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## Sulfoxide synthesis from sulfinate esters under Pummerer-like conditions†

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A facile synthetic method for the preparation of allyl sulfoxides by *S*-allylation of sulfinate esters proceeds through sulfonium intermediates without [3,3]-sigmatropic rearrangement and further Pummerer-type reactions of the resulting allyl sulfoxides. On the basis of the plausible reaction mechanism involving sulfonium salt intermediates, *S*-alkynylation and *S*-arylation were also accomplished.

Organosulfur compounds have gained attention in a broad range of research fields such as pharmaceutical sciences, agrochemistry, and materials science.<sup>1,2</sup> The recent remarkable successes of synthetic chemistry using sulfoxides have enhanced the accessibility of highly functionalized compounds by virtue of the significant transformability of sulfoxides.<sup>3–8</sup> For example, the preparations of diverse compounds 2–5 were achieved by a variety of transformations of allyl aryl sulfoxides **1** through C–S bond cleavage (Fig. 1A).<sup>6,7,8h,j</sup> In particular, multisubstituted aromatic sulfides **4** and **5** were synthesized from sulfoxides **1** by a reaction with aryne intermediate **I** in the presence of electrophiles and the [3,3]-sigmatropic rearrangement of allyl sulfonium intermediate **II**, respectively.<sup>6,7</sup> Similar interrupted Pummerer reactions of sulfoxides **6** and **8** with trifluoromethanesulfonic anhydride (Tf<sub>2</sub>O) in the presence of allyltrimethylsilane were also accomplished through the [3,3]-sigmatropic rearrangement, showing the notable reactivity of allyl sulfonium intermediates **III** and **IV** (Fig. 1B and C).<sup>4b,d,e,n</sup> Herein, we describe an efficient synthesis of various allyl sulfoxides by allylation of sulfinate esters<sup>9</sup> using allyltrimethylsilane under the Pummerer-like conditions<sup>4</sup> through sulfonium intermediate **V** having a methoxy group, enabling to avoid the [3,3]-sigmatropic rearrangement and further Pummerer-type reactions of the resulting allyl sulfoxides (Fig. 1D).

Sulfinate esters hitherto have served in the sulfoxide synthesis with Grignard reagents.<sup>9a</sup> Recently, Lewis acid-mediated

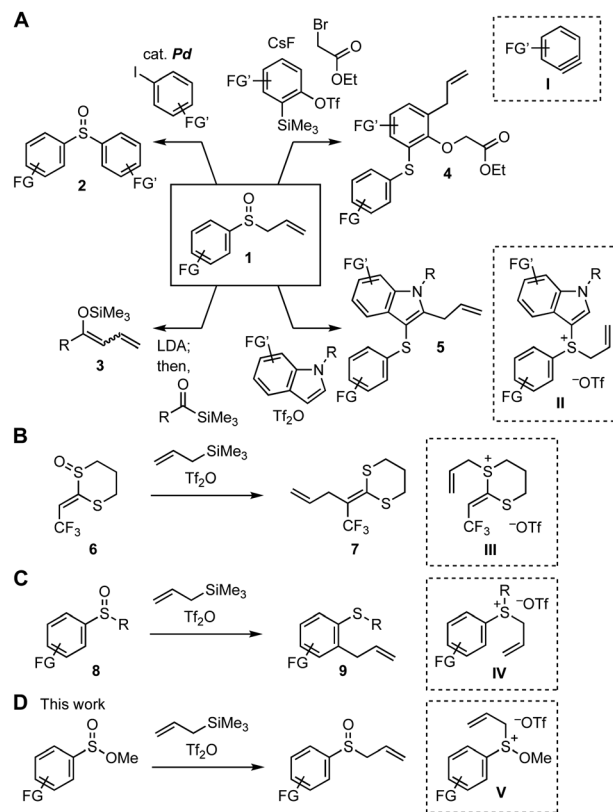


Fig. 1 Transformations through the Pummerer-type activation of sulfoxides and sulfinate esters. (A) Versatile transformations using allyl sulfoxides **1**. (B) Interrupted Pummerer reaction of ketenedithioacetal monoxide **6**. (C) Interrupted Pummerer reaction of aromatic sulfoxide **8**. (D) This work.

