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Notable Sulfur Atom Effects on the Regio- and Stereoselective Formation of Oxetanes in Paternò−Büchi Photocycloaddition of Aromatic Aldehydes with Silyl O,S-Ketene Acetals

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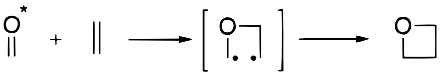
Abstract: Paternò−Büchi photocycloaddition of silyl O,S-ketene acetals (SKA) **1** and aromatic aldehydes **2** was investigated in detail. The photoreaction of aldehydes **2a−d** with β,β-dimethyl-O,S-SKA **1a−e** has been found to give, regio- (ca. 70/30 to 90/10) and stereoselectively (ca. 70/30 to 90/10), *trans*-3-siloxyoxetanes **3** independent upon the aldehyde, the substituents SR^1 and SiR_3, and reaction medium (solvent and salts). The triplet 2-oxatetramethylene 1,4-diradical **T-1,4-DR** is reasonably proposed as a common intermediate. The regioselectivity is rationalized by (1) the relative stability of 1,4-diradicals and (2) the relative nucleophilicity of sp^2-carbons in O,S-SKA. The *trans*-selectivity is explained by the sulfur atom effects in O,S-SKA **1**, which control the approach direction of the electrophilic oxygen of triplet $n\pi^*$ aldehydes to the nucleophilic alkene. The fast ISC process of the triplet 1-alkylthio-1-siloxy-2-oxatetramethylene 1,4-diradical **T-1,4-DR** in competition with the bond rotation has been proposed. The substrate-dependent formation of **3fb** from *E*- or *Z*-**1f** supports the hypothesis. The *S*-directed regio- and diastereoselectivity are found for the first time in the present study.

Introduction

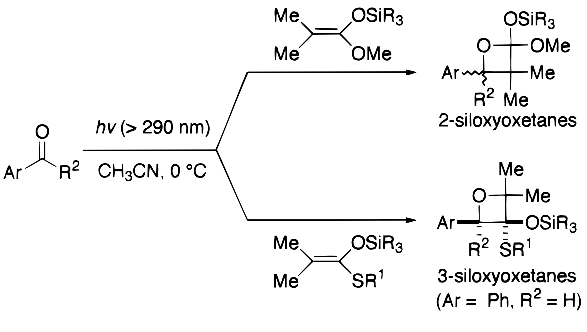
Regio- and stereoselectivity on the formation of oxetanes in photochemical [2+2] cycloaddition, the so-called Paternò−Büchi reaction,[1] of carbonyl compounds with alkenes have attracted considerable attention from the synthetic and mechanistic points of view. Numerous inter- and intramolecular reactions have been reported in the past four decades, which reveal in general that a 1,4-diradical (2-oxatetramethylene-1,4-diyl) is the key intermediate formed in the reaction of electrophilic oxygen of the excited state of carbonyls with electron-rich alkenes (Scheme 1).[2]

From the synthetic point of view, the regio- and stereoselective formation of oxetanes is still a challenging subject.[2b,3] In this regard, we have recently reported the regioselective formation of 2-siloxyoxetanes in the photochemical reaction of acyclic and cyclic silyl O,O-ketene acetals (O,O−SKA) with aromatic carbonyl compounds via the *electron-transfer reaction* (Scheme 2).[4] During the course of our continuous investigation on the Paternò−Büchi reaction, we have found the regio- and stereoselective formation of 3-siloxyoxetanes in the photoreaction of benzaldehyde (Ar = Ph, R^2 = H) with silyl O,S-ketene acetals (O,S-SKA) (Scheme 2).

Scheme 1



Scheme 2



The sharp contrast results on the regioselectivity (2-siloxy vs 3-siloxy) in the formation of siloxyoxetanes have prompted us to investigate the notable sulfur atom effects on the oxetane formation in detail. Herein, we report our study on the cycloaddition of aromatic aldehydes **2** with O,S-SKA **1**.

