Abstract
A novel method of photoinduced synthesis of unsymmetrical diaryl selenides from triarylbismuthines and diaryl diselenides has been developed. Although the arylation reactions with triarylbismuthines are usually catalyzed by transition-metal complexes, the present arylation of diaryl diselenides with triarylbismuthines proceeds upon photoirradiation in the absence of transition-metal catalysts. A variety of unsymmetrical diaryl selenides can be conveniently prepared by using this arylation method.

Introduction
A number of organoselenium compounds are known to be biologically active [1–4]. In particular, diaryl selenides are known to have antioxidative effects [5]. Therefore, many studies on the synthetic methods for unsymmetrical diaryl selenides have recently been reported [6–32]. Most of these methods use coupling reactions catalyzed by transition-metal complexes. To avoid the contamination of product selenides with transition-metals, the development of synthetic methods for unsymmetrical diaryl selenides in the absence of transition-metal catalysts is desirable. On the other hand, triarylbismuthines are gaining interest as useful arylation reagents, because organobismuth compounds are nontoxic and have excellent reactivity, which has led to several applications in organic synthesis [33]. Therefore, numerous transition-metal-catalyzed coupling reactions with organobismuth compounds have been reported [34–53]. Although triphenylbismuthine can generate a phenyl radical [33,54] in the absence of a radical initiator simply by photoirradiation, few arylation reactions using this mechanism have been reported [55,56]. We presume that a phenyl radical generated from triphenylbismuthine can be captured by organic diselenides, which have a high carbon-radical-capturing ability [57–64] and as a result, diaryl selenide will be generated (Scheme 1). In 1999, Barton and co-workers reported that diaryl selenide was obtained by the reaction of triarylbismuthine with
Results and Discussion

First, we investigated the photoinduced reaction of diphenyl diselenide with triphenylbismuthine. Diphenyl diselenide (1a, 0.1 mmol) and triphenylbismuthine (2a, 0.5 mmol) were placed in a Pyrex test tube (Ø = 9 mm) with CHCl₃ (4 mL), and the mixture was irradiated by a xenon lamp for 5 h at room temperature. As a result, 0.042 mmol (21% yield based on the amount of selenium atoms) of diphenyl selenide (3aa) was obtained after the isolation by silica gel chromatography (the yield was determined by HPLC). Next, optimization of the reaction conditions was investigated as shown in Table 1. Irradiation by a tungsten lamp instead of a xenon lamp did not induce the desired arylation reaction (Table 1, entry 2), and in the dark, the reaction did not proceed at all (Table 1, entry 3). When 2,2'-azobis(isobutyronitrile) (AIBN) was used as a radical initiator, the desired reaction proceeded ineffectively (Table 1, entry 4). Among several solvents, such as benzene, DMSO and CH₃CN, the use of CH₃CN improved the yield of 3aa (Table 1, entries 5–7). Although the solubility of 2a is different depending on the solvent, the yield of 3aa is not correlated with the solubility of 2a. It may be more important to choose a solvent that does not react with the generated aryl radical. Moreover, a lower amount of solvent and the utilization of a quartz test tube (Ø = 9 mm) contributed to the increase in the yield of 3aa (Table 1, entries 8 and 9).

Next, we investigated the scope of the synthesis of unsymmetrical diaryl selenides by using different diaryl diselenides and triarylbumthiones (Table 2). The employed diaryl diselenides were diphenyl diselenide (1a), bis(4-fluorophenyl) diselenide (1b), bis(4-(trifluoromethyl)phenyl) diselenide (1c), bis(1-naphthyl) diselenide (1d), and bis(2-naphthyl) diselenide (1e). The used triarylbismuthines were triphenylbismuthine (2a), tris(4-methylphenyl)bismuthine (2b), tris(4-chlorophenyl)bismuthine (2c), and tris(4-fluorophenyl)bismuthine (2d). A number of combinations of 1 and 2 were examined and as a result, unsymmetrical diaryl selenides 3 were obtained in moderate to high yields (45–86%) in every case (Table 2, entries 1–10) after the isolation by preparative TLC on silica gel. The chemical shifts of ⁷⁷Se NMR spectra of diaryl selenides 3 are also shown in
Table 2: Syntheses of unsymmetrical diaryl selenides.

