JOC The Journal of Organic Chemistry

Note

pubs.acs.org/joc

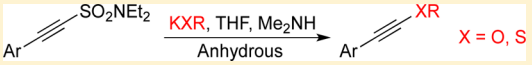
Transition-Metal-Free Synthesis of Ynol Ethers and Thioynol Ethers via Displacement at sp Centers: A Revised Mechanistic Pathway

Vincent James Gray, James Cuthbertson, and Jonathan D. Wilden*

Department of Chemistry, University College London, 20 Gordon Street, London WC1H 0AJ, U.K.

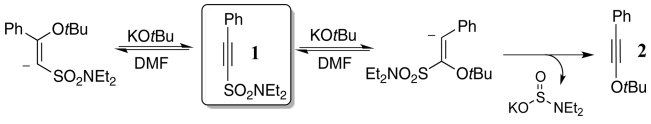
Supporting Information

ABSTRACT: We present here valuable extensions to our previous work in preparing highly functionalized, heteroatom-substituted alkynes via displacement at an sp center. Our results show that a wide range of ynol ethers can be prepared by the same methodology and that the same protocol can be applied to the synthesis of synthetically useful thioynol ethers. We also present new observations that have led us to revise our original hypothesis in favor of a pathway involving radical intermediates.



The transition-metal-free formation of carbon−carbon and carbon−heteroatom bonds has become one of the most debated and explored topics in organic chemistry in recent years.[1] To the surprise of many, various processes that were previously assumed to require a transition-metal catalyst have been found to be viable without the metal additive. Such processes include classical palladium chemistry (e.g., Sonogashira[2] and Heck[3] reactions) and many other TM-mediated processes (particularly those involving copper[4] or a variety of other metals[5]). Most of these processes have employed sodium and potassium *tert*-butoxide and an amine additive (ligand),[6,7] which can sometimes result in reactions that can compete in terms of scope and efficiency with those mediated by the metal. Our own work in this area had focused on the preparation of *tert*-butyl ynol ethers from an alkynyl sulfonamide **1**, which we suggested might proceed via an addition−elimination process to yield the ynol ether **2** with concomitant elimination of potassium *N*,*N*-diethylamidosulfite (Scheme 1 and Figure 1).[8]

Scheme 1. Original Mechanistic Hypothesis for TM-Free Synthesis of Ynol Ethers



Although at the time we made a number of important observations about this reaction, these were not always easy to explain. In particular, the reaction seemed dependent on potassium ions being present in the reaction medium (which we explained somewhat via DFT studies), the process seemed unique to DMF as the solvent, even when compared to other highly polar aprotic solvents, and the presence of an aryl group in the substrate appeared to be essential. Additionally, we have made the counterintuitive observation that those alkynyl sulfonamides bearing an electron-rich aryl group undergo the reaction much faster than their electron-deficient counterparts. Having observed the recent work in the area of TM-free processes and the body of evidence that seems to be building that these processes are radical in nature,[9] we felt compelled to critically reassess our work. We here report further findings which led us to revise our original hypothesis in favor of a radical mechanism, particularly in light of our most recent mechanistic observations.[10]

We first turned our attention to the question of the critical nature of DMF to the success of the reaction. Others had observed that TM-free processes usually proceeded most efficiently when a coordinating molecule (usually an amine)[6,7] was added to the reaction mixture. In reevaluating our work, we therefore hypothesized that DMF was fulfilling this role in our reaction. In doing so, we recognized that an alternative and more convenient solvent might be suitable for the reaction. Choosing THF as the solvent, we explored the effect of coordinating additives that have been employed in various TM-free processes. We were delighted to observe that (in common with others[6]) additives such as DMEDA and related amines not only allowed the reaction to proceed, but gave the products in enhanced yield compared to our original observation (Figure 2). Furthermore, very little variation in yield or efficiency is observed between those additives that promote the reaction, all of the yields being within 5% of each other (Figure 2).

Interestingly, additives appear to fall into two clear groups; those which promote the ynol ether formation ("effective") and those which have no effect ("ineffective") and only yield starting material at the end of the reaction. Clearly, the effective additives are all structurally related, although the exact mode of enhancement is yet to be determined.

Having established an improved strategy for the synthesis of ynol ethers, we then turned our attention to improving the scope of the reaction. Given that our original reports had focused almost exclusively on the *tert*-butyl variants, we were keen to establish a protocol where primary, secondary as well as tertiary ynol ethers could be synthesized. Using the improved protocol outlined in Figure 2, we were pleased to observe that the ynol ethers derived from a range of primary, secondary and tertiary

Received: April 10, 2014
Published: May 19, 2014

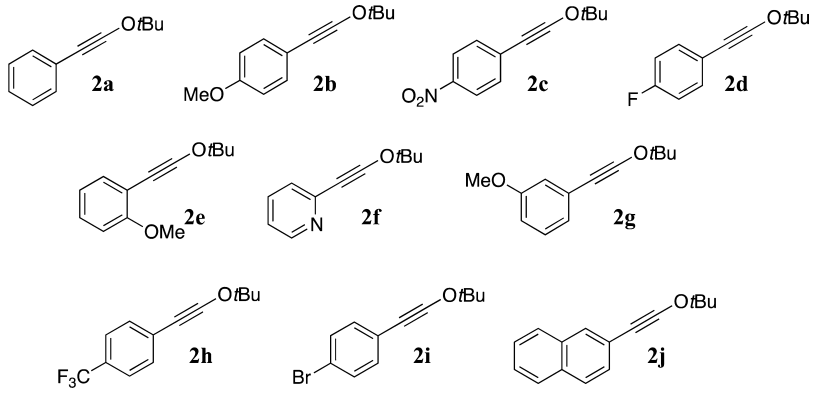


Figure 1. Range of ynol ethers **2a**–**j** prepared by our methodology.

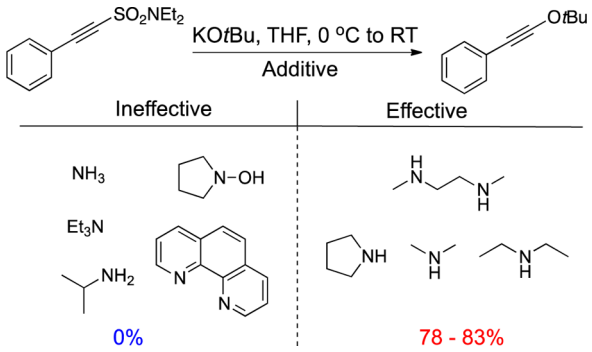


Figure 2. Effect of additives in ynol ether formation.

alkoxides (generated from the parent alcohol and either KH or potassium metal) could be prepared without incident (Figure 3). In general, although any of the additives indicated in Figure 2 can be employed, we have favored addition of dimethylamine to the reaction as its volatility means that it is more easily removed than other additives at the end of the reaction.