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10.1021/ja993997i CCC: $19.00

Scheme 3

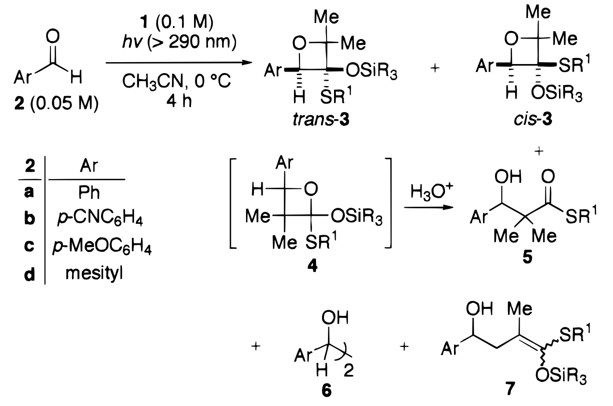

Table 1. Paternò−Büchi Coupling of O,S-KSA **1** and Aromatic Aldehydes **2** in CH_3CN at 0 °C[a]

entry	1	2	products and yields (%)[b] trans-3	cis-3	5	6	trans-3/cis-3[c]	3/5[d]
1	**1a**	**2a**	30	11	15	15	73/27	73/27
2	**1a**	**2b**	50	12	15	21	80/20	81/19
3	**1a**	**2c**	37	20	22	21	65/35	72/28
4	**1a**	**2d**	18	5	trace	0	78/22	—[e]
5	**1b**	**2b**	32	8	13	30	82/18	75/25
6[f]	**1c**	**2b**	38	18	14	22	67/33	80/20
7	**1d**	**2b**	58	8	9	25	88/12	88/12
8	**1e**	**2b**	42	4	17	25	91/9	73/27

[a] The photoreactions were performed with a high-pressure Hg lamp through a Pyrex filter (>290 nm) at 0 °C for 4 h. [b] Isolated yields (%) after column chromatography on silica gel. [c] The ratios were obtained by the ^1H NMR (270 MHz) peak areas. [d] The values were based on the isolated yields of **3** and **5**. [e] The ratio was not determined due to the low yield of **5ad**. [f] The adduct **7cb** (Ar = p-CNC_6H_4, SR^1 = SMe, SiR_3 = TIPS) was isolated in 2% yield.

Results

Photoreaction of Silyl O,S-Ketene Acetals 1a−e with Aromatic Aldehydes 2a−d. A degassed acetonitrile solution of aromatic aldehydes **2a−d** (0.05 M) and silyl O,S-ketene acetals **1a−e** (0.1 M) was irradiated with a high-pressure Hg lamp (300 W) through a Pyrex filter (>290 nm) at 0 °C (Scheme 3 and Table 1).

The photoreactions of benzaldehyde derivatives **2a−d** with O,S-SKA **1a** (SR^1 = Me, SiR_3 = TBDMS) were found to give 3-siloxyoxetane **3** (*trans*-**3**/*cis*-**3** = ca. 70/30−80/20; the configuration was determined by the ^1H NMR NOE measurements, vide infra) as a major product together with the aldol-type adduct **5** and the corresponding pinacol **6** (entries 1−4). Interestingly, the diastereoselectivities, *trans*-**3**/*cis*-**3**, were not largely dependent upon the electronic and steric effects of the substituents on the aryl group. The aldol-type adduct **5** may be formed from the acid-labile 2-siloxyoxetane **4** under the isolation conditions (silica gel), since the direct formation of the adduct **5** could not be detected by the ^1H NMR analyses (270 MHz) of the photolysate. Our previous findings on the formation of aldol-type adducts derived from 2-siloxyoxetanes strongly support the transformation.[4] Thus, the regioselectivity (3-siloxyoxetane **3**/2-siloxyoxetane **4**) was estimated from the product ratios of **3**/**5** (ca. 70/30 to 90/10) as shown in Table 1. In the photoreaction of *p*-cyanobenzaldehyde **2b** (entry 2), a high mass balance was observed (mass balance 98%). Thus, the substituent effects of R^1 and the SiR_3 group in the photoreaction were examined with *p*-cyanobenzaldehyde **2b** (entries 5−8).