Friedel–Crafts-type sulfonylation of electron-rich arenes using sulfinate esters was developed.<sup>9b</sup> Taking the sulfinate ester chemistry into account, we envisioned that the Pummerer-type activation of sulfinate esters **10** in the presence of allylsilanes **11** and stability of methoxy sulfonium intermediates<sup>10</sup> would allow for the facile synthesis of allyl sulfoxides **12**, considering that the hydrolysis of methoxy sulfonium intermediates **V'** can

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afford sulfoxides (Fig. 2A). As a result of screening the reaction conditions, we found that treatment of methyl benzenesulfinate (**10a**) with  $\text{TiF}_2\text{O}$  in the presence of allyltrimethylsilane (**11a**) followed by addition of aqueous sodium bicarbonate provided allyl phenyl sulfoxide (**12a**) in high yield (Fig. 2A and 2B). Examinations using a variety of acid anhydrides or Lewis acids showed the remarkable reactivity of  $\text{TiF}_2\text{O}$  in the *S*-allylation of sulfinate ester **10a**.<sup>11,12</sup> A wide range of allyl sulfoxides **12b–12j** were prepared by the *S*-allylation under the Pummerer-like conditions, where *C*-allylation products through the [3,3]-sigmatropic rearrangement were not obtained. Indeed, not only electron-rich aromatic sulfinate esters bearing methyl and methoxy groups but also electron-deficient substrates with chloro and nitro groups were efficiently allylated to furnish sulfoxides **12b–12e**. Sulfoxides **12f** and **12g** were obtained uneventfully by the reactions of bulky 2-bromo- and 2,6-dimethyl-substituted benzenesulfinate esters. Furthermore, *S*-allylations of 2-naphthyl-, benzyl-, and *n*-pentyl-substituted sulfinate esters also took place smoothly to provide sulfoxides **12h–12j**.

Various functionalized allylsilanes **11** participated in the *S*-allylation of sulfinate ester **10a** (Fig. 2A and C).<sup>13</sup> Sulfoxides **12k** and **12l** were efficiently synthesized by 2-methyl- and 2-phenyl-allylation, respectively. It is worth noting that the C–S bond formation enabled to prepare allyl chloride **12m**, allyl acetate

**12n**, ester **12o**, and bromoalkene **12p** leaving highly electrophilic functional groups untouched, while it is not easy to synthesize sulfoxides having electrophilic moieties by the conventional allyl sulfoxide synthesis *via* allylation of thiols and subsequent oxidation. Moreover, transformable sulfoxides **12q** and **12r** possessing a silyl and boryl groups were obtained in moderate to good yields without damaging these reactive functional groups.

To gain insight into the reaction mechanism of the *S*-allylation of sulfinate esters under the Pummerer-like conditions, we then examined control experiments (Fig. 3). Firstly, the reaction using  $[\text{18O}]\text{H}_2\text{O}$  in the hydrolysis using aqueous sodium bicarbonate was conducted to clarify the origin of the oxygen atom of sulfoxide **12a** (Fig. 3A). The result showed that  $^{18}\text{O}$ -incorporated **12a'** was obtained selectively, indicating that the sulfoxide oxygen was derived from water in the hydrolysis. We then attempted to isolate sulfonium intermediate **13** (Fig. 3B). As a result, after sulfinate ester **10a** was treated with  $\text{TiF}_2\text{O}$  in the presence of allylsilane **11a**, an addition of solid sodium bicarbonate, filtration of the resulting mixture, removal of the solvent of the filtrate, and washing with diethyl ether afforded sulfonium salt **13** quantitatively. Hydrolysis of sulfonium salt **13** with aqueous sodium bicarbonate underwent uneventfully to give sulfoxide **12a**. In addition, reduction of sulfonium salt **13** with sodium borohydride successfully provided allyl phenyl sulfide (**14**) in good yield.<sup>10c</sup> On the basis of these results, we proposed a reaction mechanism of the *S*-allylation (Fig. 3C). The Pummerer-type activation of sulfinate ester by virtue of the remarkable reactivity of  $\text{TiF}_2\text{O}$ ,<sup>14</sup> and following *S*-allylation of the resulting sulfonium intermediate **VI** would furnish sulfonium intermediate **13** along with trimethylsilyl triflate. Then, hydrolysis of sulfonium salt **13** with aqueous sodium bicarbonate involving the nucleophilic attack of external water to the sulfur atom leads