In nearly all cases, the ynol ether was isolated in good yield, the only exception being when potassium trifluoroethoxide was employed as the nucleophile, when 2 mol of the alkoxide is incorporated into the product to yield the ketene acetal. Presumably, on formation of the ynol ether, the additional electron-withdrawing capacity of the trifluoroethyl group renders the already reactive ynol ether susceptible to nucleophilic attack at the most electron-deficient carbon atom yielding the observed product.

Following successful endeavors in the synthesis of ynol ethers, we decided to explore the direct analogues with sulfur as the heteroatom in the synthesis of thioynol ethers. These species have received much less attention in the literature and appear to be difficult to prepare by other methods.[11] We began our studies by examining the reaction of the potassium salts of *tert*-butyl thiol (prepared from KH and the parent thiol) under the reaction conditions outlined in Figure 3. Once again, we were pleased to observe that the *tert*-butyl thioynol ethers could be obtained in most cases in reasonable yields (Figure 4).

We then turned our attention to exploring the scope of the thiols that could be employed in this reaction. Our initial studies have indicated that by using the procedure outlined in Figure 4, thioynol ethers can be obtained directly when simple primary alkyl thiolates are used; however, when secondary alkyl thiolates are employed, the α-addition product is isolated (Figure 5). In common with the oxygen series,[8] the α-addition products are isolated as a single geometrical isomer, in this case the (*E*)-isomer. The outcome of the reaction appears to have little or no dependence on steric factors, and this is one observation that has led us to revise our thinking in favor of a radical mechanism (discussed later).

These observations led us to the hypothesis that an intermediate vinyl anion (common also to the ynol ether synthesis) was an intermediate in the reaction mechanism. To test this hypothesis, we proceeded to dope the reaction medium with first 5% H_2O and then 5% D_2O. As expected, in both cases the α-addition product resulted in excellent yields with almost complete deuterium incorporation when D_2O was used. Furthermore, the α-addition products could be converted to

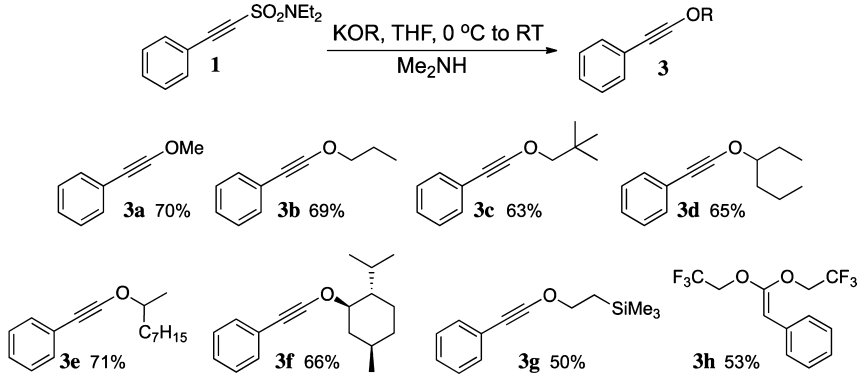


Figure 3. Ynol ethers synthesized from various alkoxides.

dx.doi.org/10.1021/jo500814y | *J. Org. Chem.* 2014, 79, 5869–5874

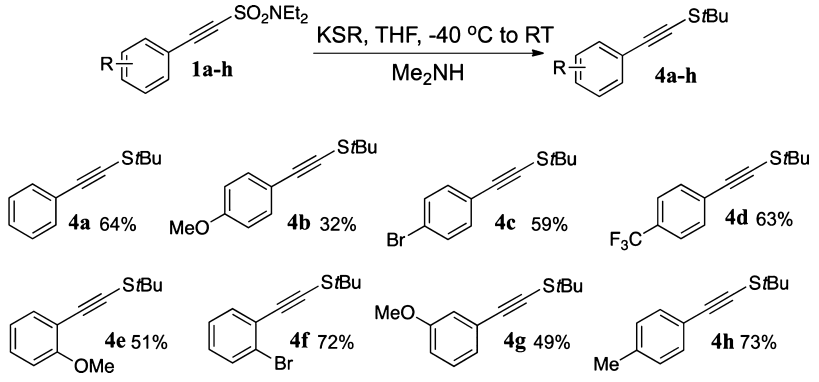


Figure 4. Synthesis of *tert*-butyl thioynol ethers.

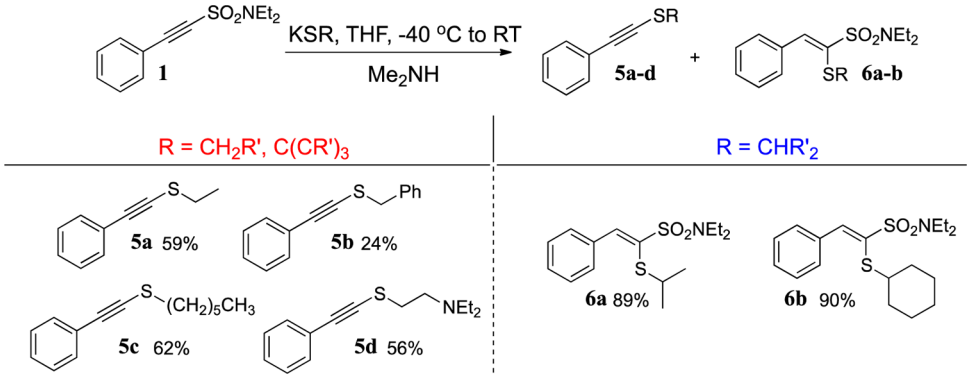
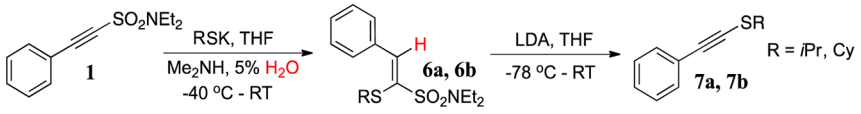


Figure 5. Comparison of the reactivity of primary and secondary thiols.