As shown in entries 5−8, the substituents, R^1 and SiR_3, did not significantly affect only the diastereoselectivity (*trans*-**3**/*cis*-**3**), but also the regioselectivivy (**3**/**5**). In the photoreaction with O,S-SKA **1c** (R^1 = Me, SiR_3 = TIPS) (entry 6), alcohol **7cb** (SR^1 = Me, SiR_3 = TIPS, Ar = *p*-CNC_6H_4) was isolated as a minor product (2%). For the other photoreactions, a trace amount of the alcohol seems to be formed, but the structural assignment was discarded due to the low yield. The formation of alcohol **7** suggest the hydrogen abstraction by the triplet $n\pi^*$ carbonyl on the allylic hydrogen of O,S-SKA **1**.

Table 2. Solvent and Salts Effects on the Formation of Siloxyoxetanes **3** and **5** in the Photoreaction of Benzaldehyde Derivatives **2** with O,S-KSA **1a**[a]

entry	2	solvent	salts	products and yields (%) trans-3	cis-3	5	6	trans-3/cis-3	3/5
1[b]	**2a**	CH_3CN	none	30	11	15	15	73/27	73/27
2	**2a**	CH_2Cl_2	none	23	11	15	16	68/32	69/31
3	**2a**	C_6H_6	none	23	10	14	13	71/29	72/28
4[b]	**2b**	CH_3CN	none	50	12	15	21	80/20	81/19
5[c]	**2b**	CH_3CN	Et_4NClO_4	46	9	10	15	83/17	84/16
6	**2b**	CH_2Cl_2	none	48	13	6	15	79/21	91/9
7[c]	**2b**	CH_2Cl_2	Bu_4NPF_6	44	12	5	16	78/22	92/8
8	**2b**	C_6H_6	none	41	11	18	17	79/21	74/26
9[b]	**2c**	CH_3CN	none	37	20	22	21	65/35	72/28
10	**2c**	CH_2Cl_2	none	22	15	11	16	63/37	70/30
11	**2c**	C_6H_6	none	39	17	22	0	69/31	80/20

[a] The photoreaction through a Pyrex filter (>290 nm) of O,S-KSA **1a** (100 mM) and benzaldehyde derivatives **2** (50 mM) was performed at 0 °C for 4 h. [b] The data were taken from Table 1. [c] The photoreaction was performed in the presence of the salts (500 mM).

As mentioned above, interestingly, the photoreaction of O,S-SKA **1** gave preferentially *trans*-3-siloxyoxetanes **3** independent of the aldehydes **2**, R^1 and SiR_3 substituents, which is in sharp contrast to the results of the predominant formation of 2-siloxyoxetanes in the photoreaction with O,O-SKA (Scheme 2).

Solvent and Salts Effects. The mechanism of a Paternò−Büchi type reaction has been found to be largely dependent upon the combination of the substrates.[5] The electron-transfer pathway is the most promising mechanism, if the electron transfer is exothermic, i.e. ΔG_{et} ($=E_{ox} - E_{red}$)[6] < 0. To understand the mechanism of our Paternò−Büchi photocycloaddition of O,S-SKA **1** and aldehydes **2**, the oxidation potential of O,S-SKA **1a** (SiR_3 = TBDMS, SR^1 = SMe) was measured by using cyclic voltanmmetry (CV). The irreversible oxidation wave (E_p) was observed at 1.22 V vs SCE. Judging from the known reduction potentials[4b] (E^*_{red}) of the triplet excited state of the aromatic carbonyl compounds ($E^*_{red} = E_T - E_{red}$ = 1.16 V for **2a** (Ar = Ph), 1.51 V for **2b** (Ar = *p*-CNC_6H_4), and 0.86 V for **2c** (Ar = *p*-$MeOC_6H_4$)), the electron transfer between O,S-SKA **1a** and *p*-cyanobenzaldehyde **2b** seems to be possible in acetonitrile used for the photoreactions. Since electron-transfer reactions have been found to be largely influenced by the reaction medium,[7] i.e. solvent (dielectric constant ϵ) and the presence of salts, the medium effects on the product distribution were examined in the photoreaction with O,S-SKA **1a** (R^1 = Me, SiR_3 = TBDMS) (Table 2).