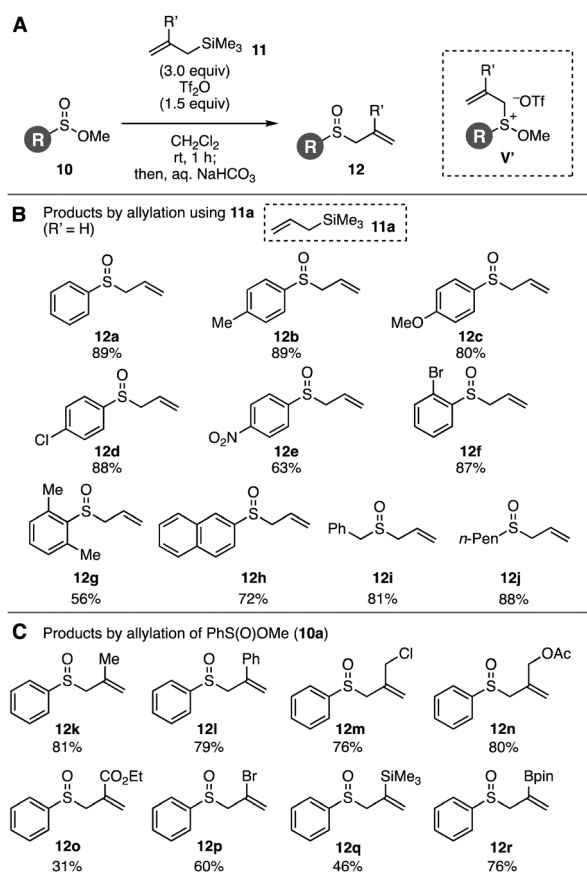


Fig. 2 Allyl sulfoxide synthesis from sulfinate esters **10** and allylsilanes **11**. (A) General scheme. (B) Results using various sulfinate esters **10** with **11a**. (C) Results using allylsilanes **11** with **10a**.

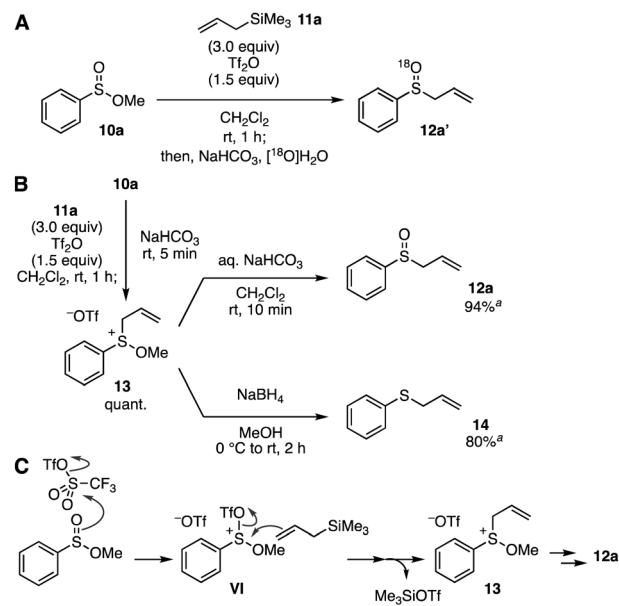


Fig. 3 Control experiments. (A) Reaction using  $[\text{18O}]\text{H}_2\text{O}$ . (B) Isolation of sulfonium salt **13**, hydrolysis of **13**, and reduction of **13**. (C) Plausible reaction mechanism. <sup>a</sup>  $^1\text{H}$  NMR yield.



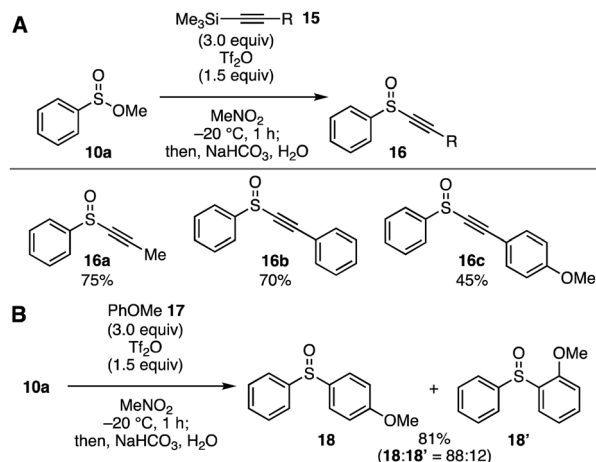


Fig. 4 Alkynylation and arylation of sulfinate ester **10a**. (A) Alkynylation with alkynylsilanes **15**. (B) Arylation with anisole (**17**).

to sulfoxide **12a**. Although the role of methoxy group is still unclear, the stability of sulfonium salt **13** would achieve the sulfoxide synthesis without [3,3]-sigmatropic rearrangement or the Pummerer-type reactions of allyl sulfoxide **12a** and further Pummerer-type reactions of the resulting allyl sulfoxides.<sup>15</sup>

Our attention then directed toward novel transformations through the cationic intermediates generated by the Pummerer-type activation of sulfinate esters with Tf<sub>2</sub>O (Fig. 4). In this context, we have developed a facile synthetic method of alkyne sulfoxides **16** using alkyne silanes **15** (Fig. 4A). Indeed, treatment of sulfinate ester **10a** dissolved in nitromethane with Tf<sub>2</sub>O in the presence of ethynylsilanes **15** at -20 °C furnished alkyne sulfoxides **16** in moderate to high yields. This novel transformation enabled the preparation of alkyne sulfoxides **16a–16c** having a methyl, phenyl, and 4-anisyl group. Since alkyne sulfoxides serve in a variety of reactions including carbometallation, [2+2] cycloaddition, and cyclopropanation, the alkyne sulfoxide synthesis developed in this study would allow for the preparation of a range of organo-sulfur compounds.<sup>4k,16</sup> In addition, Friedel–Crafts-type arylation of sulfinate ester **10a** also took place smoothly to afford a regioisomeric mixture of diaryl sulfoxides **18** and **18'** in good yield (Fig. 4B).<sup>9b</sup>

Wide transformability of allyl aryl sulfoxides synthesized from sulfinate esters was showcased by the syntheses of multi-substituted aromatic compounds (Fig. 5). Modifying the conditions for the trifunctionalization of aryne intermediates reported by Li and coworkers<sup>6</sup> (Fig. 1A, **1** to **4**), we found that 2,3,6-trisubstituted phenol **20a** was obtained in moderate yield with avoiding further arylation between phenol **20a** and 3-methoxybenzylne when the aryne trifunctionalization was performed in hot 1,4-dioxane in the absence of electrophiles such as ethyl bromoacetate (Fig. 5A). Iodine-mediated cyclization of the resulting phenol **20a** and subsequent elimination with a base successfully furnished benzofuran **21**.<sup>17</sup> Methallylation of sulfinate ester **10d** followed by the aryne trifunctionalization led to the synthesis of highly functionalized phenol **20b** (Fig. 5B). Furthermore, tetra-substituted indole **23** was prepared through 2-bromoallylation

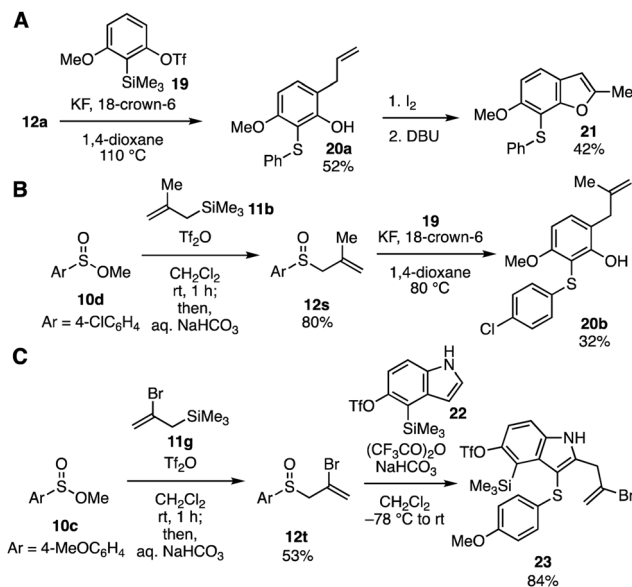


Fig. 5 Transformations of allyl sulfoxides. (A) Benzofuran synthesis. (B) Trisubstituted phenol synthesis. (C) Multisubstituted indole synthesis.

of sulfinate ester **10c** and following 2,3-difunctionalization of indole **22** according to the reports by Procter and coworkers<sup>7</sup> (Fig. 5C). Functionalized allyl aryl sulfoxide **12t** and indole **22** bearing *o*-silylaryl triflate moiety<sup>18</sup> for the aryne generation participated in the 2,3-disubstituted indole synthesis leaving the reactive functional groups intact. Thus, a wide variety of indoles would be synthesized by *S*-allylation of sulfinate esters, 2,3-difunctionalization of indoles, and further transformations through indolyne intermediates with a number of arynophiles.<sup>18,19</sup>

In summary, we have developed a facile synthetic method of allyl sulfoxides by *S*-allylation of sulfinate esters through sulfonium intermediates without [3,3]-sigmatropic rearrangement and further Pummerer-type reactions of the resulting allyl sulfoxides. On the basis of the plausible reaction mechanism, *S*-alkynylation and *S*-arylation were also accomplished. Further studies to expand the scope of these transformations using sulfinate esters under the Pummerer-like conditions, chiral sulfoxide synthesis, and the applications to the synthesis of bioactive compounds are now in progress.

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## Conflicts of interest

There are no conflicts to declare.



## Notes and references

- For selected reviews of bioactive sulfur-containing compounds, see: (a) K. Pluta, B. Morak-Młodawska and M. Jeleń, *Eur. J. Med. Chem.*, 2011, **46**, 3179; (b) E. A. Ilardi, E. Vitaku and J. T. Njardarson, *J. Med. Chem.*, 2014, **57**, 2832.
- For selected reviews of sulfur-containing compounds in materials science, see: (a) A. S. Rahate, K. R. Nemade and S. A. Waghuley, *Rev. Chem. Eng.*, 2013, **29**, 471; (b) S. Dadashi-Silab, C. Aydogan and Y. Yagci, *Polym. Chem.*, 2015, **6**, 6595.
- (a) S. K. Bur and A. Padwa, *Chem. Rev.*, 2004, **104**, 2401; (b) K. S. Feldman, *Tetrahedron*, 2006, **62**, 5003; (c) S. Akai and Y. Kita, *Top. Curr. Chem.*, 2007, **274**, 35; (d) L. H. S. Smith, S. C. Coote, H. F. Sneddon and D. J. Procter, *Angew. Chem., Int. Ed.*, 2010, **49**, 5832; (e) X. Huang, S. Klimczyk and N. Maulide, *Synthesis*, 2012, 175; (f) A. Shafir, *Tetrahedron Lett.*, 2016, **57**, 2673; (g) A. P. Pulis and D. J. Procter, *Angew. Chem., Int. Ed.*, 2016, **55**, 9842; (h) H. Yorimitsu, *Chem. Rev.*, 2017, **17**, 1156; (i) T. Yanagi, K. Nogi and H. Yorimitsu, *Tetrahedron Lett.*, 2018, **59**, 2951; (j) D. Kaiser, I. Klose, R. Oost, J. Neuhaus and N. Maulide, *Chem. Rev.*, 2019, **119**, 8701; (k) L. Zhang, M. Hu and B. Peng, *Synlett*, 2019, 2203.
- For selected examples, (a) S. Akai, N. Kawashita, H. Satoh, Y. Wada, K. Kakiguchi, I. Kuriwaki and Y. Kita, *Org. Lett.*, 2004, **6**, 3793; (b) S. Yoshida, H. Yorimitsu and K. Oshima, *Org. Lett.*, 2009, **11**, 2185; (c) X. Huang and N. Maulide, *J. Am. Chem. Soc.*, 2011, **133**, 8510; (d) A. J. Eberhart, J. Cicoira, E. Imbriglio and D. J. Procter, *Org. Lett.*, 2011, **13**, 5882; (e) A. J. Eberhart, C. Cicoira and D. J. Procter, *Org. Lett.*, 2013, **15**, 3994; (f) M. Tayu, K. Higuchi, T. Ishizaki and T. Kawasaki, *Org. Lett.*, 2014, **16**, 361; (g) G. Hu, J. Xu and P. Li, *Org. Lett.*, 2014, **16**, 6036; (h) L. Hu, Q. Gui, X. Chen, Z. Tan and G. Zhu, *J. Org. Chem.*, 2016, **81**, 4861; (i) D. Chen, Q. Feng, Y. Yang, X.-M. Cai, F. Wang and S. Huang, *Chem. Sci.*, 2017, **8**, 1601; (j) L. Shang, Y. Chang, F. Luo, J.-N. He, X. Huang, L. Zhang, L. Kong, K. Li and B. Peng, *J. Am. Chem. Soc.*, 2017, **139**, 4211; (k) D. Kaldre, I. Klose and N. Maulide, *Science*, 2018, **361**, 664; (l) L. Zhang, J.-N. He, Y. Liang, M. Hu, L. Shang, X. Huang, L. Kong, Z.-X. Wang and B. Peng, *Angew. Chem., Int. Ed.*, 2019, **58**, 5316; (m) K. Okamoto, M. Hori, T. Yanagi, K. Murakami, K. Nogi and H. Yorimitsu, *Angew. Chem., Int. Ed.*, 2019, **58**, 7813; (n) J. Yan, A. P. Pulis, G. J. P. Perry and D. J. Procter, *Angew. Chem., Int. Ed.*, 2019, **58**, 15675; (o) X. Meng, D. Chen, X. Cao, J. Luo, F. Wang and S. Huang, *Chem. Commun.*, 2019, **55**, 12495; (p) J. Li, Y. Chen, R. Zhong, Y. Zhang, J. Yang, H. Ding and Z. Wang, *Org. Lett.*, 2020, **22**, 1164; (q) Z. He, G. J. Perry and D. J. Procter, *Chem. Sci.*, 2020, **11**, 2001; (r) X. Huang, Y. Zhang, W. Liang, Q. Zhang, Y. Zhan, L. Kong and B. Peng, *Chem. Sci.*, 2020, **11**, 3048.
- For our previous reports on sulfoxides chemistry, see: (a) S. Yoshida, K. Uchida and T. Hosoya, *Chem. Lett.*, 2014, **43**, 116; (b) S. Yoshida, K. Uchida and T. Hosoya, *Chem. Lett.*, 2015, **44**, 691; (c) S. Yoshida, F. Karaki, K. Uchida and T. Hosoya, *Chem. Commun.*, 2015, **51**, 8745; (d) T. Matsuzawa, K. Uchida, S. Yoshida and T. Hosoya, *Org. Lett.*, 2017, **19**, 5521; (e) Y. Nakamura, Y. Miyata, K. Uchida, S. Yoshida and T. Hosoya, *Org. Lett.*, 2019, **21**, 5252.
- Y. Li, D. Qiu, R. Gu, J. Wang, J. Shi and Y. Li, *J. Am. Chem. Soc.*, 2016, **138**, 10814.
- M. Šiaučiulis, S. Sapmaz, A. P. Pulis and D. J. Procter, *Chem. Sci.*, 2018, **9**, 754.
- (a) R. Hunter and C. D. Simon, *Tetrahedron Lett.*, 1986, **27**, 1385; (b) Y. Kita, O. Tamura, F. Itoh, H. Yasuda, T. Miki and Y. Tamura, *Chem. Pharm. Bull.*, 1987, **35**, 562; (c) D. H. Hua, M. J. Coulter and I. Badejo, *Tetrahedron Lett.*, 1987, **28**, 5465; (d) M. R. Binns, R. K. Haynes, A. G. Katsifis, P. A. Schober and S. C. Vonwiller, *J. Am. Chem. Soc.*, 1988, **110**, 5411; (e) R. Hunter and C. D. Simon, *Tetrahedron Lett.*, 1988, **29**, 2257; (f) E. Alonso, D. Guijarro and M. Yus, *Tetrahedron*, 1995, **51**, 2699; (g) W. A. Loughlin and M. A. McCleary, *Synthesis*, 2005, 761; (h) E. Bernoud, G. Le Duc, X. Bantreil, G. Prestat, D. Madec and G. Poli, *Org. Lett.*, 2010, **12**, 320; (i) S. Fustero, S. Catalán, M. Sánchez-Roselló, A. Simón-Fuentes and C. del Pozo, *Org. Lett.*, 2010, **12**, 3484; (j) M. Honda, T. Nakajima, M. Okada, K. Yamaguchi, M. Suda, K.-K. Kunimoto and M. Segi, *Tetrahedron Lett.*, 2011, **52**, 3740; (k) Z. Huang and J. Xu, *RSC Adv.*, 2013, **3**, 15114; (l) D. Qiu, J. Shi, Q. Guo, Q. Xu, B. Li and Y. Li, *J. Am. Chem. Soc.*, 2018, **140**, 13214.
- For the sulfoxide synthesis with Grignard reagents, see: (a) H. Gilman, J. Robinson and N. J. Beaber, *J. Am. Chem. Soc.*, 1926, **48**, 2715; For recent transformations of sulfinate esters, see: (b) F. Yuste, A. H. Linares, V. M. Mastranzo, B. Ortiz, R. Sánchez-Obregón, A. Fraile, J. Luis and G. Ruano, *J. Org. Chem.*, 2011, **76**, 4635; (c) J. A. Lujan-Montelongo, A. O. Estevez and F. F. Fleming, *Eur. J. Org. Chem.*, 2015, 1602; (d) N.-L. T. Nguyen, H.-T. Vo, F. Duus and T. X. T. Luu, *Molecules*, 2017, **22**, 1458; (e) A. Mohd, T. Anitha, K. R. Reddy, J. Wencel-Delord and F. Colobert, *Eur. J. Org. Chem.*, 2019, 7836; (f) G.-J. Li, Y.-L. Pan, Y.-L. Liu, H.-F. Xu and J.-Z. Chen, *Tetrahedron Lett.*, 2019, **60**, 151260; (g) L. Chen, J. Zhang, Y. Wei, Z. Yang, P. Liu, J. Zhang and B. Dai, *Tetrahedron*, 2019, **75**, 130664.
- (a) C. R. Johnson and W. G. Phillips, *Tetrahedron Lett.*, 1965, **6**, 2101; (b) C. R. Johnson and W. G. Phillips, *J. Org. Chem.*, 1967, **32**, 1926; (c) C. R. Johnson and W. G. Phillips, *J. Org. Chem.*, 1967, **32**, 3233.
- See the ESI† for the details.
- The reaction at 80 °C in a sealed tube also provided sulfoxide **12a**, where [3,3]-sigmatropic rearrangement did not proceed.
- The reaction using a  $\gamma$ -phenyl-substituted allylsilane afforded a complex mixture of products.
- For recent examples, see: (a) Y. Unoh, K. Hirano and M. Miura, *J. Am. Chem. Soc.*, 2017, **139**, 6106; (b) H. Huang, J. Ash and J. Y. Kang, *Org. Lett.*, 2018, **20**, 4938; (c) C. R. Gonçalves, M. Lemmerer, C. J. Teskey, P. Adler, D. Kaiser, B. Maryasin, L. González and N. Maulide, *J. Am. Chem. Soc.*, 2019, **141**, 18437; (d) J. Wang, Y.-J. Deng, X.-X. Yan, Y.-J. Liu, C.-P. Ge, Y. Yan, S. Chao and P.-X. Zhou, *Org. Chem. Front.*, 2020, **7**, 715.
- Although detailed studies involving the theoretical calculation should be performed, the resonance effect of the methoxy group might prevent the [3,3]-sigmatropic rearrangement leading to the sulfenate.
- (a) J. P. Marino, M. B. Rubio, G. Cao and A. de Dios, *J. Am. Chem. Soc.*, 2002, **124**, 13398; (b) G. Sklute, D. Amsallem, A. Shabli, J. P. Varghese and I. Marek, *J. Am. Chem. Soc.*, 2003, **125**, 11776; (c) N. Maezaki, S. Yagi, R. Yoshigami, J. Maeda, T. Suzuki, S. Ohsawa, K. Tsukamoto and T. Tanaka, *J. Org. Chem.*, 2003, **68**, 5550; (d) Q. Xu and X. Huang, *Tetrahedron Lett.*, 2004, **45**, 5657; (e) G. Sklute and I. Marek, *J. Am. Chem. Soc.*, 2006, **128**, 4642; (f) F. Sandrinelli, C. Boudou, C. Caupène, M.-T. Averbuch-Pouchot, S. Perrio and P. Metzner, *Synlett*, 2006, 3289; (g) G. Zhang and L. Zhang, *J. Am. Chem. Soc.*, 2008, **130**, 12598; (h) J. Wei and Z. Sun, *Org. Lett.*, 2015, **17**, 5396; (i) M. J. Barrett, G. F. Khan, P. W. Davies and R. S. Grainger, *Chem. Commun.*, 2017, **53**, 5733; (j) B. Alcaide, P. Almendros and C. Lázaro-Milla, *Adv. Synth. Catal.*, 2017, **359**, 2630.
- A. K. Yadav, B. K. Singh, N. Singh and R. P. Tripathi, *Tetrahedron Lett.*, 2007, **48**, 6628.
- G.-Y. J. Im, S. M. Bronner, A. E. Goetz, R. S. Paton, P. H.-Y. Cheong, K. N. Houk and N. K. Garg, *J. Am. Chem. Soc.*, 2010, **132**, 17933; and references therein.
- For selected reviews of arynes, see: (a) S. Yoshida and T. Hosoya, *Chem. Lett.*, 2015, **44**, 1450; (b) J. Shi, Y. Li and Y. Li, *Chem. Soc. Rev.*, 2017, **46**, 1707; (c) F. I. M. Idris and C. R. Jones, *Org. Biomol. Chem.*, 2017, **15**, 9044; (d) H. Takikawa, A. Nishii, T. Sakai and K. Suzuki, *Chem. Soc. Rev.*, 2018, **47**, 8030; (e) T. Roy and A. T. Biju, *Chem. Commun.*, 2018, **54**, 2580.