| entry | (ArSe)$_2$ 1 | Ar$_3$Bi 2 | product 3 (ArSeAr') | $^{77}$Se NMR, $\delta$ ppm | yield$^a$ |
|-------|--------------|-------------|---------------------|---------------------------|----------|
| 1$^b$ | 1a           | 2b          | 3ab                 | 407                       | 65%      |
| 2$^b$ | 1a           | 2c          | 3ac                 | 416                       | 45%      |
| 3$^c$ | 1a           | 2d          | 3ad                 | 411                       | 66%      |
| 4$^b$ | 1b           | 2a          | 3ba                 | 411                       | 57%      |
| 5$^b$ | 1b           | 2b          | 3bb                 | 404                       | 86%      |
Table 2: Syntheses of unsymmetrical diaryl selenides. (continued)

|   | Structure | Product | Yield |
|---|-----------|---------|-------|
| 6\(^b\) | ![Structure](image) | ![Structure](image) | 427 67% |
| 7\(^b\) | ![Structure](image) | ![Structure](image) | 418 51% |
| 8\(^c\) | ![Structure](image) | ![Structure](image) | 355 51% |
| 9\(^c\) | ![Structure](image) | ![Structure](image) | 418 71% |
| 10\(^c\) | ![Structure](image) | ![Structure](image) | 354 57% |

\(^a\)The yields were determined after isolation. \(^b\)0.5 mmol of triarylbismuthine was used. \(^c\)0.3 mmol of triarylbismuthine was used.

Table 2, because \(^{77}\)Se NMR is a tool well suited to identify diorganyl monoselenides.

To get information about the reaction pathway of this arylation, we first investigated the arylation of diphenyl diselenide by varying the 1a:2a molar ratio (Table 3). When excess amounts of either starting substrate were employed, the yields of 3aa increased (Table 3, entries 1, 2 and 5).

In the case of the reaction of triphenylbismuthine with diphenyl disulfide (4) instead of diphenyl diselenide, diphenyl sulfide 5 was obtained in lower yield with unidentified byproducts, unlike in the case of diphenyl selenide 3aa (Scheme 2). Additionally, air is entrained in the reaction system, since a test tube with a septum was used in which a needle was inserted. When the reaction of diaryl diselenide with triaryl bismuthine was conducted with a strictly sealed tube in Ar atmosphere, a bismuth mirror was observed and the yield of 3aa decreased. We assume that the reaction proceeds with bismuth residue getting oxidized.

A plausible reaction pathway for the photoinduced reaction of diaryl diselenide with triaryl bismuthine is shown in Scheme 3. First, an aryl radical is generated from triaryl bismuthine by near-UV light irradiation \([33,54,55]\). The generated aryl radical is captured by diaryl diselenide to produce diaryl selenide and a...
Table 3: The yield of diphenyl selenide 3aa upon changing the ratio 1a/2a.

| entry | amount of 1a | amount of 2a | yield of 3aa\textsuperscript{a} |
|-------|-------------|-------------|-----------------------------|
| 1     | 0.1 mmol    | 0.5 mmol    | 69%                         |
| 2     | 0.1 mmol    | 0.3 mmol    | 69%                         |
| 3     | 0.1 mmol    | 0.1 mmol    | 59%                         |
| 4     | 0.1 mmol    | 0.067 mmol (2/3 equiv) | 57%                         |
| 5     | 0.2 mmol    | 0.1 mmol    | 88%\textsuperscript{b}            |

\textsuperscript{a}The yields were determined by HPLC based on the amount of 1a. \textsuperscript{b}The yield was calculated based on the amount of 2a.

Scheme 2: Photoinduced reaction of diphenyl disulfide with triphenylbismuthine.

seleno radical. The seleno radical may dimerize to re-form diselenide. Diphenyl diselenide has its absorption maximum (λ\textsubscript{max}) at 340 nm (ε = 10\textsuperscript{3}) \cite{66} and accordingly, the seleno radical could be produced by the irradiation with a tungsten lamp. However, the irradiation by a tungsten lamp instead of a xenon lamp did not result in the desired reaction (Table 1, entry 3). This fact strongly suggests that the formation of a phenylseleno radical is not important for the formation of diphenyl selenide. Conceivably, when the reaction proceeds, a phenyl radical may be formed directly from triphenylbismuthine upon photoirradiation. Moreover, the use of an excess amount of 1, which has a relatively high carbon-radical-capturing ability, increased the yield of 3, and the use of diphenyl disulfide (4), which has a lower carbon-radical-capturing ability than diselenide, decreased the yield of 5. (The exact capturing abilities of diselenide and disulfide toward the phenyl radical are not known, but they have been reported toward vinyl radicals, where diselenide has a higher capturing ability than disulfide: k\textsubscript{Se}/k\textsubscript{S} = 160 \cite{57-59}.) These facts also support that the reaction starts from the generation of an aryl radical. On the other hand, a pale yellow solid, insoluble in organic solvents, was obtained as a byproduct after the reaction. We assume that this solid is a bismuth residue, which can consist of bismuth oxides and/or bismuth selenides. Moreover, it may form biaryls (Ar–Ar) as byproducts, but no biaryl was observed after the reaction.

Scheme 3: A plausible reaction pathway for the photoinduced reaction of diaryl diselenide with triarylbismuthine.
Conclusion

We have found that the photoinduced reaction of diaryl diselenides with triarylbismuthines affords unsymmetrical diaryl selenides in good yields. This method is efficient, because two arylseleno groups from diaryl selenides can be used as a selenium source, and its advantage is that the reaction proceeds in the absence of transition-metal catalysts.

Experimental

General comments

Compounds 1a, 2a, 3aa, 4, and 5 were obtained from commercially available materials. Diaryl diselenides 1b-e [67] and triarylbismuthines 2b-d [68] were synthesized according to the literature procedures.

General procedure for the photoinduced synthesis of unsymmetrical diaryl selenides from diaryl diselenide and triarylbismuthine

\((\text{Ar}_2\text{Se})_2\) (0.1 mmol), and \(\text{Ar}_2\text{Bi}\) (0.3 mmol) were dispersed in CH\(_3\text{CN}\) (2 mL) with a stirring bar in a quartz test tube (\(\phi = 9\) mm) with a septum in which a needle was inserted. The mixture was stirred and irradiated by a xenon lamp for 5 h at room temperature. The reaction mixture was filtered through a bed of celite (Celite 535). The crude product was purified by preparative TLC on silica gel (eluent: hexane/EtOAc). Details about compounds 3ab [30], 3ac [14], 3ad [17], 3ba [17], 3bb [31], 3ca [17], 3da [32], 3ea [28] and 3de [30] were reported in the corresponding articles.

Supporting Information

Supporting Information File 1
Spectral and analytical data of the new compound 3cb.
[http://www.beilstein-journals.org/bjoc/content supplementary/1860-5397-9-127-S1.pdf]

Acknowledgements

This work is supported by a Grant-in-Aid for Scientific Research (C, 23550057) from the Ministry of Education, Culture, Sports, Science and Technology.

References

1. Klayman, D. L.; Günther, W. H. H. Organic Selenium Compounds: Their Chemistry and Biology; John Wiley & Sons: New York, 1973.
2. Wirth, T., Ed. Organoselenium Chemistry; Topics in Current Chemistry, Vol. 208; Springer: Berlin, 2000. doi:10.1007/3-540-48171-0
3. Ogawa, A. Selenium and Tellurium in Organic Synthesis; Main Group Metals in Organic Synthesis; Yamamoto, H.; Oshima, K., Eds.; Wiley-VCH: Weinheim, Germany, 2004; Vol. 2, pp 813–866.
4. Nogueira, C. W.; Rocha, J. B. Arch. Toxicol. 2011, 85, 1313–1359. doi:10.1007/s00204-011-0720-3
5. Andersson, C.-M.; Hallberg, A.; Linden, M.; Brattsand, R.; Moldeus, P.; Cotgreave, I. Free Radical Biol. Med. 1994, 16, 17–28. doi:10.1016/0891-5849(94)90238-0
6. Campbell, T. W.; Walker, H. G.; Copping, G. M. Chem. Rev. 1952, 50, 279–349. doi:10.1021/cr60156a003
7. Greenberg, B.; Gould, E. S.; Burlant, W. J. Am. Chem. Soc. 1956, 78, 4028–4029. doi:10.1021/ja10597a043
8. Cristau, H. J.; Chabaud, B.; Labaudiniere, R.; Christol, H. Organomet. 1985, 4, 657–661. doi:10.1010/00123a007
9. Beletskaia, I. P.; Sigeev, A. S.; Peregodov, A. S.; Petrovskii, P. V. J. Organomet. Chem. 2000, 605, 96–101. doi:10.1016/S0022-328X(00)00295-5
10. Gujadhur, R. K.; Venkatacharan, D. Tetrahedron Lett. 2003, 44, 81–84. doi:10.1016/S0040-4039(02)02482-2
11. Taniguchi, N.; Onami, T. J. Org. Chem. 2004, 69, 915–920. doi:10.1021/jo0303000
12. Kumar, S.; Engman, L. J. Org. Chem. 2006, 71, 5400–5403. doi:10.1021/jo060969a
13. Varala, R.; Ramu, E.; Adapa, S. R. Bull. Chem. Soc. Jpn. 2006, 79, 140–141. doi:10.1246/bcsj.79.140
14. Taniguchi, N. J. Org. Chem. 2007, 72, 1241–1245. doi:10.1021/jo06231+
15. Alves, D.; Santos, C. G.; Paixão, M. W.; Soares, L. C.; Souza, D. D.; Rodrigues, O. E. D.; Braga, A. L. Tetrahedron Lett. 2009, 50, 6635–6638. doi:10.1016/j.tetlet.2009.08.052
16. Murthy, S. N.; Madhav, B.; Reddy, V. P.; Nageswar, V. D. Eur. J. Org. Chem. 2009, 5902–5905. doi:10.1002/ ejoc.200900988
17. Reddy, V. P.; Kumar, A. A.; Swapna, K.; Rao, K. R. Org. Lett. 2009, 11, 951–953. doi:10.1021/ol802734f
18. Singh, D.; Alberti, E. E.; Rodrigues, O. E. D.; Braga, A. L. Green Chem. 2009, 11, 1521–1524. doi:10.1039/b916266f
19. Bhadr, S.; Saha, A.; Ranu, B. C. J. Org. Chem. 2010, 75, 4864–4867. doi:10.1021/jo100755g
20. Li, Y.; Wang, H.; Li, X.; Chen, T.; Zhao, D. Tetrahedron 2010, 66, 8583–8586. doi:10.1016/j.tet.2010.09.061
21. Freitas, C. S.; Barcellos, A. M.; Ricordi, V. G.; Pena, J. M.; Perin, G.; Jacob, R. G.; Lenardão, E. J.; Alves, D. Green Chem. 2011, 13, 2931–2938. doi:10.1039/c1gc15725f
22. Swapna, K.; Murthy, S. N.; Nageswar, V. D. Eur. J. Org. Chem. 2011, 1940–1946. doi:10.1002/ ejoc.2010101639
23. Zhao, H.; Hao, W.; Xi, Z.; Cai, M. New J. Chem. 2011, 35, 2661. doi:10.1039/c1nj02514e
24. Ricordi, V. G.; Freitas, C. S.; Perin, G.; Lenardão, E. J.; Jacob, R. G.; Savegnago, L.; Alves, D. Green Chem. 2012, 14, 1030–1034. doi:10.1039/c2gc16427b
25. Beletskaia, I. P.; Sigeev, A. S.; Peregodov, A. S.; Petrovskii, P. V.; Khrustalev, V. N. Chem. Lett. 2010, 39, 720–722. doi:10.1246/cl.2010.720
26. Beletskaia, I. P.; Sigeev, A. S.; Peregodov, A. S.; Petrovskii, P. V. Russ. J. Org. Chem. 2001, 37, 1463–1475. doi:10.12303/1013460213633
27. Ren, K.; Wang, M.; Wang, L. Org. Biomol. Chem. 2009, 7, 4858–4861. doi:10.1039/b914533h
28. Reddy, K. H. V.; Satish, G.; Ramesh, K.; Karnakar, K.; Nageswar, V. D. Chem. Lett. 2012, 41, 585–587. doi:10.1246/cl.2012.585
29. Wang, M.; Ren, K.; Wang, L. Adv. Synth. Catal. 2009, 351, 1586–1594. doi:10.1002/adsc.200900095
30. Hayashi, S.; Yamane, K.; Nakashiki, W. J. Org. Chem. 2007, 72, 7587–7596. doi:10.1021/jo070988g