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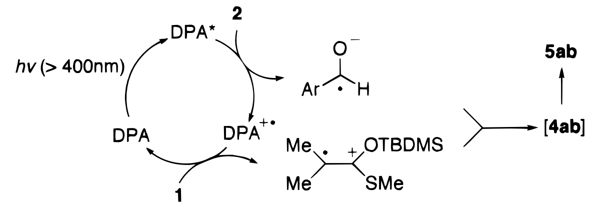
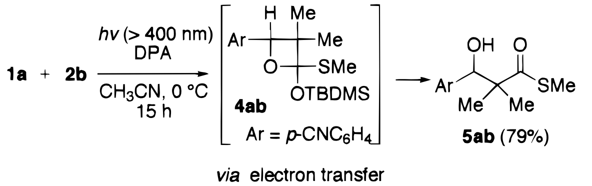
Scheme 4



As shown in Table 2, the solvent polarity (CH_3CN, ϵ 37.5; CH_2Cl_2, ϵ 8.9; benzene, ϵ 2.3) did not affect the product ratios, i.e. *trans*-**3**/*cis*-**3** and **3**/**5** (entries 1−3, 4, 6, and 8−11). Furthermore, the salts (Et_4NClO_4, Bu_4NPF_6) gave no effects (entries 5 and 7). The negligible solvent and salt effects on the diastereoselectivity (*trans*-**3**/*cis*-**3**) and the regioselectivity (**3**/**5**) suggest that the electron-transfer mechanism between the triplet excited state of aldehydes **2** and O,S-SKA **1** is unlikely at least for the formation of oxetanes observed.

DPA-Photosensitized Reaction of *p*-Cyanobenzaldehyde 2b with O,S-SKA 1a. To ensure the mechanism for the formation of siloxyoxetanes **3** and **4**, the 9,10-diphenylanthracene (DPA, $E_S = 3.15$ eV, $E_{ox} = 1.22$ V, $E_{red} = -1.94$ V vs SCE)[8]-sensitized photoreaction (>400 nm) of O,S-SKA **1a** with *p*-cyanobenzaldehyde **2b** ($E_{red} = -1.38$ V vs SCE) was performed (eq 1). Under such conditions, the electron-transfer reaction would be the most promising process as judged by their redox potentials, generating the cation radical of **1a** and anion radical of **2b** (Scheme 4).[9] After irradiation for 15 h (conversion of aldehyde **2b**, 100%), the aldol-type adduct **5ab** (Ar = *p*-CNC_6H_4) was the only isolable product (79%). We could not detect any trace amounts of 3-siloxyoxetane **3ab**. Thus, the predominant formation of 2-siloxyoxetane **4ab** should be expected under electron-transfer conditions. This result is quite consistent with the exclusive formation of 2-siloxyoxetanes derived from O,O−SKA ($E_{ox} = 0.90$ V vs SCE)[4b,10] with much lower oxidation potential than O,S-SKA **1** ($E_{ox} = 1.22$ V vs SCE), as shown in Scheme 2.



(1)

Under the direct irradiation of aromatic aldehydes **2**, 3-siloxyoxetanes **3** were major products (Table 1). Thus, 3-siloxyoxetanes **3** should be derived from the triplet 1,4 diradicals (**T-1,4-DR**) formed directly or via exciplex between the $n\pi^*$ triplet excited state of aldehydes **2** and O,S-SKA **1** (Scheme 5), not by the coupling between the radical ion pair. Because if the direct electron transfer is occurred, the resulting radical ion pair would give the 2-siloxyoxetanes **4** as shown in Scheme 4.

Paternò−Büchi Coupling of *p*-Cyanobenzaldehyde 2b and O,S-SKA *E*- or/and *Z*-1f. To understand the *trans*-selective formation of 3-siloxyoxetane **3** shown above, O,S-SKA *E*- or/and *Z*-**1f** have been chosen and reacted with *p*-cyanobenzaldehyde **2b** (eq 2, Table 3).