Scheme 2



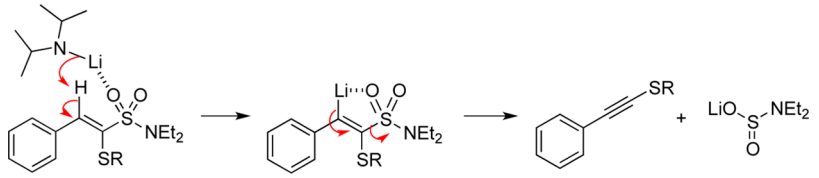


Figure 6. Mechanistic pathway for the LDA-promoted elimination.

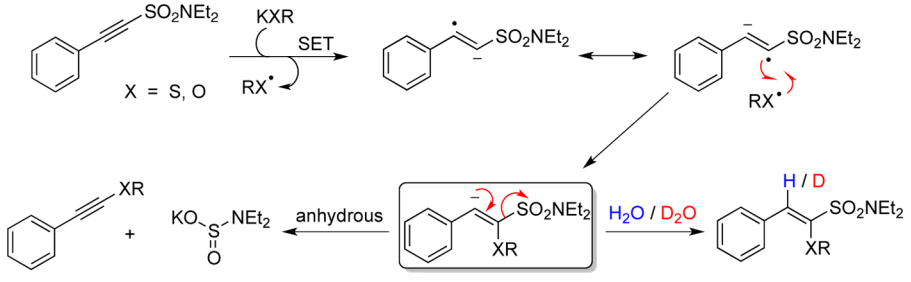


Figure 7. Revised mechanistic pathway involving radical intermediates.

the thioynol ether in excellent yields by treatment with LDA (Scheme 2).

Presumably, the well-known propensity of the sulfonamide moiety to direct metalation to adjacent carbon atoms results in facile deprotonation (facilitated by the fact that the compound is the appropriate geometrical isomer for such a reaction)[12] followed by elimination of lithium *N*,*N*-diethylamidosulfite as described previously (Figure 6). This approach is a reliable method of obtaining the thioynol ethers where the initial procedure yields predominantly the α-addition products.

dx.doi.org/10.1021/jo500814y | *J. Org. Chem.* 2014, 79, 5869−5874

The course of our work has led us to revise our original hypothesis in favor of a related addition−elimination pathway, but one that proceeds via a radical process. Our most recent work (along with a growing body of work in the literature) suggests that potassium alkoxides (and certainly thiolates) have inherent electron-transfer ability and might feasibly promote a single electron transfer to the alkynyl sulfonamide. This process is highly reminiscent of dissolving metal reduction of alkynes to yield *trans*-alkenes via a single electron transfer pathway. Additionally, the observation that doping the reaction mixture with 5% water results in the anti-Michael products being isolated as single geometrical isomers is consistent with a *trans*-disposed radical anion intermediate as shown in Figure 7. The resulting highly electrophilic heteroatom-centered radical can then combine with the vinyl radical anion at the site of greatest electron density. This might also explain why the more electron-rich species react faster than those alkynyl sulfonamides bearing an electron-withdrawing group. Furthermore, the observation that excess O_2 and radical inhibitors such as galvinoxyl inhibit the reaction led us to propose the revised mechanism outlined in Figure 7.

It is noteworthy that others working in this area while studying similar systems, have postulated a reaction mechanism involving a polar mechanism via coordination of a potassium bound alkoxide to the sulfonyl unit. Given our mechanistic observations in this paper and our previous studies which suggest the potassium counterion is essentially dissociated from the oxygen anion, we feel that the radical mechanism (Figure 7) that results from an initial single electron transfer from the alkoxide to the acetylene is a more accurate description of the observed behavior in these systems.

CONCLUSIONS

We have significantly improved the scope and applicability of our original methodology in the synthesis of a wide range of ynol ethers derived from primary, secondary and tertiary alkoxides. Furthermore, we have applied the same methodology to the synthesis of thioynol ethers along with a strategy to synthesize both α-addition products and the thioynol ethers via sequential addition−elimination. The course of our work has given us cause to reassess the mechanistic pathway and to revise our original hypothesis in favor of an addition−elimination pathway involving radical intermediates.

EXPERIMENTAL SECTION

General Experimental Methods. All reactions were carried out at atmospheric pressure, under argon, unless otherwise stated. Normal-phase silica gel (BDH) was used for flash chromatography. Reactions were monitored by thin-layer chromatography (TLC) using plates precoated with silica gel 60 F_{254} on aluminum visualized by UV (254 nm) and chemical stain (potassium permanganate). Mass spectra were measured in EI and CI mode. Electron-spray ionization spectra were measured on a LC-TOF mass spectrometer. ^{1}H NMR and ^{13}C NMR spectra were recorded at 500 or 600 MHz and 125 or 150 MHz, respectively, at ambient temperature. All chemical shifts were referenced to the residual proton impurity of the deuterated solvent. Coupling constants, *J*, are quoted in hertz to one decimal place. Infrared spectra were obtained on a FTIR Spectrometer operating in ATR mode. Melting points are uncorrected.

General Procedure for the Synthesis of Ynol Ethers 3a−h. *1-Methoxy-2-phenylethyne (**3a**).*[13] To a flame-dried, 25 mL round-bottomed flask purged with argon were added anhydrous methanol (36.3 mg, 1.13 mmol, 5.4 equiv) and anhydrous THF (0.3 mL). Freshly cut potassium metal (44.0 mg, 1.13 mmol, 5.4 equiv) was then carefully added and the reaction mixture stirred at rt for 10 min, followed by reflux at 50 °C for 20 min. The reaction mixture was then allowed to cool to rt, and the contents were concentrated in vacuo. The reaction flask was then cooled to 0 °C, and 2 M dimethylamine in THF (0.28 mL, 0.57 mmol, 2.7 equiv) was added, followed by alkynyl sulfonamide **1** (50.0 mg, 0.21 mmol, 1.0 equiv). The reaction mixture was then allowed to stir for 10 min while warming to rt, followed by *careful* addition of *i*-PrOH (1.0 mL) to quench any residual potassium. The reaction mixture was then dissolved in CH_2Cl_2 (20 mL) and washed with water (10 mL). The organic fraction was dried over $MgSO_4$, filtered, and concentrated in vacuo to give a pale yellow oil, which was purified via flash chromatography (0−5% Et_2O/PE) to give the product as a colorless film (19.5 mg, 0.15 mmol, 70%); IR ν_{max} (film)/cm^{-1} 2965, 2266, 1732, 1444, 1324, 1058, 905; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.35 (m, 2 H), 7.26 (m, 2 H), 7.22 (m, 1 H), 3.99 (s, 3 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.6, 128.3, 126.8, 123.8, 100.2, 66.0, 38.9; LRMS (EI) 132 (98), 105 (99), 91 (36), 89 (100), 77 (81), 63 (36); HRMS (EI) calcd for C_9H_8O (M^+) 132.0570, found 132.0571.

*1-Propoxy-2-phenylethyne (**3b**).* Synthesized using **1** as limiting reagent (50.0 mg, 0.21 mmol, 1.0 equiv): colorless film, 23.2 mg, 69%; IR ν_{max} (film)/cm^{-1} 2968, 2261, 1724, 1323, 1064, 754; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.34 (d, *J* = 7.1 Hz, 2 H), 7.26 (t, *J* = 7.1 Hz, 2 H), 7.21 (t, *J* = 7.1 Hz, 1 H), 4.12 (t, *J* = 6.5 Hz, 2 H), 1.84 (sex., *J* = 7.2 Hz, 2 H), 1.02 (t, *J* = 7.2 Hz, 3 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.6, 128.3, 126.6, 124.2, 99.1, 80.8, 39.6, 22.4, 10.0; LRMS (EI) 160 (35), 118 (100), 117 (25), 90 (20), 90 (16); HRMS (EI) calcd for $C_{11}H_{12}O$ (M^+) 160.0883, found 160.0886.

*1-(Neopentyloxy)-2-phenylethyne (**3c**).* Synthesized using **1** as limiting reagent (50.0 mg, 0.21 mmol, 1.0 equiv): colorless film, 24.9 mg, 63%; IR ν_{max} (film)/cm^{-1} 2968, 2259, 1728, 1326, 1069, 904; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.32 (d, *J* = 7.9 Hz, 2 H), 7.25 (t, *J* = 7.9 Hz, 2 H), 7.20 (t, *J* = 7.9 Hz, 1 H), 3.88 (s, 2 H), 1.01 (s, 9 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.5, 128.3, 126.6, 124.2, 100.3, 89.5, 38.7, 32.6, 26.1; LRMS (EI) 188 (6), 159 (5), 119 (10), 118 (100), 90 (43); HRMS (EI) calcd for $C_{13}H_{16}O$ (M^+) 188.1196, found 188.1193.

*(±)-(Hexan-3-yloxy)ethynyl)benzene (**3d**).* Synthesized using **1** as limiting reagent (50.0 mg, 0.21 mmol, 1.0 equiv): colorless oil, 27.6 mg, 65%; IR ν_{max} (film)/cm^{-1} 2963, 2254, 1461, 1324, 1063, 753; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.33 (d, *J* = 7.3 Hz, 2 H), 7.24 (t, *J* = 7.3 Hz, 2 H), 7.19 (t, *J* = 7.3 Hz, 1 H), 4.05 (tt, *J* = 7.5, 4.9 Hz, 1 H), 1.80−1.83 (m, 2 H), 1.72 (m, 1 H), 1.60 (m, 1 H), 1.52 (m, 1 H), 1.44 (m, 1 H), 1.01 (t, *J* = 7.4 Hz, 3 H), 0.97 (t, *J* = 7.3 Hz, 3 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.5, 128.2, 126.4, 124.6, 97.8, 91.0, 40.8, 35.2, 26.5, 18.6, 14.1, 9.6; LRMS (EI) 202 (6), 145 (6), 119 (8), 118 (100), 86 (30); HRMS (EI) calcd for $C_{14}H_{18}O$ (M^+) 202.1352, found 202.1349.

*(±)-(Nonan-2-yloxy)ethynyl)benzene (**3e**).* Synthesized using **1** as limiting reagent (50.0 mg, 0.21 mmol, 1.0 equiv): colorless oil, 36.4 mg,71%; IR ν_{max} (film)/cm^{-1} 2928, 2253, 1724, 1264, 1063, 753; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.33 (d, *J* = 7.1 Hz, 2 H), 7.25 (t, *J* = 7.1 Hz, 2 H), 7.20 (t, *J* = 7.1 Hz, 1 H), 4.25 (sex., *J* = 6.1 Hz, 1 H), 1.82 (m, 1 H), 1.58 (m, 1 H), 1.42 (d, *J* = 6.1 Hz, 3 H), 1.27−1.40 (m, 10 H), 0.88 (t, *J* = 6.2 Hz, 3 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.5, 128.3, 126.4, 124.5, 97.6, 86.2, 41.1, 35.6, 31.9, 29.5, 29.3, 25.3, 22.8, 19.5, 14.2; LRMS (CI) 245 (25), 237 (37), 147 (26), 119 (100), 91 (20); HRMS (CI) calcd for $C_{17}H_{24}O$ (M + H)$^+$ 245.1899, found 245.1892.

*1-(−)-Menthoxy-2-phenylethyne (**3f**).*[14] Synthesized using **1** as limiting reagent (50.0 mg, 0.21 mmol, 1.0 equiv): colorless oil, 35.5 mg, 66%; IR ν_{max} (film)/cm^{-1} 2951, 2869, 2248, 1730, 1460, 1317, 1062; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.34 (d, *J* = 7.3 Hz, 2 H), 7.25 (t, *J* = 7.3 Hz, 2 H), 7.20 (t, *J* = 7.3 Hz, 1 H), 3.96 (td, *J* = 11.0, 4.5 Hz, 1 H), 2.34 (m, 1 H), 2.23 (sept. d, *J* = 7.0, 2.7 Hz, 1 H), 1.67−1.73 (m, 2 H), 1.43−1.55 (m, 2 H), 1.27 (q, *J* = 11.0 Hz, 1 H), 1.04 (qd, *J* = 13.1, 3.5 Hz, 1 H), 0.98 (d, *J* = 6.6 Hz, 3 H), 0.96 (d, *J* = 6.9 Hz, 3 H), 0.89 (m, 1 H), 0.88 (d, *J* = 6.9 Hz, 3 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.7, 128.3, 126.4, 124.6, 97.8, 88.7, 47.2, 40.9, 40.0, 34.1, 31.8, 26.1, 23.5, 22.2, 20.8, 16.6; LRMS (CI) 256 (15), 237 (20), 139 (100), 118 (15), 83 (15); HRMS (CI) calcd for $C_{18}H_{24}O$ (M^+) 256.1821, found 256.1813; $[\alpha]_D$ = −58 (*c* 1.1, cyclohexane) [lit.[14] $[\alpha]_D$ = −60 (*c* 1.5, cyclohexane)].

*Trimethyl(2-((phenylethynyl)oxy)ethyl)silane (**3g**).* Synthesized using **1** as limiting reagent (50.0 mg, 0.21 mmol, 1.0 equiv): colorless film, 22.9 mg, 50%; IR ν_{max} (film)/cm^{-1} 2948, 2256, 1724, 1639, 1316,

dx.doi.org/10.1021/jo500814y | J. Org. Chem. 2014, 79, 5869−5874

1062; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.34 (d, J = 7.0 Hz, 2 H), 7.25 (t, J = 7.0 Hz, 2 H), 7.20 (t, J = 7.0 Hz, 1 H), 4.24 (m, 2 H), 1.25 (m, 2 H), 0.10 (s, 9 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.6, 128.3, 126.6, 124.3, 98.8, 77.9, 40.5, 18.2, −1.3; LRMS (CI) 219 (66), 191 (51), 175 (33), 119 (38), 101 (30); HRMS (CI) calcd for $C_{13}H_{19}OSi$ $(M + H)^+$ 219.1205, found 219.1209.

(2,2-Bis(2,2,2-trifluoroethoxy)vinyl)benzene (**3h**). Synthesized using **1** as limiting reagent (50.0 mg, 0.21 mmol, 1.0 equiv): yellow oil, 33.4 mg, 53%; IR ν_{max} (film)/cm^{-1} 2935, 1725, 1450, 1152, 1065, 1015; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.42 (d, J = 7.4 Hz, 2 H), 7.30 (t, J = 7.4 Hz, 2 H), 7.16 (t, J = 7.4 Hz, 1 H), 4.87 (s, 1 H), 4.21 (q, J = 8.3 Hz, 2 H), 4.28 (q, J = 7.9 Hz, 2 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 155.1, 133.5, 128.6, 127.6, 125.9, 123.3 (q, J = 275.0 Hz), 122.8 (q, J = 275.0 Hz), 85.8, 66.4 (q, J = 36.0 Hz), 64.3 (q, J = 36.0 Hz); LRMS (EI) 300 (100), 217 (38), 189 (70), 136 (20), 118 (16); HRMS (EI) calcd for $C_{12}H_{10}O_2F_6$ (M^+) 300.0579, found 300.0577.

General Procedure for the Synthesis of Alkynyl Sulfides. *tert-Butyl(phenylethynyl)sulfane* (**4a**).[15] A 25 mL three-necked flame-dried flask was charged with a stirring bar and *tert*-butyl thiol (87.0 mg, 0.96 mmol, 4.0 equiv), followed by anhydrous THF under argon. To the mixture was added KH (39.0 mg, 0.96 mmol, 4.0 equiv, supplied as a 30% weight dispersion in mineral oil which was rinsed with PE and dried between filter paper immediately prior to use) as a single portion. The reaction mixture was stirred at rt for 10 min and then gently heated to 50 °C. The white suspension was stirred at 50 °C for 20 min before being allowed to cool first to rt and then to −40 °C. Dimethylamine solution (2.0 M in THF, 0.24 mL, 0.48 mmol, 2.0 equiv) was added via syringe, followed immediately after by alkynyl sulfonamide **1a** (58 mg, 0.24 mmol, 1.0 equiv). The solution was allowed to warm to rt over 10 min and then carefully quenched with *i*-PrOH (1 mL). The crude mixture was diluted in CH_2Cl_2 (20 mL) and washed with water (10 mL) and brine (10 mL). The organic portions were combined, dried over $MgSO_4$, filtered, and concentrated in vacuo. The crude product was purified via column chromatography (EtOAc/PE) to yield the alkynyl sulfide as a pale yellow oil: 29.7 mg, 64%; IR ν_{max} (film)/cm^{-1} 2963, 2922, 2897, 2164, 1596, 1487, 1456, 1365, 1162; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.44−7.42 (m, 2 H), 7.32−7.28 (m, 3 H), 1.48 (s, 9 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.4, 128.4, 128.0, 123.9, 96.2, 79.1, 48.6, 30.5; LRMS (EI) 190 (19), 134 (100), 84 (23), 57 (33); HRMS (EI) calcd for $C_{12}H_{14}S$ (M^+) 190.0816, found 190.0813.

tert-Butyl((4-methoxyphenyl)ethynyl)sulfane (**4b**). Synthesized using **1b** as limiting reagent (50.0 mg, 0.19 mmol, 1.0 equiv): pale yellow oil, 13.3 mg, 32%; IR ν_{max} (film)/cm^{-1} 2963, 2163, 1603, 1507, 1288, 1247, 1162, 1026; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.39 (d, J = 8.6 Hz, 2 H), 6.83 (d, J = 8.6 Hz, 2 H), 3.81 (s, 3 H), 1.46 (s, 9 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 159.6, 133.4, 116.0, 114.0, 95.9, 77.0, 55.4, 48.4, 30.4; LRMS (EI) 220 (30), 164 (100), 149 (53), 97 (22), 86 (23), 84 (38); HRMS (EI) calcd for $C_{13}H_{16}SO$ (M^+) 220.0916, found 220.0912.

((4-Bromophenyl)ethynyl)(tert-butyl)sulfane (**4c**). Synthesized using **1c** as limiting reagent (60.0 mg, 0.16 mmol, 1.0 equiv): pale yellow oil, 30.0 mg, 59%; ν_{max} (film/cm^{-1}) 2962, 2922, 2861, 2163, 1584, 1482, 1456, 1393, 1365, 1240, 1162, 1069; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.43 (d, J = 8.4 Hz, 2 H), 7.27 (d, J = 8.4 Hz, 2 H), 1.47 (s, 9 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 132.8, 131.6, 122.8, 122.1, 95.2, 80.7, 48.8, 30.5; LRMS (EI) 270 (22), 268 (21), 214 (100), 212 (97), 169 (10), 167 (10), 132 (28); HRMS (EI) calcd for $C_{12}H_{13}BrS$ (M^+) 267.9916, found 267.9915.

tert-Butyl((4-(trifluoromethyl)phenyl)ethynyl)sulfane (**4d**). Synthesized using **1d** as limiting reagent (18.0 mg, 0.06 mmol, 1.0 equiv): colorless oil, 9.40 mg, 62%; IR ν_{max} (film/cm^{-1}) 2964, 2926, 2861, 2163, 1614, 1458, 1367, 1322, 1165, 1127, 1105, 1066, 1017; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.55 (d, J = 8.3 Hz, 2 H), 7.49 (d, J = 8.3 Hz, 2 H), 1.49 (s, 9 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.2, 129.3 (q, J = 32.7 Hz), 127.6, 125.3 (q, J = 3.6 Hz), 125.0 and 123.1 (q, J = 272.0 Hz), 95.3, 82.8, 49.0, 30.5; LRMS (EI) 258 (44), 202 (100), 183 (20), 173 (22), 157 (18), 130 (19); HRMS (EI) calcd for $C_{13}H_{13}F_3S$ (M^+) 258.0685, found 258.0685.

tert-Butyl((2-methoxyphenyl)ethynyl)sulfane (**4e**). Synthesized using **1e** as limiting reagent (56.0 mg, 0.21 mmol, 1.0 equiv): colorless oil, 23.7 mg, 51%; IR ν_{max} (film/cm^{-1}) 2961, 2923, 2898, 2863, 2167, 1593, 1574, 1490, 1456, 1365, 1256, 1161, 1114, 1047; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.38 (dd, J = 7.7, 1.7 Hz, 1 H), 7.25 (t, J = 7.8 Hz, 1 H), 6.89 (t, J = 7.4 Hz, 1 H), 6.86 (d, J = 8.4 Hz, 1 H), 3.87 (s, 3 H), 1.49 (s, 9 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 160.0, 132.9, 129.2, 120.5, 113.3, 110.7, 92.5, 83.1, 55.9, 48.7, 30.4; LRMS (EI) 220 (32), 164 (100), 148 (40), 135 (15), 131 (29), 121 (19); HRMS (EI) calcd for $C_{13}H_{16}OS$ (M^+) 220.0916, found 220.0915.

((2-Bromophenyl)ethynyl)(tert-butyl)sulfane (**4f**). Synthesized using **1f** as limiting reagent (60.0 mg, 0.19 mmol, 1.0 equiv): pale yellow oil, 36.8 mg, 72%; IR ν_{max} (film/cm^{-1}) 2962, 2922, 2898, 2863, 2169, 1465, 1365, 1161, 1046, 1025; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.56 (d, J = 8.1 Hz, 1 H), 7.42 (dd, J = 8.0, 1.3 Hz, 1 H), 7.24 (t, J = 7.6 Hz, 1 H), 7.12 (dt, J = 7.9, 1.5 Hz, 1 H), 1.53 (s, 9 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 132.7, 132.4, 128.8, 127.1, 126.0, 124.8, 94.9, 84.8, 49.4, 30.6; LRMS (EI) 270 (10), 268 (9), 214 (53), 212 (52), 132 (31), 86 (30), 84 (48); HRMS (EI) calcd for $C_{12}H_{13}BrS$ (M^+) 267.9916, found 267.9916.

tert-Butyl((3-methoxyphenyl)ethynyl)sulfane (**4g**). Synthesized using **1g** as limiting reagent (45.0 mg, 0.17 mmol, 1.0 equiv): pale yellow oil, 18.4 mg, 49%; IR ν_{max} (film)/cm^{-1} 2962, 2158, 1601, 1573, 1456, 1365, 1283,1042; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.21 (t, J = 7.9 Hz, 1 H), 7.03 (d, J = 7.6 Hz, 1 H), 6.95 (s, 1 H), 6.85 (ddd, J = 8.3, 2.6, 0.9 Hz, 1 H), 3.80 (s, 3 H), 1.48 (s, 9 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 159.4, 129.5, 124.8, 124.0, 116.2, 114.6, 96.2, 79.0, 55.4, 48.6, 30.5; LRMS (CI) 220 (50), 164 (100), 135 (6), 86 (4), 84 (4); HRMS (CI) calcd for $C_{13}H_{16}OS$ (M^+) 220.0922, found 220.0921.

tert-Butyl(p-tolylethynyl)sulfane (**4h**). Synthesized using **1h** as limiting reagent (55.0 mg, 0.22 mmol, 1.0 equiv): yellow oil, 32.7 mg, 73%; IR ν_{max} (film/cm^{-1}) 2963, 2922, 2897, 2864, 2164, 1508, 1455, 1365, 1162, 1020; ^{1}H NMR (500 MHz, $CDCl_3$) δ_H 7.33 (d, J = 8.1 Hz, 2 H), 7.11 (d, J = 8.1 Hz, 2 H), 2.34 (s, 3 H), 1.47 (s, 9 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 138.2, 131.5, 129.1, 120.8, 96.3, 78.0, 48.4, 30.4, 21.6; LRMS (EI) 204 (16), 148 (100), 86 (49), 84 (77); HRMS (EI) calcd for $C_{13}H_{16}S$ (M^+) 204.0967, found 204.0969.

General Procedure for the Synthesis of Alkynyl Sulfides 5a−d. To a flame-dried flask under argon were added thiol (4.0 equiv) and anhydrous THF (0.70 mL). To the stirring solution was added potassium hydride (4.0 equiv) as a single portion to give a bubbling, white paste. The mixture was stirred at rt for 10 min and then gently warmed to 30 °C for 20 min. The resulting solution was allowed to cool to rt and was then cooled further to −40 °C using a dry ice/acetonitrile bath. To the cooled solution was added dimethylamine (2.0 M in THF, 2.0 equiv), followed by sulfonamide **1** as a single portion. The reaction mixture was allowed to warm to rt over 10 min and then quenched by the addition of *i*-PrOH (1.0 mL). The crude mixture was diluted with CH_2Cl_2 (20 mL), washed with water (10 mL) and then brine (10 mL), and then dried over $MgSO_4$. The crude material was filtered, concentrated *in vacuo* and purified by column chromatography (EtOAc/PE or CH_2Cl_2/MeOH) to yield the alkynyl sulfides **5a−d**.

Ethyl(phenylethynyl)sulfane (**5a**).[15] Synthesized using **1a** as limiting reagent (45.0 mg, 0.19 mmol, 1.0 equiv): colorless oil, 18.0 mg, 59%; IR ν_{max} (film)/cm^{-1} 2965, 2926, 2869, 2165, 1595, 1486, 1442, 1375, 1263, 1069; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.42−7.40 (m, 2 H), 7.31−7.28 (m, 3 H), 2.82 (q, J = 7.3 Hz, 2 H), 1.46 (t, J = 7.3 Hz, 3 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.5, 128.4, 128.1, 123.6, 93.6, 79.3, 30.1, 14.9; LRMS (CI) 224 (23), 163 (100), 134 (45), 129 (49); HRMS (CI) calcd for $C_{10}H_{11}S$ $(M + H^+)$ 163.0576, found 163.0573.

Benzyl(phenylethynyl)sulfane (**5b**).[16] Synthesized using **1a** as limiting reagent (36.0 mg, 0.15 mmol, 1.0 equiv): colorless oil, 7.4 mg, 24%; IR ν_{max} (film)/cm^{-1} 3061, 3029, 2925, 2853, 2166, 1596, 1487, 1453, 1419, 1237, 1201, 1070; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.40−7.27 (m, 10 H), 4.02 (s, 2 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 136.7, 131.4, 129.3, 128.7, 128.4, 128.2, 127.9, 123.5, 94.7, 79.2, 40.6; LRMS (CI) 224 (58), 213 (30), 191 (100), 181 (10), 147 (17); HRMS (CI) calcd for $C_{15}H_{12}S$ (M^+) 224.0654, found 224.0651.

Hexyl(phenylethynyl)sulfane (**5c**). Synthesized using **1a** as limiting reagent (45.0 mg, 0.19 mmol, 1.0 equiv): pale yellow oil, 24.3 mg, 62%; IR ν_{max} (film)/cm^{-1} 2956, 2927, 2856, 2166, 1595, 1486, 1464, 1441, 1378, 1259, 1069; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.41−7.39 (m, 2 H), 7.30−7.27 (m, 3 H), 2.80 (t, J = 7.4 Hz, 2 H), 1.80 (quint, J = 7.4 Hz, 2

dx.doi.org/10.1021/jo500814y | J. Org. Chem. 2014, 79, 5869−5874

H), 1.48−1.43 (m, 2 H), 1.34−1.32 (m, 4 H), 0.90 (t, J = 7.0 Hz, 3 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.5, 128.4, 128.0, 123.7, 92.9, 79.8, 35.9, 31.4, 29.4, 28.1, 22.7, 14.2; LRMS (CI) 218 (100), 134 (10), 129 (4); HRMS (CI) calcd for $C_{14}H_{18}S$ (M^+) 218.1124, found 218.1123.

*N,N-Diethyl-2-((phenylethynyl)thio)ethanamine (**5d**).* Synthesized using **1a** as limiting reagent (45.0 mg, 0.19 mmol, 1.0 equiv): pale yellow oil, 23.3 mg, 56%; IR ν_{max} (film)/cm^{-1} 2968, 2932, 2803, 2164, 1595, 1487, 1442, 1383, 1285, 1200, 1068; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.40−7.38 (m, 2 H), 7.30−7.27 (m, 3 H), 2.89 (app. s, 4 H), 2.59 (q, J = 7.2 Hz, 4 H), 1.06 (t, J = 7.2 Hz, 6 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.5, 128.4, 128.1, 123.6, 92.9, 79.6, 52.1, 47.3, 33.5, 12.1; LRMS (CI) 234 (100), 218 (13), 205 (81), 161 (7); HRMS (CI) calcd for $C_{14}H_{20}NS$ (M + H$^+$) 234.1311, found 234.1310.

General Procedure for the Synthesis of α-Addition Products 6a and 6b. To a flame-dried flask under argon was added thiol (4.0 equiv) and anhydrous THF (0.7 mL). To the solution was added potassium hydride (4.0 equiv) as a single portion to give a white paste. The mixture was stirred at rt for 10 min and then gently warmed to 30 °C for 20 min. The resulting solution was allowed to cool to rt, and was then cooled further to −40 °C. To the cooled solution was added dimethylamine (2.0 M in THF, 2.0 equiv), followed by a solution of sulfonamide **1** (dissolved in 95% THF, 5% H_2O; 1 mL) as a single portion. The reaction mixture was allowed to warm to rt over 10 min and then quenched by the addition of *i*-PrOH (1 mL). The crude mixture was diluted with CH_2Cl_2 (20 mL) and washed with water (10 mL) and then brine (10 mL), then dried over $MgSO_4$. The crude material was filtered, concentrated in vacuo ,and purified by column chromatography (EtOAc/PE) to yield the alkynyl sulfides **6a** and **6b**.

*(±)-(E)-N,N-Diethyl-1-(isopropylthio)-2-phenylethenesulfonamide **6a**.* Synthesized using **1a** as limiting reagent (36.0 mg, 0.15 mmol); colorless oil, 42.7 mg, 89%; IR ν_{max} (film)/cm^{-1} 2970, 2930, 2867, 1446, 1320, 1201, 1138.1016; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 8.03 (s, 1 H), 7.95 (m, 2 H), 7.42−7.38 (m, 3 H), 3.67 (sept, J = 6.6 Hz, 1 H), 3.38 (q, J = 7.1 Hz, 4 H), 1.23−1.20 (m, 12 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 144.8, 134.5, 133.5, 131.0, 130.3, 128.5, 43.1, 40.4, 23.0, 14.9; LRMS (CI) 313 (39), 177 (100), 135 (12); HRMS (CI) calcd for $C_{15}H_{23}NO_2S_2$ (M^+) 313.1165, found 313.1166.

*(±)-(E)-1-(Cyclohexylthio)-N,N-diethyl-2-phenylethenesulfonamide (**6b**).* Synthesized using **1a** as limiting reagent (51.0 mg, 0.22 mmol): pale yellow oil, 85.4 mg, 90%; IR ν_{max} (film)/cm^{-1} 2929, 2853, 1446, 1321, 1201, 1139, 1017, 943; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 8.03 (s, 1 H), 7.96−7.94 (m, 2 H), 7.41−7.38 (m, 3 H), 3.45−3.40 (m, 1 H), 3.37 (q, J = 7.2 Hz, 4 H), 1.92−1.90 (m, 2 H), 1.67−1.63 (m, 2 H), 1.54−1.52 (m, 1 H), 1.31−1.14 (m, 11 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 145.0, 133.8, 133.6, 131.0, 130.3, 128.5, 48.5, 43.2, 33.3, 26.0, 25.7, 14.9; LRMS (CI) 353 (32), 217 (100), 134 (17); HRMS (CI) calcd for $C_{18}H_{27}NO_2S_2$ (M^+) 353.1478, found 353.1479.

General Procedure for the Conversion 6a and 6b to Alkynyl Sulfides 7a and 7b. To a flame-dried flask under argon were added α-addition products **6a** or **6b** (1.0 equiv) and anhydrous THF (2.0 mL). The resulting solution was cooled to −78 °C. To the solution was added dropwise lithium diisopropylamide solution (1.8 M in THF/heptanes/ethylbenzene, 2.0 equiv). The resulting yellow solution was stirred at −78 °C for 30 min before being allowed to warm to rt. The reaction was diluted with CH_2Cl_2 (20 mL) and washed with water (10 mL) and brine (10 mL). The organic fractions were dried over $MgSO_4$, filtered, and concentrated in vacuo and then purified via column chromatography (EtOAc/PE) to yield alkynyl sulfides **7a**-**7b**.

*(±)-Isopropyl(phenylethynyl)sulfane (**7a**).* Synthesized using **6a** as limiting reagent (30.0 mg, 0.06 mmol): pale yellow oil, 13.0 mg, 77%; IR ν_{max} (film)/cm^{-1} 2958, 2924, 2854, 2165, 1596, 1487, 1455, 1380, 1238, 1155, 1069; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.43−7.41 (m, 2 H), 7.30−7.28 (m, 3 H), 3.26 (sept, J = 6.8 Hz, 1 H), 1.44 (d, J = 6.8 Hz, 6 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.5, 128.4, 128.0, 123.7, 94.9, 78.7, 40.0, 23.1; LRMS (EI) 176 (37), 134 (100); HRMS (EI) calcd for $C_{11}H_{12}S$ (M^+) 176.0654, found 176.0654.

*(±)-Cyclohexyl(phenylethynyl)sulfane (**7b**).* Synthesized using **6b** as limiting reagent (55.0 mg, 0.16 mmol): colorless oil, 23.6 mg, 71%; IR ν_{max} (film)/cm^{-1} 2928, 2853, 2164, 1486, 1447, 1262, 1201; ^{1}H NMR (600 MHz, $CDCl_3$) δ_H 7.42−7.41 (m, 2 H), 7.31−7.27 (m, 3 H), 3.00 (tt, J = 7.2, 3.5 Hz, 1 H), 2.11 (m, 2 H), 1.83 (dt, J = 13.5, 3.7 Hz, 2 H), 1.67−1.63 (m, 1 H), 1.56 (dq, J = 11.9, 3.4 Hz, 2 H), 1.37 (tq, J = 11.9, 3.4 Hz, 2 H), 1.30−1.24 (m, 1 H); ^{13}C NMR (150 MHz, $CDCl_3$) δ_C 131.5, 128.4, 128.0, 123.8, 94.5, 78.7, 47.8, 33.1, 26.2, 25.6; LRMS (EI) 216 (26), 134 (100); HRMS (EI) calcd for $C_{14}H_{16}S$ (M^+) 216.0967, found 216.0968.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

^{1}H and ^{13}C NMR spectra are provided. This material is provided free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: j.wilden@ucl.ac.uk.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We gratefully acknowledge UCL for providing studentships for J.C. and V.J.G. and Dr. A. Aliev for spectroscopic support.

■ REFERENCES

(1) Arancon, R. A. D.; Lin, C. S. K.; Vargas, C.; Luque, R. *Org. Biomol. Chem.* **2014**, *12*, 10−35.

(2) Appukkuttan, P.; Dehaen, W.; Van der Eycken, E. *Eur. J. Org. Chem.* **2003**, 4713−4716.

(3) Rueping, M.; Leiendecker, M.; Das, A.; Poisson, T.; Bui, L. *Chem. Commun.* **2011**, *47*, 10629−10631.

(4) Jin, G.; Zhang, X.; Cao, S. *Org. Lett.* **2013**, *15*, 3114−3117.

(5) Sun, C.-L.; Li, H.; Yu, D.-G.; Yu, M.; Zhou, X.; Lu, X.-Y.; Huang, K.; Zheng, S.-F.; Li, B. J.; Shi, Z.-J. *Nat. Chem.* **2010**, *2*, 1044−1049.

(6) Liu, W.; Cao, H.; Zhang, H.; Zhang, H.; Chung, K. H.; He, C.; Wang, H.; Kwong, F. Y.; Lei, A. *J. Am. Chem. Soc.* **2010**, *132*, 16737−16740.

(7) Shirakawa, E.; Itoh, K.-I.; Higashino, T.; Hayashi, T. *J. Am. Chem. Soc.* **2010**, *132*, 15537−15539.

(8) Gray, V. J.; Slater, B.; Wilden, J. D. *Chem.—Eur. J.* **2012**, *18*, 15582−15585.

(9) Zhou, H.; Anderson, G. M.; Mondal, B.; Doni, E.; Ironmonger, V.; Kranz, M.; Tuttle, T.; Murphy, J. A. *Chem. Sci.* **2014**, *5*, 476−482.

(10) Cuthbertson, J.; Gray, V. J.; Wilden, J. D. *Chem. Commun.* **2014**, *50*, 2575−2578.

(11) (a) Miyachi, N.; Shibasaki, M. *J. Org. Chem.* **1990**, *55*, 1975−1976. (b) Kabanyane, S. T.; MaGee, D. I. *Can. J. Chem.* **1992**, *70*, 2758−2763. (c) Braga, A. L.; Reckziegel, A.; Menezes, P. H.; Stefani, H. A. *Tetrahedron Lett.* **1993**, *34*, 393−394. (d) Takeda, H.; Shimada, S.; Ohnishi, S.; Nakanishi, F.; Matsuda, H. *Tetrahedron Lett.* **1998**, *39*, 3701−3704. (e) Back, T. G. *Tetrahedron* **2001**, *57*, 5263−5301.

(12) Marzo, L.; Parra, A.; Frias, M.; Aleman, J.; Garcia Ruano, J. L. *Eur. J. Org. Chem.* **2013**, 4405−4409.

(13) Tanaka, R.; Rodgers, M.; Simonaitis, R.; Miller, S. I. *Tetrahedron* **1971**, *27*, 2651−2669.

(14) Minehan, T. G.; Sosa, J. R.; Tudjarian, A. A. *Org. Lett.* **2008**, *10*, 5091−5094.

(15) Voets, M.; Smet, M.; Dehaen, W. *J. Chem. Soc., Perkin Trans. 1* **1999**, 1473−1475.

(16) Riddell, N.; Tam, W. *J. Org. Chem.* **2006**, *71*, 1934−1937.