Sulfur-Alkyne Cyclizations for Formation of Dihydrothiophenes and Annulated Thiophenes

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Abstract: Cycloisomerization of homopropargylic thiols to dihydrothiophenes is promoted by group VI metal carbonyls. Related thiacyclization transformations under basic and radical conditions are also described, including regioselective formation of benzothiophenes from aryl methyl sulfides and alkynes.

Key words: alkynes, diazo compounds, sulfur heterocycles, thiacyclizations, transition metals

Our laboratory has studied transition metal-promoted cyclizations of terminal alkynes tethered to various nucleophiles. In the course of this work we have discovered novel cycloisomerization transformations with oxygen,[1] nitrogen,[2] and carbon[3] nucleophiles (Figure 1). Sulfur heterocycles have broad utility as isosteric analogs of other cyclic structures,[4] and these substructures are found in a wide range of pharmaceutically important compounds as well as conducting organic polymers. This communication describes our studies on cycloisomerizations of terminal alkynyl thiols to dihydrothiophenes, as well as related transformations for forming annulated thiophenes from various alkyne and sulfide reactants.

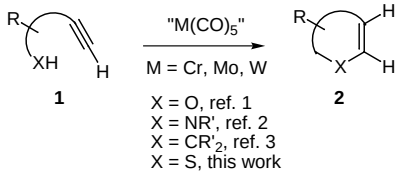
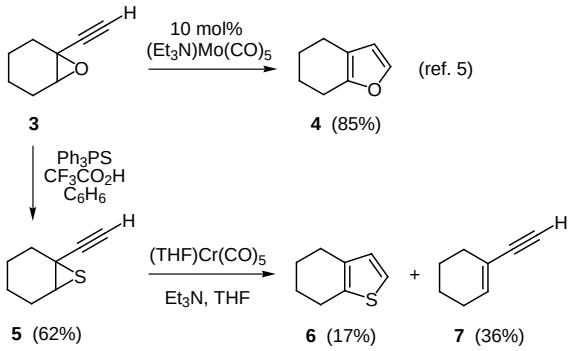


Figure 1 Group VI metal-promoted cycloisomerizations

With our precedent of a particularly efficient cycloisomerization of alkynyl epoxide **3** to tetrahydrobenzofuran **4**,[5] we began our studies by preparing the analogous alkynyl episulfide **5** (Scheme 1).[6] Although compound **5** was thermally sensitive and would extrude sulfur upon warming to provide enyne **7**, reaction of **5** with $(THF)Cr(CO)_5$[7] led to formation of tetrahydrobenzothiophene **6** and the enyne **7**.[8]

We then explored cycloisomerizations of alkynylthiols **8** and **9**.[9] Catalytic $(Et_3N)Mo(CO)_5$[7] gave a modest yield of dihydrothiophene **10** from substrate **8** (Table, Entry 1), but the yield was not significantly improved by increasing the quantity of molybdenum catalyst. Cyclizations promoted by $(THF)W(CO)_5$ in the absence of an amine base furnished metal complexes[10] of dihydrothiophenes **10**/**11** as the major products (Table, Entry 2), whereas $(THF)Cr(CO)_5$ gave mixtures of metal-free and complexed dihydrothiophenes. After finding that decomplexation of **11**-$W(CO)_5$ to metal-free dihydrothiophene **11** occurred upon treatment with DBU, we developed a better preparative procedure in which dihydrothiophenes **10** and **11** were obtained as the major products upon irradiation of a mixture of the corresponding substrate **8** or **9**, $Cr(CO)_6$,



Scheme 1 Cycloisomerization of alkynyl episulfide **5**

Table Conditions for Alkynylthiol Cycloisomerization

8 R = Ph
9 R = *n*-C_8H_{17}

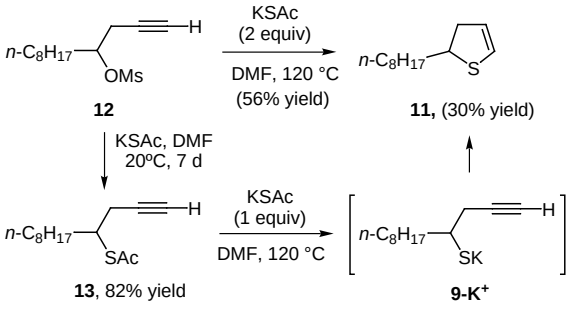
10 R = Ph
11 R = *n*-C_8H_{17}

Entry	Substrate	Conditions	Product	Yield[a] (%)
1	**8**	20 mol% $(Et_3N)Mo(CO)_5$ Et_2O, 5 h	**10**	15
2	**9**	1 equiv $(THF)W(CO)_5$ THF, 17 h	**11**-$W(CO)_5$	65
3	**8**	1 equiv $Cr(CO)_6$, hν (350 nm) THF, DBU, 3 h	**10**	43
4	**9**	2 equiv $Cr(CO)_6$, hν (350 nm) THF, DBU, 3 h	**11**	76

[a] Yield of isolated product.

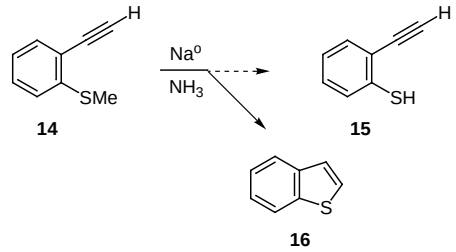
DBU, and THF at 350 nm (Table, Entries 3, 4). For substrate **9** without a chromophoric substituent, dihydrothiophene **11** was obtained in 76% yield when 2 equivalents of $Cr(CO)_6$ were used (Table, Entry 4).

In the course of preparing alkynylthiol **9**, we discovered that reaction of mesylate **12** with excess potassium thioacetate proceeded very slowly at room temperature and required seven days for nearly complete conversion to the alkynyl thioacetate **13**. An attempt to carry out this displacement reaction at elevated temperatures unexpectedly furnished a 56% yield of dihydrothiophene **11** (Scheme 2). Formation of compound **11** was also observed when thioacetate **13** was combined with potassium thioacetate at higher temperatures, suggesting the intermediacy of **13** and the alkynylthiolate **9-K**[11] in the single-step formation of dihydrothiophene **11** from alkynyl mesylate **12**.



Scheme 2 Formation of dihydrothiophene **11** from **12**

In order to explore analogous cycloisomerizations of arylthiol nucleophiles, we sought to prepare *o*-ethynylthiophenol **15** (Scheme 3). Surprisingly, reaction of compound **14**[12] with sodium-ammonia (precedented conditions for demethylation of aryl methyl sulfides)[13] produced benzothiophene **16** instead of alkynylthiol **15**, presumably by 5-*endo*-dig cyclization of the arylthiol radical generated in the demethylation of **14**.



Scheme 3 Thiacyclization of alkyne-aryl methyl sulfide **14**

One of our general goals in this area was to develop a novel, short, and regioselective synthetic route to 2-arylbenzothiophenes. One specific target compound was structure **17** (Figure 2),[14] which is an advanced intermediate in the preparation of the antiestrogenic drug raloxifene (**18**), a selective estrogen receptor modulator which has been recently approved for treating bone loss associated with postmenopausal osteoporosis.[15]

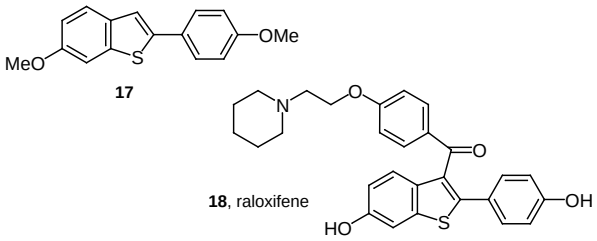
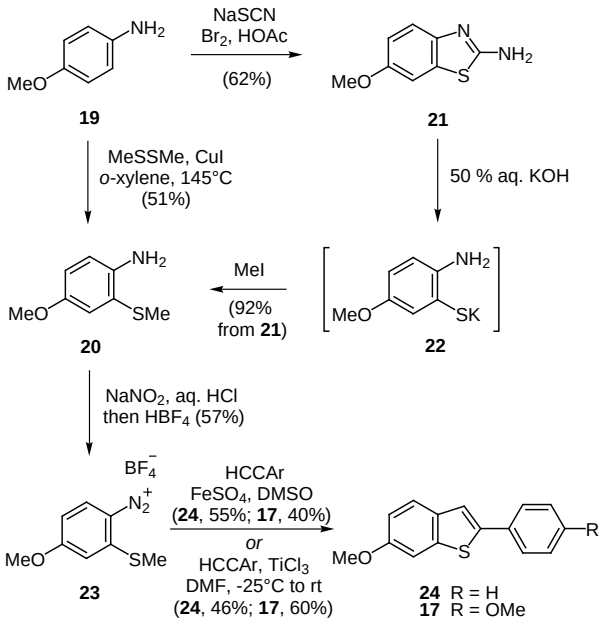


Figure 2 Structures of target compound **17** and raloxifene **(18)**

The standard published route for preparing 2-arylbenzothiophenes including compound **17** proceeds in only two steps from commercial materials, but the benzothiophene-forming step proceeds with modest regioselectivity.[14a] As a result, several other synthetic approaches to raloxifene have been reported which are somewhat longer but highly regioselective.[16] We now report that radical bond-forming methods can be used to effect carbon-carbon bond formation, sulfur demethylation and cyclization in a single step, beginning with *o*-diazonium aryl methyl sulfide **23**. We developed two routes for the preparation of compound **23** from commercial *p*-anisidine (**19**) (Scheme 4). The 2-aminobenzothiazole **21** could be prepared from **19** by reaction with sodium thiocyanate and bromine,[17] which upon hydrolytic cleavage and selective *S*-methylation of intermediate **22** afforded 4-methoxy-2-thiomethylaniline (**20**) in excellent yield. Alternatively, compound **20** could be prepared in a single step by copper iodide-promoted thiomethylation.[18] Diazotization under standard conditions afforded crystalline diazonium tetrafluoroborate **23**. Annulation of **23** with phenylacetylene and 1-ethynyl-4-methoxybenzene[19] could be accomplished with either $FeSO_4$ in pyridine or DMSO,[20] or with $TiCl_3$ in DMF,[21] to effect regioselective formation of 2-arylbenzothiophene products **24** and **17**.[22]

In conclusion, this communication documents a variety of methods and strategies for construction of sulfur heterocycles by thiacyclizations and annulations of alkynes with sulfur reactants. We anticipate that these methods will find considerable use in selective preparations of other sulfur heterocyclic compounds.

^{1}H NMR spectra were measured in $CDCl_3$ or DMSO-d_6 at 300 MHz on a Varian Mercury 300 NMR spectrometer and were referenced with residual $CHCl_3$ (7.26 ppm) or DMSO (2.50 ppm). ^{13}C NMR spectra were recorded at 75 MHz on the Varian Mercury 300 and were referenced with the 77.0 ppm resonance of $CDCl_3$ or 39.7 ppm of DMSO-d_6. IR spectra were recorded on Mattson Genesis II FT-IR. Mass spectra (EI) or high-resolution mass spectra (EI) were measured at 70 eV on VG-70S instrument. High-resolution FAB mass spectra were recorded on Jeol SX102 at 6kV-Xe using 3-nitrobenzyl alcohol, in some cases with addition of LiI as a matrix. Melting points were determined with a Fisher-Johns melting point apparatus and are uncorrected. Elemental analyses were performed



Scheme 4 Concise syntheses of 2-arylbenzothiophenes

by Atlantic Microlab, Inc. in Norcross, GA. All reactions were conducted in oven-dried (125°C) or flame-dried glassware under dry N_2. Et_2O and THF for reactions were distilled from sodium benzophenone ketyl; CH_2Cl_2 was distilled from CaH_2; DMF, DMSO, and *o*-xylene were used without purification from Sure-Seal bottles (Aldrich). All reagents were purchased from Aldrich Chemical Co. and used without further purification unless noted. Flash chromatography was performed with silica gel (40 microns; 32−63 μ) purchased from Scientific Adsorbent, Inc.

Dodec-1-yne-4-thiol (9)

$LiAlH_4$ (140 mg, 3.6 mmol) was suspended in anhyd Et_2O (20 mL), and a solution of thioacetate **13** (378 mg, 1.6 mmol) in Et_2O (10 mL) was added in small portions. The mixture was stirred for 2 h at r.t. and then poured into ice-water, diluted with Et_2O and shaken. The layers were separated, and the aqueous layer was extracted twice with Et_2O. The combined organic fractions were dried (Na_2SO_4). Chromatography with hexane/ether (1:20) gave 220 mg (70%) of thiol **9**.

^{1}H NMR ($CDCl_3$): δ = 2.94 (m, 1 H, C*H*SH), 2.53 (m, 2 H, $CH_2C{\equiv}C$), 2.09 (t, 1 H, *J* = 1.8 Hz, acetylenic H), 1.82 (d, 1 H, *J* = 5.4 Hz, SH), 1.28 (br s, 14 H, CH_2's), 0.89 (t, 3 H, *J* = 6.6 Hz, CH_3).

^{13}C NMR ($CDCl_3$): δ = 81.5 (*C*≡CH), 70.9 (C≡*C*H), 39.3, 37.6, 32.0, 29.6, 29.4, 29.3, 27.4, 22.8, 14.3.

IR (neat): ν = 3310 (s), 2920 (s), 2855 (s), 2120 (w), 1465 (m), 1260 (m), 1120 (m) cm^{-1}.

Anal. calcd for $C_{12}H_{22}S$: C 72.73; H 11.11, S 16.16. Found: C 72.14; H 11.20; S 15.94.

2-Octyl-2,3-dihydrothiophene (11)

Method A from Dodeca-1-yne-4-thiol (**9**): Alkynylthiol **9** (70 mg, 0.35 mmol), $Cr(CO)_6$ (154 mg, 0.7 mmol), DBU (5 mL) and THF (20 mL) were premixed into an air-free Pyrex reaction tube fitted with a reflux condenser. This solution was irradiated (350 nm, Rayonet photoreactor) for 3 h, and an internal fan was used to cool the reaction vessel. The reaction mixture was then stirred at r.t. for 7 d, diluted with 1% HCl and extracted three times with Et_2O. Combined organic layers were washed with 1% HCl and dried (Na_2SO_4). Flash chromatography with hexane gave 54 mg (76%) of dihydrothiophene **11**.

Method B from Dodeca-1-yn-4-ol Mesylate Ester (12): A solution of mesylate **12** (4.00 g, 15.3 mmol) and KSAc (5.26 g, 46 mmol) in DMF (60 mL) was stirred overnight at 120 °C. The reaction mixture was diluted with H_2O and extracted three times with Et_2O. Combined organic fractions were washed with aq satd $NaHCO_3$ solution and dried (Na_2SO_4). Flash chromatography with hexane gave 1.7 g (56%) of dihydrothiophene **11**.

Method C from Dodeca-1-yne-4-thioacetate (13): A solution of thioacetate **13** (150 mg, 0.63 mmol) and KSAc (72 mg, 0.63 mmol) in DMF (2.5 mL) was stirred at 120 °C over 4 d and additionally for 6 d at r.t. The reaction mixture was diluted with 1% HCl and extracted three times with Et_2O. The combined organic fractions were dried (Na_2SO_4). Chromatography with pentane gave 36 mg (30%) of dihydrothiophene **11**; bp 73−76°C/0.3 Torr.

^{1}H NMR ($CDCl_3$): δ = 6.11 (dt, 1 H, *J* = 6, 2.4 Hz, olefinic proton), 5.54 (dt, 1 H, *J* = 6, 2.7 Hz, olefinic proton), 3.77 (m, 1 H, CH of the thiophene ring), 2.82 (m, 1 H, one of the CH_2 protons from the thiophene ring), 2.43 (m, 1 H, one of the CH_2 protons from the thiophene ring), 1.6−1.71 (br m, 2 H, CH_2 next to the thiophene ring), 1.27 (br s, 12 H, CH_2's), 0.88 (t, 3 H, *J* = 6.6 Hz, CH_3).

^{13}C NMR ($CDCl_3$): δ = 125.0, 121.3, 50.5, 41.4, 36.9, 31.9, 29.6, 29.5, 29.3, 28.3, 22.7, 14.2.

IR (neat): ν = 2925 (s), 2855 (s), 1940 (w), 1720 (w), 1465 (m) cm^{-1}.

MS (EI): *m*/*z* (%) = 198 (M^+), 85 ($M^+ - C_8H_{17}$).

HRMS (EI): *m*/*z* calcd for $C_{12}H_{22}S$ 198.1442, found 198.1441.

Anal. calcd for $C_{12}H_{22}S$: C 72.73; H 11.11; S 16.16. Found: C 70.24; H 10.69; S 15.51.

Dodeca-1-yne-4-mesylate (12)

Dodeca-1-yn-4-ol (3.0 g, 10.5 mmol) and Et_3N (3.4 mL, 24.8 mmol) were dissolved in CH_2Cl_2 (100 ml) and then cooled to 0 °C. $MeSO_2Cl$ (2.8 mL, 36 mmol) was then added and the reaction mixture was stirred overnight at r.t.. The mixture was then diluted with aq sat. $NaHCO_3$ solution, the aqueous layer separated from organics, and extracted twice with CH_2Cl_2. The combined organic fractions were washed with H_2O and dried (Na_2SO_4). Chromatography with hexane/Et_2O (5:1) gave 4.0 g (93%) of mesylate **12**.

^{1}H NMR ($CDCl_3$): δ = 4.73 (m, 1 H, $CHOSO_2$), 3.05 (s, 3 H, CH_3SO_2), 2.62 (q, 2 H, *J* = 2.7, 6 Hz, $CH_2C{\equiv}C$), 2.07 (t, 1 H, *J* = 2.7 Hz, acetylenic H), 1.77 (m, 2 H, CH_2CHOSO$_2$CH$_3$), 1.26 (br s, 12 H, CH_2's), 0.87 (t, 3 H, *J* = 6.3 Hz, CH_3).

^{13}C NMR ($CDCl_3$): δ = 80.5, 78.9, 71.5, 38.8, 34.1, 32.0, 29.5, 29.4, 25.1, 22.8, 14.3.

IR (neat): 3290 (m), 2930 (s), 2855 (s), 2125 (w), 1355 (s), 1175 (s), 915 (s) cm^{-1}.

HRMS (FAB^+): *m*/*z* calcd for $C_{12}H_{24}O_3SLi$ ($[M+Li]^+$) 267.1606, found 267.1604.

Anal. Calcd for $C_{12}H_{24}O_3S$: C 60.00; H 9.23; S 12.31. Found: C 60.06; H 9.28; S 12.20.

Dodeca-1-yne-4-thioacetate (13)

A solution of mesylate **12** (500 mg, 1.9 mmol) and KSAc (438 mg, 3.8 mmol) in DMF (7.5 mL) was stirred at r.t. for 4 d. Additional KSAc (438 mg, 3.8 mmol) was then added to the reaction mixture, and stirring continued for another 3 d at r.t. The mixture was diluted with 1% HCl and extracted three times with Et_2O. The combined organic layers were dried (Na_2SO_4). Chromatography with hexane/Et_2O (12:1) gave 378 mg (82%) of thioacetate **13**.

^{1}H NMR ($CDCl_3$): δ = 3.63 (m, 1 H, C*H*SAc), 2.55 (m, 2 H, CH_2C≡C), 2.34 (s, 3 H, $COCH_3$), 2.03 (t, 1 H, *J* = 2.7 Hz, acetylenic H), 1.27 (br s, 14 H, CH_2's), 0.88 (t, 3 H, *J* = 6.6 Hz, CH_3).

^{13}C ($CDCl_3$): δ = 195.6 (CO), 76.5 (*C*≡CH), 65.9 (C≡*C*H), 42.9 ($COCH_3$), 33.0, 32.1, 31.0, 29.7, 29.5, 29.4, 27.1, 25.2, 22.9, 14.4.

IR (neat): ν = 3310 (m), 2925 (s), 2855 (s), 2120 (w, C≡C), 1690 (s, C=O), 1465 (m), 1120 (s), 950 (m) cm^{-1}.

HRMS (EI): *m*/*z* calcd for $C_{14}H_{22}OS$ 240.1548, found 240.1541; for $C_{12}H_{21}S$ ($C_{14}H_{22}OS$ − acetate) calcd 197.1364, found 197.1389.

Anal. calcd for $C_{14}H_{24}OS$: C 70.00; H 10.00; S 13.33. Found: C 69.73; H 9.93; S 13.60.

6-Methoxy-1-(4-methoxyphenyl)benzo[*b*]thiophene (17)

Diazonium tetrafluoroborate **23** (100 mg, 0.37 mmol) and 1-ethynyl-4-methoxybenzene (0.35 mL, 1.48 mmol) were dissolved in DMF (0.2 mL), and $TiCl_3$ (57 mg, 0.37 mmol) was added in one portion at −25 °C. The reaction mixture was stirred at −25 °C for 2.5 h, and then overnight at r.t.. The mixture was diluted with 1% HCl and extracted with CH_2Cl_2 and EtOAc. The combined organic fractions were dried (Na_2SO_4) and absorbed onto silica gel. After chromatography with hexane/Et_2O (50:1), 201 mg of 1-ethynyl-4-methoxybenzene was recovered, and 61 mg (60%) of benzothiophene **17** was separated in the form of white crystals; mp 200−204°C.

^{1}H NMR ($CDCl_3$): δ = 7.58−7.66 (m, 3 H), 7.35 (s, 1 H), 7.30 (d, 1 H, *J* = 2.1 Hz), 6.92−7.01 (m, 3 H), 3.89 (s, 3 H, OCH_3), 3.86 (s, 3 H, OCH_3).

^{13}C NMR ($CDCl_3$): δ = 159.7, 157.4, 141.7, 140.8, 135.1, 127.6, 124.1, 117.9, 114.5, 105.1, 55.8 (OCH_3) 55.6 (OCH_3).

IR (KBr): ν = 2960 (m), 2925 (m), 2360 (w), 2340 (w), 1600 (s), 1500 (s), 1400 (s), 1250 (s), 1025 (s) cm^{-1}.

HRMS (EI): *m*/*z* calcd for $C_{16}H_{14}O_2S$ (M^+) 270.0711, found 270.0713.

Anal. calcd for $C_{16}H_{14}O_2S$: C 71.11, H 5.19, S 11.85. Found: C 70.82; H 5.79; S 11.05.

2-Thiomethyl-4-methoxyaniline (20)

Method A: A mixture of *p*-anisidine (**19**; 1.23 g, 10 mmol, recrystallized from a mixture of EtOH/H_2O before reaction), CuI (1.9 g, 10 mmol), Me_2S_2 (2.5 mL, 25 mmol) and *o*-xylene (5 mL) was refluxed for 94 h, then cooled to r.t., diluted with 3 N aq NaOH (5 mL) and left overnight with stirring. The liquid was decanted from the black precipitate, which was washed with Et_2O several times. The combined aqueous and organic fractions were shaken and separated, and the aqueous layer was then extracted twice with Et_2O. The combined organic fractions were washed twice with 3 N HCl. The acidic aqueous fractions were filtered, basified with aq 5 N NaOH and extracted with Et_2O, and the ethereal extracts were dried (Na_2SO_4). After silica gel chromatography with EtOAc/hexane (1:2), the product **20** was obtained in 51% yield (865 mg) as a colorless oil.

Method B: A suspension of benzothiazole **21** (17.8 g, 99 mmol) in 25% aq KOH (200 g) was refluxed for 17 h. After cooling to r.t., MeI (6.2 mL, 99 mmol) was added in one portion. The reaction mixture was stirred for an additional hour at r.t. and extracted with Et_2O. Combined organic fractions were dried (Na_2SO_4) and concentrated. Distillation of the crude gave 15.5 g (92%) of aniline **20**; bp 95−110°C/0.5 Torr.

^{1}H NMR ($CDCl_3$): δ = 6.92 (m, 1 H, aromatic H), 6.68 (m, 2 H, aromatic H), 3.95 (br s, 0-1 H, NH_2), 3.75 (s, 3 H, OCH_3), 2.38 (s, 3 H, SCH_3).

^{13}C NMR ($CDCl_3$): δ = 152.6, 140.6, 121.8, 117.6, 116.1, 114.8, 56.0 (OCH_3), 17.7 (SCH_3).

IR (neat): ν = 3420 (m, N−H), 3340 (m, N−H), 1595 (s), 1490 (s), 1280 (s), 1240 (s), 1040 (s, C−O) cm^{-1}.

6-Methoxy-2-aminobenzothiazole (21)

A solution of Br_2 (16 ml, 320 mmol) in glacial AcOH (50 mL) was added dropwise to a mixture of *p*-anisidine (**19**; 20 g, 160 mmol), NaSCN (26 g, 320 mmol) and AcOH (550 mL) at 10−15°C over 3 h. After additional stirring for 45 min at r.t., the precipitate was filtered, dissolved into warm water and basified with concentrated NaOH to pH 8. The beige precipitate was filtered and recrystallized from MeOH to give 17.8 g (62%) of **21** with mp 160−166°C.

^{1}H NMR ($CDCl_3$): δ = 7.29 (d, 1 H, $J_{H7\text{-}H5}$ = 3 Hz, H-5 of benzothiazole ring), 7.21 (s, 2 H, NH_2), 7.21 (d, 1 H, $J_{H8\text{-}H7}$ = 9 Hz, H-8 of benzothiazole ring), 6.80 (dd, 1 H, $J_{H8\text{-}H7}$ = 9 Hz, $J_{H7\text{-}H5}$ = 3 Hz, H-7 of benzothiazole ring), 3.72 (s, 3 H, OCH_3).

^{13}C NMR ($CDCl_3$): δ = 165.0, 154.0, 147.0, 132.0, 118.0, 113.0, 105.0, 58.0 (OCH_3).

IR (KBr): ν = 3390 (m, N−H), 3290 (m, N−H), 3115 (s), 1640 (s), 1547 (s), 1465 (s), 1400 (s), 1280 (m), 1205 (m), 1055 (m) cm^{-1}.

HRMS (EI): *m*/*z* calcd for $C_8H_8N_2OS$ (M^+) 180.0357, found 180.0361.

Anal. calcd for $C_8H_8N_2OS$: C 53.33; H 4.44; N 15.56; S 17.78. Found: C 51.92; H 4.43; N 15.44; S 17.67.

2-Thiomethyl-4-methoxydiazobenzene Tetrafluoroborate (23)

A suspension of aniline **20** (550 mg, 3.2 mmol) in H_2O (1 mL) was mixed with concd HCl (37% in H_2O, 8.1 mL, 9.7 mmol). The reaction mixture was stirred at r.t. for 1 h and then cooled to −5 °C. A solution of $NaNO_2$ (224 mg, 3.2 mmol) in H_2O (1 mL) was added dropwise over 25 min, followed by rapid addition of aq HBF_4 (47%, 5.9 mL, 31 mmol), keeping the reaction temperature at or below 0°C. After addition of all components, the temperature was gradually increased to r.t. Partial evaporation of the aqueous layer, cooling and filtration gave 490 mg (57%) of diazonium salt **23**.

^{1}H NMR (DMSO-d_6): δ = 8.57 (d, 1 H, $J_{H6\text{-}H5}$ = 9.3 Hz, H-6 of aromatic ring, *meta* to SCH_3), 7.31 (br s, 1 H, H-3 of aromatic ring, *ortho* to SCH_3), 7.27 (d, 1 H, $J_{H6\text{-}H5}$ = 9.3 Hz, H-5 of aromatic ring, *para* to SCH_3), 4.08 (s, 3 H, OCH_3), 2.85 (s, 3 H, SCH_3).

^{13}C NMR (DMSO-d_6): δ = 150.4, 168.1, 136.2, 115.3, 113.7, 100.6, 57.7 (OCH_3), 15.6 (SCH_3).

IR (KBr): ν = 3430 (m), 3395 (m), 3130 (m), 2210 (m, N≡N) 2190 (m, N≡N), 1575 (s), 1400 (m), 1250 (m), 1120 (m) cm^{-1}.

HRMS (FAB$^+$): *m*/*z* calcd for $C_8H_9ON_2S$ ($[M\text{-}BF_4]^+$) 181.0436, found 181.0432.

6-Methoxy-2-phenylbenzo[*b*]thiophene (24)

This compound was prepared analogous to **17** from diazonium tetrafluoroborate **23** and phenylacetylene in DMF and $TiCl_3$ as a promoter with 46% yield. The similar reaction of **23** with phenylacetylene in DMSO at r.t. with 1 equiv of $FeSO_4$–$7H_2O$ gave **24** in 55% yield; mp 155−158°C.

^{1}H NMR ($CDCl_3$): δ = 7.62−7.71 (m, 3 H), 7.37−7.48 (m, 3 H), 7.28−7.35 (m, 2 H), 6.98 (dd, 1 H, *J* = 2, 6 Hz), 3.88 (s, 3 H, OCH_3).

^{13}C NMR ($CDCl_3$): δ = 157.6, 141.8, 141.1, 134.9, 134.5, 129.0, 128.0, 126.5, 124.3, 115.1, 114.8, 105.0, 56.0 (OCH_3).

IR (KBr): ν = 1595 (m), 1520 (m), 1465 (m), 1400 (s), 1260 (m), 1220 (m), 1120 (m), 1060 (m), 1025 (m), 840 (m), 750 (m) cm^{-1}.

HRMS (EI): *m*/*z* calcd for $C_{15}H_{12}OS$ (M^+) 240.0690, found 240.0617.

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(8) A control experiment in which **5** was stirred with Et_3N and THF (without metal catalyst) gave no reaction at room temperature, indicating that the metal carbonyl is required for this transformation.

(9) Alkynylthiol **8** was prepared in two steps from the known homopropargylic alcohol: (i) PPh_3, DEAD, HSAc, Et_2O; (ii) $LiAlH_4$, Et_2O. Alkynylthiol **9** was best prepared by thioacetate displacement of the mesylate: (i) MsCl, Et_3N, CH_2Cl_2; (ii) KSAc, DMF; (iii) $LiAlH_4$, Et_2O. Both homopropargylic alcohols were prepared by standard methods, as described by: Brandsma, L. *Preparative Acetylenic Chemistry*, 2nd ed.; Elsevier: Amsterdam, 1988; p 67, and p 95.

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