Scheme 5

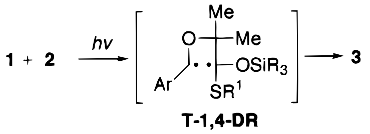
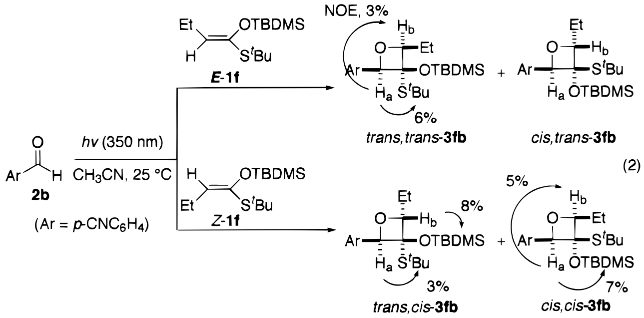


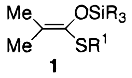
Table 3. Paternò−Büchi Coupling of O,S-KSA *E*- or/and *Z*-**1f** with *p*-Cyanobenzaldehyde **2b** in CH_3CN at 25 °C[a]

		diastereomer ratios of **3fb**[b]			
entry	**1f**	*trans,trans*-**3fb**	*cis,trans*-**3fb**	*trans,cis*-**3fb**	*cis,cis*-**3fb**
1	*E*-**1f** (*E*/*Z* = 90/10)	96	4	0	0
2	*Z*-**1f** (*E*/*Z* = 10/90)	50	4	20	26
3	*E*,*Z*-**1f** (*E*/*Z* = 47/53)	72	6	10	12

[a] A solution of **2** (0.05 M) and O,S-KSA *E*- or/and *Z*-**1f** (0.5 M) was irradiated by using a Xenon lamp (350 ± 5 nm) at room temperature (ca. 25 °C). All of the reactions were stopped at ca. 50% consumption of the aldehyde **2b**. [b] The isomer ratios, normalized to 100%, were determined by ^1H NMR (270 MHz) peak area, error ±5%.

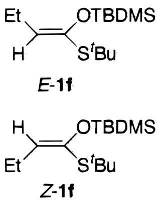


Since the photochemical isomerization between O,S-SKAs *E*- and *Z*-**1f** was observed, the photoreactions by using Xenon lamp ($h\nu = 350 \pm 5$ nm) were performed in the presence of large excess amounts of *E*- or/and *Z*-**1f** (10 equiv) and stopped at ca. 50% conversion of the aldehyde **2b**, to minimize the change of the isomer ratios (*E*-/*Z*-**1f**) during the course of the reaction. Unfortunately, the four possible diastereomers of 3-siloxyoxetanes **3fb**, *trans,trans*-, *cis,trans*-, *trans,cis*-, and *cis,cis*-, could not be perfectly separated by using HPLC analysis. Thus, the relatively high conversions (50%) of aldehyde **2b** were needed to determine the product ratios by ^1H NMR (270 MHz) analyses. Fortunately, all of the benzylic protons H_a were well distinguished in d_6-benzene, thus, the determination of the accurate ratios (error ±5%) was feasible (Table 3, the configurational determination will be discussed below). As shown in Table 3, the obtained ratios were largely dependent upon the configuration of the starting material **1f**. When the *E*-isomer *E*-**1f** (*E*/*Z* = 90/10) was used for the



1

1	**a**	**b**	**c**	**d**	**e**
R^1	Me	Me	Me	^tBu	^tBu
SiR_3	TBDMS	TMS	TIPS	TBDMS	TMS



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(9) The fluorescence of DPA was actually quenched by *p*-cyanobenzaldehyde **2b**, but not by O,S-SKA **1a**. For the generation of radical ion pairs by means of such a photosensitization, see; (a) Majima, T. Pac, C.; Sakurai, H. *J. Am. Chem. Soc.* **1980**, *102*, 5265. (b) Pac, C. *Pure Appl. Chem.* **1986**, *58*, 1249.

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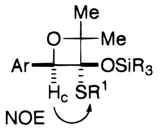
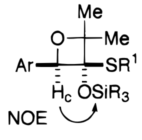
photoreaction, only *trans,trans*- and *cis,trans*-**3fb** (75% yield) were detected by ^{1}H NMR, and the isomer ratio was 96/4 (entry 1, final ratio of *E*-/*Z*-**1f** = 88/12). Namely, the configuration of the starting material *E*-**1f** was perfectly retained in the products. The *trans,trans*-isomer could be isolated as a pure form and fully characterized. The triplet quenching experiment was also performed in the presence of 1,3-pentadiene (0.5 M, $E_T = 59$ kcal/mol)[8] under similar irradiation conditions. The formation of the oxetane **3fb** (ca. 10%) was suppressed, and the starting materials **1f** and **2b** were recovered in reasonable yields. Thus, the 3-siloxyoxetanes **3** are mainly formed by the triplet excited state of aldehydes **2** (E_T = ca. 70 kcal/mol).[8]

Alternatively, in the photoreaction with *Z*-**1f** (*E*/*Z* = 10/90), all of the four possible isomers (total yield, 72%) were observed (entry 2, *trans,trans*-, *cis,trans*-, *trans,cis*-, *and cis,cis*-**3fb** = 50/4/20/26, final ratio of *E*-/*Z*-**1f** = 15/85). The *trans,cis*- and *cis,cis*-isomers could be isolated after several trials of column chromatography on silica gel. Unfortunately, the *cis,trans*-isomer could not be obtained as a pure form, but with the *cis,cis*-isomer (*cis,cis*/*cis,trans* = 2/3).

Finally, the competitive reaction of *E*- and *Z*-**1f** (*E*/*Z* = 47/53) was performed (entry 3). The product ratio obtained in the reaction was found to be 72/6/10/12 (total yields, 68%, final ratio of *E*/*Z* = 51/49). The results suggest that the reaction of aldehyde **2b** with *E*-**1f** is much faster than that with the *Z*-isomer. If we assume that all of the *trans,trans*- and *cis,trans*-**3fb** come from the *E*-**1f**, the reaction with the *E*-isomer is about four times faster than that with the *Z*-isomer (*trans,trans*- + *cis,trans*-**3fb**/*trans,cis*- + *cis,cis*-**3fb** = 78/22). Thus, we feel that the production of *trans,trans*- and *cis,trans*-**3fb** in the photoreaction with *Z*-**1f** (initial ratio, *E*/*Z* = 10/90; final ratio, *E*/*Z* = 15/85) mainly derived from *E*-**1f**, which is already included as a minor component in the starting materials. The substrate-dependent reactions clearly suggest that the product ratios were not controlled by the relative thermodynamic stability of the 3-siloxyoxetanes **3fb** formed in the photoreaction.[11]

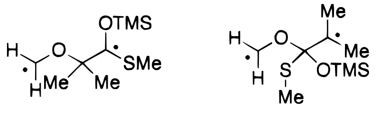


trans-**3**



cis-**3**

Configurational Determination of 3-Siloxyoxetanes 3. First of all, the stereochemical determination of the 2,2-dimethyl-3-siloxyoxetanes **3** formed from O,S-SKA **1a-e** is discussed on the basis of both the NOE measurements and the comparison of the chemical shifts of SiR$_3$ and SR^1 groups. The isomer with clear NOE enhancements (in the range of 3−7%) between H$_c$ and the protons of SR^1 was determined as the *trans*-isomer. Alternatively, in the cis-isomer the clear NOE enhancements between H$_c$ and the protons of silyl group were found in the range of 2−5%. Furthermore, in the trans-isomer, the upfield chemical shift (ca. 0.5 ppm) of the protons of the SiR$_3$ group and the low-field shift (ca. 0.3 ppm) of those of the SR^1 group were observed in comparison with those in the *cis*-isomer (see the Experimental Section in the Supporting Information). Thus, the stereochemical determinations for all of the 3-siloxyoxetanes **3** were feasible.



T-1,4-DR-1 ΔH_f = -113.5 kcal/mol

T-1,4-DR-2 ΔH_f = -110.3 kcal/mol

Figure 1.

Similarly, we could determine the configuration of the four diastereomers of **3fb**. Namely, the isomer with the clear NOE enhancements between H$_a$ and H$_b$ (3%), and also H$_b$ and S^{t}Bu (6%), was determined as *trans,trans*-**3fb**. In the same way, the stereochemical determination for *trans,cis*- and *cis,cis*-**3fb** was done as depicted in eq 2. Thus, the rest of isomer could be determined as the *cis,trans*-isomer.

Discussion

Regioselectivity: 3-Siloxy- vs 2-Siloxyoxetane Formation. As mentioned above, we have concluded that 3-siloxyoxetanes **3** may be formed via triplet 1,4-diradical species. The conclusion is quite reasonable from experimental results: (1) the regioselectivity, **3**/**5**, was not dependent upon the reduction potential of the excited carbonyl compounds **2** (see, entries 2−4 in Table 1) and (2) the insensible solvent and salt effects on the regioselectivity, **3**/**5** in Table 2, (3) the selective formation of 2-siloxyoxetane **4** in the DPA-sensitized electron-transfer reaction (eq 1), and (4) the formation of oxetanes **3, 4** were effectively suppressed by the presence of 1,3-pentadiene (triplet quencher).

The question quickly arose; Why was the 3-siloxyoxetane **3** selectively formed via triplet 1,4-diradical **T-1,4-DR**? In this regard, we should consider the following two effects:[12] (1) the relative stability of the regioisomeric diradicals, **T-1,4-DR-1** vs **T-1,4-DR-2** and (2) the relative nucleophilicity of the C1 and C2 carbons of O,S-SKA **1**. To elucidate the first point, semiempirical calculations (PM3/UHF, Triplet)[13,14] were performed for the two triplet states of diradicals, **T-1,4-DR-1** vs **T-1,4-DR-2** (SiR$_3$ = TMS, SR^1 = SMe) as models (Figure 1). Consequently, the heat of formation (ΔH_f) of **T-1,4-DR-1**, which leads to 3-siloxyoxetane, was found to be lower than that of **T-1,4-DR-2** at such a level of theory, $\Delta\Delta H_f$ = ca. 3.0 kcal/mol. The calculation results suggest that the diradical **T-1,4-DR-1** (optimized structure, see below) is more stable than the regioisomeric diradical **T-1,4-DR-2**.

Next, to ensure the relative nucleophilicity of C1 and C2 carbons, the HOMO coefficients were calculated for O,S-SKA **1b** (Figure 2). The relatively large coefficient at C2 (+0.54) was calculated, compared to that at C1 (+0.32). The obtained results are consistent with experimental observations, i.e. the Mukaiyama aldol reaction.[15] Additionally, a large HOMO coefficient at the sulfur atom (−0.65) with the opposite phase was also found, while the oxygen of the siloxy group has an almost negligible coefficient. The significant difference of the relative nucleophilicity suggests that the electrophilic oxygen of the triplet excited carbonyls **2** would attack preferentially the C2 carbon of O,S-SKA **1** to generate 1,4-diradicals, e.g. **T-1,4-DR-1**.

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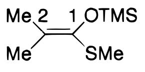
[11] Stereoselective formation of siloxyoxetanes controlled by product stability, see; (a) Bach, T.; *Tetrahedron Lett.* **1991**, *32*, 7037. (b) Bach, T.; Jödicke, K. *Chem. Ber.* **1993**, *126*, 2457. (c) Bach, T. *Tetrahedron Lett.* **1994**, *35*, 5845. (d) Bach, T. *Liebigs Ann.* **1995**, 855. (e) Bach, T.; Jödicke, K.; Kather, K.; Fröhlich, R. *J. Am. Chem. Soc.* **1997**, *119*, 2437.

[12] For the concept for regioselectivity of Paternò −Büchi reactions, see; (a) Turro, N. J. *Modern Molecular Photochemistry*; Benjamin/Cummings Publishing Co., Inc.: Menlo Park, 1978; p 432. (b) Sengupta, P.; Chardra, A. K.; Nguyen, M. T. *J. Org. Chem.* **1997**, *62*, 6404.

[13] Stewart, J. J. P. *J. Comput. Chem.* **1989**, *10*, 209.

[14] PM3 calculations were run on a CAChe system, Sony/Tektonix Co.

[15] (a) Mukaiyama, T.; Banno, K.; Narasaka, K. *J. Am. