] we have synthesized halogenoacetylenes that contain an ethoxalyl substituent and demonstrated that these compounds are active dienophiles; they react with many dienes even at 20 °C. Though trifluoroacetyl group is related to the most powerful electron-withdrawing groups, still only few examples of the Diels—Alder reactions with acetylenes activated by this substituent are known.[5—7] At present, halogen-activated trufluoroacetylacetylenes are intensively investigated in our laboratory; it turned out that these compounds with high electrophilicity undergo [2+2] cycloaddition with alkyl vinyl ethers[8] and even with non-activated alkenes[9] in the absence of a catalyst and radiation.

Earlier, in a short communication[10] we have described the reaction of bromide **1b** with the simplest dienes. It seemed promising to investigate acetylenes **1a,b** as dienophilies in the reaction with different dienes, including heterocyclic dienes. Cycloadduct that formed should contain β-halogenovinyl trifluoromethyl ketone fragments, which are of great interest for biochemistry and organic synthesis.[11]

Scheme 1



X = Cl (**a**), Br (**b**)

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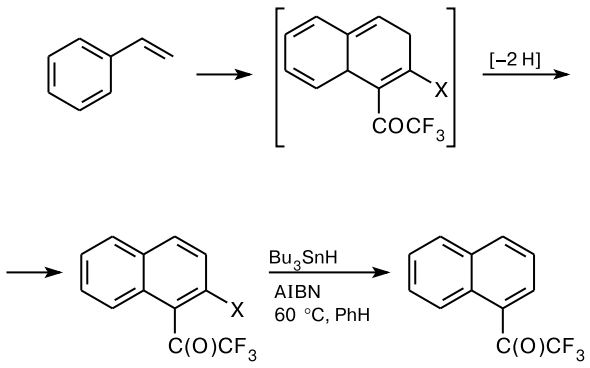
We have established that dienophiles **1a,b** react with cyclopentadienes even at −20 °C giving the corresponding cycloadducts **2a,b** in virtually quantitative yields (Scheme 1). Less reactive cyclohexa-1,3-diene and 2,3-dimethylbutadiene exothermically add compounds **1a,b** at room temperature. The least reactive diene of the studied dienes, anthracene, reacts with acetylenes **1a,b** when refluxed in benzene to afford cycloadducts **5a,b** in high yields as well.

Starting to investigate the reaction of acetylenes **1a,b** with styrene, we thought that as in the reaction with alkenes,[9] [2+2] cycloaddition would be observed, but, in reality, 1-trifluoroacetyl-2-halogenonaphthalenes **6a,b** were isolated in 36—39% yields. Apparently, [4+2] cycloaddition takes place in the first step of this transformation, and then the intermediate dihydronaphthalene is oxidized by the second dienophile molecule, which explains low yield of the final products (Scheme 2).

Scheme 2



6a,b (36—39%)

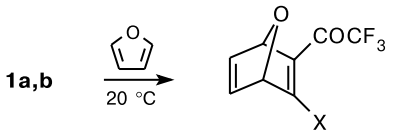
X = Cl (**a**), Br (**6b**)

Reaction of styrene with dienophiles **1a,b** can result in two regioisomers. The position of the substituents in compound **6b** was determined by the chemical method: hydrodebromination of this compound with Bu_3SnH gives the known 1-trifluoroacetylnaphthalene (see Scheme 2).

One of the very promising directions of the Diels—Alder reactions is the involvement of heterocyclic dienes, among which furans and *N*-acylpyrroles are the most often used. However, it is known[1,2] that even reactive dienophiles of the acetylene series react with these dienes only on heating to 90—100 °C for 20—30 h. We found that acetylenes **1a,b** exothermically react with furan even at 20 °C giving bicyclic cycloadducts **7a,b** in good yields (Scheme 3).

Similarly to the known processes with halogenoacetylenes[1,2] activated by electron-withdrawing substituents, it can be supposed that the reaction of *N*-methoxycarbonylpyrrole with acetylenes **1a,b** would also follow the [4+2] cycloaddition pattern. In fact, chloride **1a** gives

Scheme 3

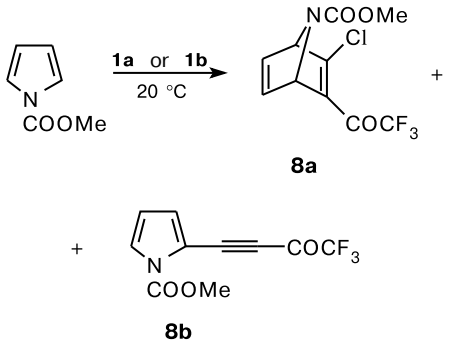


7a,b (70—75%)

X = Cl (**a**), Br (**b**)

the expected unstable bicyclic compound **8a** together with the unusual product of electorophilic alkynylation **8b**. It is worth noting that bromide **1b**, contrary to **1a**, exothermically react with *N*-methoxycarbonylpyrrole giving only compound **8b** without any admixture of the corresponding [4+2] cycloadduct (Scheme 4).

Scheme 4

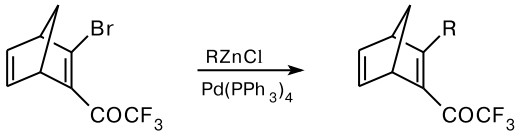


1a: products **8a** (62%) and **8b** (19%); **1b:** product **8b** (78%)

Thus, the Diels—Alder reactions involving acetylenes **1a,b** represent a simple method for the synthesis of compounds with a β-halogenovinyl trifluoromethyl ketone fragment that can be used in different functionalization and heterocyclization processes.[11] However, till now only the simplest (mainly, acyclic) representatives of this class of compounds have been known, for which the synthetic potential is mainly undisclosed. We made an attempt to elaborate a convenient method for their β-functionalization by substituting the halogen atom with different aryl substituents in the Negishi reaction. At the same time, we were concerned that organozinc compounds, in addition to halogen substitution, would also add to the reactive carbonyl center, which would result in a mixture of products. Fortunately, it turned out that the reaction of bromide **2b** with (het)arylzinc chlorides in the presence of tetrakis(triphenylphosphine)palladium leads exclusively to the cross-coupling products **9a—c** in high yields (Scheme 5).

Thus, halogenated trifluroacetylacetylenes are reactive dienophiles in the Diels—Alder reaction, they smoothly react with different dienes under mild conditions. The

Scheme 5



2b **9a—c** (75—80%)

R = 2-thienyl (**9a**), 2-furyl (**9b**), 4-FC_6H_4 (**9c**)

synthetic potential of the obtained adducts, undoubtedly, requires further investigations.

Experimental

1,1,1-Trifluooro-4-chlorobut-3-yn-2-one (**1a**) and 4-bromo-1,1,1-trifluorobut-3-yn-2-one (**1b**) were synthesized by halogenation of 4-trimethylstannyl-1,1,1-trifluorobut-3-yn-2-one as described.[9,10] Dienes were distilled directly before the reaction, anthracene was used without purification. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker AMX 400 instrument (working frequencies 400 and 100 MHz, respectively) in $CDCl_3$. IR spectra were obtained on a Bruker IFS 25 spectrometer in thin layer or Nujol.

1-(3-Chlorobicyclo[2.2.1]hepta-2,5-dien-2-yl)-2,2,2-trifluoroethanone (2a). Freshly distilled cyclopentadiene (0.79 g, 0.012 mol) in dichloromethane (5.0 mL) was added dropwise with stirring to a solution of acetylene **1a** (1.56 g, 0.010 mol) in anhydrous dichloromethane (5.0 mL) at −20 °C. The cooling bath was kept, the reaction mixture was allowed to warm to 20 °C, after 15 min the mixture was concentrated *in vacuo*, and the residue was distilled. Yield 2.05 g (92%), b.p. 40—41 °C (1 Torr). Found (%): C, 48.40; H, 2.62; F, 25.80. $C_9H_6ClF_3O$. Calculated (%): C, 48.56; H, 2.72; F, 25.60. IR, ν/cm^{-1}: 1706 (C=O); 1602 (C=C). ^{1}H NMR, δ: 2.22 (d, 1 H, CH_2, J = 7.2 Hz); 2.36 (d, 1 H, CH_2, J = 7.2 Hz); 3.64 (s, 1 H, HC(1)); 4.14 (s, 1 H, HC(4)); 6.84 (d, 1 H, CH=CH, J = 4.9 Hz); 6.89 (d, 1 H, CH=CH, J = 4.9 Hz). ^{13}C NMR, δ: 51.0 (C(7)); 60.7, 70.7 (C(1), C(4)); 115.9 (q, CF_3, J = 290 Hz); 139.5, 140.1 (CH=CH); 143.3, 170.5 (C(2), C(3)); 175.8 (q, C=O, J = 37 Hz).

1-(3-Bromobicyclo[2.2.1]hepta-2,5-dien-2-yl)-2,2,2-trifluoroethanone (2b) was obtained as described for compound **2a** starting from acetylene **1b** (0.010 mol) and cyclopentadiene (0.012 mol). Yield 2.51 g (94%), b.p. 55—56 °C (1 Torr). Found (%): C, 40.61; H, 2.42; Br, 29.61; F, 21.09. $C_9H_6BrF_3O$. Calculated (%): C, 40.48; H, 2.26; Br, 29.92; F, 21.34. IR, ν/cm^{-1}: 1702 (C=O); 1600 (C=C). ^{1}H NMR, δ: 2.23 (d, 1 H, CH_2, J = 8.4 Hz); 2.39 (d, 1 H, CH_2, J = 8.4 Hz); 3.69 (s, 1 H, HC(1)); 4.10 (s, 1 H, HC(4)); 6.85 (d, 1 H, CH=CH, J = 5.0 Hz); 6.90 (d, 1 H, CH=CH, J = 5.0 Hz). ^{13}C NMR, δ: 51.7 (C(7)); 62.6, 71.1 (C(1), C(4)); 115.8 (q, CF_3, J = 289 Hz); 140.2, 142.7 (CH=CH); 143.0, 160.4 (C(2), C(3)); 175.4 (q, C=O, J = 36 Hz).

Cycloadducts 3a,b and 4a,b (general method). Cyclohexa-1,3-diene (1.00 g, 0.013 mol) or 2,3-dimethylbuta-1,3-diene (1.03 g, 0.013 mol) was added with stirring to a solution of acetylene **1a** or **1b** (0.010 mol) in dichloromethane (5.0 mL) at 0 °C. The cooling bath was removed and after completion of the exothermic reaction the reaction mixture was stirred at 20 °C for 5 h. The mixture was concentrated *in vacuo*, the residue was distilled.

1-(3-Chlorobicyclo[2.2.2]octa-2,5-dien-2-yl)-2,2,2-trifluoroethanone (3a) was obtained from chloroacetylene **1a** and cyclohexa-1,3-diene. Yield 2.10 g (89%), b.p. 53—54 °C (1 Torr). Found (%): C, 50.56; H, 3.30; F, 24.40. $C_{10}H_8ClF_3O$. Calculated (%): C, 50.76; H, 3.41; F, 24.40. IR, ν/cm^{-1}: 1608, 1665 (C=C); 1706 (C=O). ^{1}H NMR, δ: 1.44—1.68 (m, 4 H, $CH_{2CH}CH_2$); 4.08 (m, 1 H, HC(1)); 4.27 (m, 1 H, HC(4)); 6.35 (m, 1 H, CH=C); 6.48 (m, 1 H, CH=C). ^{13}C NMR, δ: 24.9, 25.2 (CH_2CH_2); 38.4, 49.9 (C(1), C(4)); 114.5 (q, CF_3, J = 290 Hz); 133.8, 135.2 (CH=CH); 137.0, 146.4 (C=C); 176.1 (q, C=O, J = 36 Hz).

1-(3-Bromobicyclo[2.2.2]octa-2,5-dien-2-yl)-2,2,2-trifluoroethanone (3b) was obtained from bromoacetylene **1b** and cyclohexa-1,3-diene. Yield 2.39 g (85%), b.p. 68—69 °C (1 Torr). Found (%): C, 42.47; H, 2.86; Br, 28.09; F, 20.00. $C_{10}H_8BrF_3O$. Calculated (%): C, 42.73; H, 2.87; Br, 28.43; F, 20.28. IR, ν/cm^{-1}: 1603, 1660 (C=C); 1700 (C=O). ^{1}H NMR, δ: 1.40—1.66 (m, 4 H, CH_2CH_2); 4.05 (m, 1 H, HC(1)); 4.24 (m, 1 H, HC(4)); 6.32 (m, 1 H, CH=C); 6.46 (m, 1 H, CH=C). ^{13}C NMR, δ: 24.1, 24.6 (CH_2CH_2); 39.7, 51.6 (C(1), C(4)); 115.6 (q, CF_3, J = 290 Hz); 132.0, 133.5 (CH=CH); 135.8, 144.3 (C=C); 176.6 (q, C=O, J = 36 Hz).

1-(2-Chloro-4,5-dimethyl-1,4-cyclohexadien-1-yl)-2,2,2-trifluoroethanone (4a) was obtained from chloroacetylene **1a** and 2,3-dimethylbuta-1,3-diene. Yield 1.32 g (79%), b.p. 50—51 °C (1 Torr). Found (%): C, 50.44; H, 4.19; F, 24.02. $C_{10}H_{10}ClF_3O$. Calculated (%): C, 50.33; H, 4.23; F, 23.88. IR, ν/cm^{-1}: 1598, 1652 (C=C); 1703 (C=O). ^{1}H NMR, δ: 1.65 (d, 3 H, Me, J = 0.7 Hz); 1.69 (d, 3 H, Me, J = 0.7 Hz); 2.90 (m, 2 H, CH_2); 3.28 (m, 2 H, CH_2). ^{13}C NMR, δ: 18.1, 19.5 (2 Me); 35.8, 42.9 (2 CH_2); 116.8 (q, CF_3, J = 290 Hz); 120.9, 123.9 (CH=CH); 132.2, 144.2 (C=C); 175.2 (q, C=O, J = 36 Hz).

1-(2-Bromo-4,5-dimethyl-1,4-cyclohexadien-1-yl)-2,2,2-trifluoroethanone (4b) was obtained from bromoacetylene **1b** and 2,3-dimethylbuta-1,3-diene. Yield 2.38 g (84%), b.p. 65—66 °C (1 Torr). Found (%): C, 42.63; H, 3.77; Br, 28.63; F, 20.33. $C_{10}H_{10}BrF_3O$. Calculated (%): C, 42.43; H, 3.56; Br, 28.23; F, 20.13. IR, ν/cm^{-1}: 1600, 1650 (C=C); 1700 (C=O). ^{1}H NMR, δ: 1.63 (d, 3 H, Me, J = 0.5 Hz); 1.65 (d, 3 H, Me, J = 0.5 Hz); 2.91 (m, 2 H, CH_2); 3.24 (m, 2 H, CH_2). ^{13}C NMR, δ: 18.6, 19.9 (2 Me); 37.0, 42.6 (2 CH_2); 118.2 (q, CF_3, J = 290 Hz); 121.5, 124.5 (CH=CH); 134.8, 145.6 (C=C); 177.6 (q, C=O, J = 38 Hz).

12-Chloro-11-trifluoroacetyl-9,10-dihydro-9,10-ethenoanthracene (5a). A solution of acetylene **1a** (1.56 g, 0.010 mol) and anthracene (1.78 g, 0.010 mol) in anhydrous benzene (10 mL) was refluxed for 6 h. The reaction mixture was cooled to 50 °C, the precipitate that formed was filtered off, the filtrate was concentrated *in vacuo*, the residue was chromatographed (silica gel, ethyl acetate—hexane (1 : 20)). Yield 2.40 g (72%), m.p. 102—103 °C. Found (%): C, 64.81; H, 2.95; Cl, 10.68; F, 17.24. $C_{18}H_{10}ClF_3O$. Calculated (%): C, 64.58; H, 3.02; Cl, 10.59; F, 17.03. IR, ν/cm^{-1}: 1610 (C=C); 1700 (C=O). ^{1}H NMR, δ: 5.52 (s, 1 H, HC(9)); 5.80 (s, 1 H, HC(10)); 7.06—7.19 (m, 4 H, HAr); 7.40—7.59 (m, 4 H, HAr). ^{13}C NMR, δ: 63.5, 64.9 (C(9), C(10)); 117.5 (q, CF_3, J = 288 Hz); 124.4, 124.9, 126.9, 128.0 (Ar); 180.6 (q, C=O, J = 38 Hz).

11-Bromo-12-trifluoroacetyl-9,10-dihydro-9,10-ethenoantracene (5b) was obtained as described for compound **5a**.

Yield 2.85 g (75%), m.p. 81—83 °C. Found (%): C, 56.85; H, 2.87; F, 15.34. $C_{18}H_{10}BrF_3O$. Calculated (%): C, 57.02; H, 2.66; F, 15.03. ^{1}H NMR, δ: 5.45 (s, 1 H, HC(9)); 5.76 (s, 1 H, HC(10)); 7.04—7.20 (m, 4 H, HAr); 7.38—7.55 (m, 4 H, HAr). ^{13}C NMR, δ: 63.8, 65.2 (C(9), C(10)); 116.8 (q, CF_3, J = 288 Hz); 122.6, 125.7, 127.4, 128.7 (Ar); 178.4 (q, C=O, J = 40 Hz).

2-Chloro-1-trifluoroacetylnaphthalene (6a). Acetylene **1a** (1.56 g, 0.010 mol) and freshly distilled styrene (1.04 g, 0.010 mol) were mixed. After completion of the exothermic reaction, the reaction mixture was kept at 20 °C for 12 h and distilled *in vacuo*. The fraction with b.p. 102—108 °C (1 Torr) was collected and chromatographed (silica gel, ethyl acetate—hexane (1 : 20)). Compound **6a** was obtained as an yellowish oil (0.95 g, 37%). Found (%): C, 55.96; H, 2.40; Cl, 13.39; F, 21.83. $C_{12}H_6ClF_3O$. Calculated (%): C, 55.73; H, 2.34; Cl, 13.71; F, 22.04. IR, ν/cm^{-1}: 1703 (C=O). ^{1}H NMR, δ: 7.48—7.67 (m, 3 H, HAr); 7.82—8.05 (m, 3 H, HAr). ^{13}C NMR, δ: 119.4 (q, CF_3, J = 288 Hz); 126.9, 128.4, 129.9, 131.0, 132.8, 134.5, 139.4, 148.2, 148.8, 150.3, 176.9 (q, C=O, J = 40 Hz).

2-Bromo-1-trifluoroacetylnaphthalene (6b) was obtained as described for compound **6a**, fraction with b.p. 111—115 °C (1 Torr) was collected. Yield 1.03 g (34%). Found (%): C, 47.40; H, 2.25; F, 18.65. $C_{12}H_6BrF_3O$. Calculated (%): C, 47.56; H, 2.00; F, 18.81. IR, ν/cm^{-1}: 1701 (C=O). ^{1}H NMR, δ: 7.50—7.70 (m, 3 H, HAr); 7.81—8.00 (m, 3 H, HAr). ^{13}C NMR, δ: 118.6 (q, CF_3, J = 288 Hz); 127.2, 128.9, 129.5, 132.1, 133.0, 134.9, 139.9, 146.2, 148.5, 152.2, 174.9 (q, C=O, J = 40 Hz).

1-(3-Chloro-7-oxabicyclo[2.2.1]hepta-2,5-dien-2-yl)-2,2,2-trifluoroethanone (7a). Furan (0.075 g, 0.011 mol) was added with stirring to a solution of acetylene **1a** (1.56 g, 0.010 mol) in absolute dioxane (5.0 mL) in an argon atmosphere. After completion of the exothermic reaction, the reaction mixture was kept at 20 °C for 12 h. The reaction mixture was concentrated *in vacuo*, the residue was distilled. Compound **7a** was obtained (1.68 g, 75%), b.p. 42—43 °C (1 Torr). Found (%): C, 42.62; H, 2.02; F, 25.40. $C_8H_4ClF_3O$. Calculated (%): C, 42.79; H, 1.80; F, 25.38. IR, ν/cm^{-1}: 1690 (C=C); 1710 (C=O). ^{1}H NMR, δ: 5.31 (d, 1 H, HC(4), J = 0.6 Hz); 5.88 (d, 1 H, HC(1), J = 0.6 Hz); 7.18 (dd, 1 H, HC=C, J = 4.9 Hz, J = 0.6 Hz); 7.26 (dd, 1 H, HC=C, J = 4.9 Hz, J = 0.6 Hz). ^{13}C NMR, δ: 84.3, 88.7 (C(1), C(4)); 115.6 (q, CF_3, J = 290 Hz); 140.3, 140.4 (CH=CH); 144.7, 169.0 (C=C); 174.3 (q, C=O, J = 38 Hz).

1-(3-Bromo-7-oxabicyclo[2.2.1]hepta-2,5-dien-2-yl)-2,2,2-trifluoroethanone (7b) was obtained as described for compound **2a** starting from acetylene **1b** (0.010 mol) and furan (0.011 mol). Yield 1.88 g (70%), b.p. 48—49 °C (1 Torr). Found (%): C, 36.09; H, 1.64; F, 20.85. $C_8H_4BrF_3O$. Calculated (%): C, 35.70; H, 1.50; F, 21.18. IR, ν/cm^{-1}: 1694 (C=C); 1707 (C=O). ^{1}H NMR, δ: 5.46 (d, 1 H, HC(4), J = 0.5 Hz); 5.90 (d, 1 H, HC(1), J = 0.5 Hz); 7.21 (dd, 1 H, HC=C, J = 4.9 Hz, J = 0.5 Hz); 7.30 (dd, 1 H, HC=C, J = 4.9 Hz, J = 0.5 Hz). ^{13}C NMR, δ: 84.4, 90.2 (C(1), C(4)); 115.5 (q, CF_3, J = 288 Hz); 140.8, 143.9 (CH=CH); 144.2, 159.2 (C=C); 174.5 (q, C=O, J = 38 Hz).

2-Chloro-3-trifluoroacetyl-7-methoxycarbonyl-7-azabicyclo-[2.2.1]hepta-2,5-diene (8a). *N*-Methoxycarbonylpyrrole (1.38 g, 0.011 mol) was added with stirring to a solution of acetylene **1a** (1.56 g, 0.01 mol) in absolute dioxane (5.0 mL) in an argon atmosphere. The reaction mixture was kept at 20 °C for 6 h and concentrated *in vacuo*. The residue was dissolved in a mixture of ethyl acetate (2.0 mL) and hexane (8.0 mL), the solution was kept at 0 °C for 12 h. The precipitate that formed was filtered off, the filtrate was concentrated and chromatographed (silica gel, ethyl acetate—hexane (1 : 10)). Compound **8a** was obtained as a yellowish oil (1.74 g, 62%), which was storage-unstable (the attempt to perform elemental analysis was unsuccessful). IR, ν/cm^{-1}: 1608 (C=C); 1702 (C=O). ^{1}H NMR, δ: 3.94 (s, 3 H, MeO); 5.54 (s, 1 H, HC(1)); 5.79 (s, 1 H, HC(4)); 7.38 (m, 2 H, CH=CH). ^{13}C NMR, δ: 54.9, 56.4, 58.2 (C(1), C(4), MeO); 114.9 (q, CF_3, J = 288 Hz); 142.8, 145.4 (CH=CH); 148.7, 152.2 (C=C); 154.2 (NC=O); 172.9 (q, C=O, J = 40 Hz).

2-(4,4,4-Trifluoro-3-oxobut-1-ynyl)-1-methoxycarbonyl-1*H*-pyrrole (8b). *N*-Methoxycarbonylpyrrole (1.38 g, 0.011 mol) was added with stirring to a solution of acetylene **1b** (2.01 g, 0.010 mol) in absolute dioxane (3.0 mL) in an argon atmosphere. After completion of the exothermic reaction, the reaction mixture was kept at 20 °C for 4 h and concentrated *in vacuo*. The residue was recrystallized from ethyl acetate—hexane (1 : 5). Yield 1.91 g (78%), m.p. 93 °C. Found (%): C, 49.04; H, 2.51; N, 5.71. $C_{10}H_6F_3NO_3$. Calculated (%): C, 48.99; H, 2.47; N, 5.71. IR, ν/cm^{-1}: 1700, 1748 (C=O). ^{1}H NMR, δ: 4.06 (s, 3 H, MeO); 6.40 (d, 1 H, HAr, J = 3.7 Hz); 7.09 (dd, 1 H, HAr, J = 3.7 Hz, J = 1.1 Hz); 7.62 (m, 1 H, HAr). ^{13}C NMR, δ: 54.7 (MeO); 89.8, 93.6 (C≡C); 110.7, 113.1 (Ar); 115.0 (q, CF_3, J = 288 Hz); 127.8, 129.7 (Ar); 149.5 (N–C=O); 166.6 (q, C=O, J = 42 Hz).

Compounds 9a—c (general method). ***A.*** 2-Thienyl, 2-furyl- and 4-fluorophenylzinc chlorides. A solution of *n*-butyllithium in hexane (6.2 mL, 0.010 mol, 1.6 mol L^{-1}) was added dropwise at 0 °C in argon flow to a solution of thiophene (0.012 mol) or furan (0.012 mol) in absolute THF (10.0 mL). The reaction mixture was stirred at 0 °C for 0.5 h (2-thienyllithium and 2-furyllithium are formed in quantitative yields under these conditions[12]). 4-Fluorophenyllithium was obtained by addition of a solution of *n*-butyllithium in hexane (6.2 mL, 0.010 mol, 1.6 mol L^{-1}) to a stirred solution of 4-bromofluorobenzene (0.011 mol) in THF (10.0 mL) at −70 °C followed by holding the reaction mixture at −70 °C for 1 h. A solution of anhydrous $ZnCl_2$ (1.57 g, 0.012 mol) in THF (15.0 mL) was added dropwise with stirring to a solution or suspension of the obtained organolithium compounds cooled to −70 °C, the reaction mixture was allowed to warm to 20 °C. The solutions of organozinc compounds thus obtained were further used in cross-coupling reactions.

B. Cross-coupling reactions of compound **2b** with organozinc compounds. Compound **2b** (2.670 g, 0.010 mol) and $Pd(PPh_3)_4$ (0.005 g, 0.001 mol) were added in one portion to a stirred solution of the organozinc compound at 20 °C. After completion of the exothermic stage of the reaction, the reaction mixture was stirred at 20 °C for 18 h, then a saturated solution of ammonium chloride (30 mL) was added. The organic layer was separated, the aqueous layer was extracted with ether (4×20.0 mL). Combined organic fractions were washed with a saturated solution of ammonium chloride (20 mL), dried with sodium sulfate, and concentrated *in vacuo*. Hexane (30 mL) was added to the residue, catalyst decomposition products were filtered off and the filtrate was concentrated *in vacuo*. The solution of the residue in hexane–ethyl acetate (2 : 1) was passed through a thin layer of silica gel; the solution was concentrated. Adduct **9a** was purified by recrystallization form hexane, adducts **9b,c** were distilled *in vacuo*.

2-Trifluoroacetyl-3-(2-thienyl)bicyclo[2.2.1]hepta-2,5-diene (9a). Yield 2.16 g (80%), m.p. 62 °C. Found (%): C, 58.1; H, 3.32; F, 20.95; S, 11.65. $C_{13}H_9F_3OS$. Calculated (%): C, 57.77; H, 3.36; F, 21.09; S, 11.86. IR, ν/cm^{-1}: 1665 (C=C); 1700 (C=O). ^{1}H NMR, δ: 2.20 (d, 1 H, CH_2, J = 7.4 Hz); 2.32 (d, 1 H, CH_2, J = 7.4 Hz); 4.24 (d, 1 H, HC(4), J = 1.7 Hz); 4.36 (d, 1 H, HC(1), J = 1.7 Hz); 6.88 (dd, 1 H, HC(5), J = 1.7 Hz, J = 5.2 Hz); 7.01 (dd, 1 H, HC(6), J = 1.7 Hz, J = 5.2 Hz); 7.33 (dd, 1 H, HAr, J = 3.4 Hz, J = 5.0 Hz); 7.70 (d, 1 H, HAr, J = 3.4 Hz); 8.16 (d, 1 H, HAr, J = 5.0 Hz). ^{13}C NMR, δ: 51.2, 58.2, 67.8 (C(1), C(4), C(7)); 117.2 (q, CF_3, J = 288 Hz); 128.3, 133.3 (C(5), C(6)); 133.7, 134.7, 137.8, 138.8 (C arom.); 144.4; 169.8 (C(2), C(3)); 175.5 (q, C=O, J = 40 Hz).

2-Trifluoroacetyl-3-(2-furyl)bicyclo[2.2.1]hepta-2,5-diene (9b). Yield 1.96 g (77%), b.p. 83—84 °C (1 Torr), m.p. 34 °C. Found (%): C, 61.68; H, 3.60; F, 22.19. $C_{13}H_9F_3O_2$. Calculated (%): C, 61.42; H, 3.54; F, 22.42. IR, ν/cm^{-1}: 1659 (C=C); 1703 (C=O). ^{1}H NMR, δ: 2.29 (d, 1 H, CH_2, J = 7.1 Hz); 2.36 (d, 1 H, CH_2, J = 7.1 Hz); 4.11 (d, 1 H, HC(4), J = 2.5 Hz); 4.28 (d, 1 H, HC(1), J = 2.5 Hz); 6.93 (dd, 1 H, HAr, J = 1.8 Hz, J = 3.8 Hz); 6.98 (dd, 1 H, HC(5), J = 2.5 Hz, J = 5.2 Hz); 7.10 (dd, 1 H, HC(6), J = 2.5 Hz, J = 5.2 Hz); 7.69 (m, 1 H, HAr); 7.91 (d, 1 H, HAr, J = 3.8 Hz). ^{13}C NMR, δ: 49.4, 56.7, 67.1 (C(1), C(4), C(7)); 116.1 (q, CF_3, J = 288 Hz); 126.6, 131.5, 136.2, 140.2, 144.9, 146.4, 149.8, 156.4 (C(5), C(6), C(2), C(3), Ar); 173.6 (q, C=O, J = 40 Hz).

2-Trifluoroacetyl-3-(4-fluorophenyl)bicyclo[2.2.1]hepta-2,5-diene (9c). Yield 2.09 g (74%), b.p. 104—105 °C (1 Torr). Found (%): C, 64.11; H, 3.62; F, 26.70. $C_{15}H_{10}F_4O$. Calculated (%): C, 63.83; H, 3.58; F, 26.93. IR, ν/cm^{-1}: 1660 (C=C); 1700 (C=O). ^{1}H NMR, δ: 2.21 (d, 1 H, CH_2, J = 7.1 Hz); 2.30 (d, 1 H, CH_2, J = 7.1 Hz); 3.98 (d, 1 H, HC(4), J = 3.0 Hz); 4.25 (d, 1 H, HC(1), J = 3.0 Hz); 6.98 (dd, 1 H, HC(5), J = 3.0 Hz, J = 5.1 Hz); 7.14 (dd, 1 H, HC(6), J = 3.0 Hz, J = 5.1 Hz); 7.19 (dd, 2 H, HAr, J = 8.4 Hz, J = 8.9 Hz); 8.15 (dd, 2 H, HAr, J = 5.5 Hz, J = 8.9 Hz). ^{13}C NMR, δ: 52.0, 59.4, 70.4 (C(1), C(4), C(7)); 115.9 (d, Ar, J = 22.0 Hz); 116.9 (q, CF_3, J = 292 Hz); 129.8 (Ar); 132.5 (d, Ar, J = 9.0 Hz); 140.0, 140.8, 145.0 (C(5), C(6), C(3)); 166.8 (d, Ar, J = 30.0 Hz); 171.2 (C(2)); 177.2 (q, C=O, J = 38.0 Hz).

References

1. C. Zhang, C. J. Ballay, M. L. Truddel, *J. Chem. Soc., Perkin Trans.*, 1999, **1**, 675.
2. C. Zhang, M. L. Trudell, *Tetrahedron*, 1998, **54**, 8349.
3. R. E. Ireland, L. Courthey, B. J. Fitzsimmons, *J. Org. Chem.,* 1983, **48**, 5186.
4. A. B. Koldobskii, E. B. Solodova, I. A. Godovikov, V. N. Kalininin, *Dokl. Akad. Nauk*, 2008, **420**, 768 [*Dokl. Chem.* (*Engl. Transl.*), 2008].
5. A. Yu. Zenova, A. A. Borisenko, V. V. Platonov, M. V. Proskurnina, N. S. Zefirov, *Zh. Org. Khim.*, 1996, **32**, 992 [*Russ. J. Org. Chem.* (*Engl. Transl.*), 1996, **32**].
6. A. B. Koldobskii, E. B. Solodova, V. N. Kalininin, *Dokl. Akad. Nauk*, 1999, **366**, 58 [*Dokl. Chem.* (*Engl. Transl.*), 1999].
7. D. Obrecht, C. Zumbrunn, K. Muller, *J. Org. Chem.*, 1999, **64**, 6182.
8. A. B. Koldobskii, N. P. Tsvetkov, I. A. Godovikov, V. N. Kalinin, *Izv. Akad. Nauk, Ser. Khim.*, 2009, 1397 [*Russ. Chem. Bull., Int. Ed.*, 2009, **58**, 1438].
9. A. B. Koldobskii, N. P. Tsvetkov, P. V. Verteletskii, I. A. Godovikov, V. N. Kalinin, *Izv. Akad. Nauk, Ser. Khim.*, 2009, 1390 [*Russ. Chem. Bull., Int. Ed.*, 2009, **58**, 1431].
10. A. B. Koldobskii, O. S. Shilova, V. N. Kalinin, *Mendeleev Commun.*, 2001, 99.
11. S. V. Druzhinin, E. S. Balenkova, V. G. Nenajdenko, *Tetrahedron*, 2007, **63**, 7753.
12. L. Brandsma, H. D. Verkruijsse, *Preparative Polar Organometallic Chemistry*, Springer-Verlag, New York, 1988, **1**.

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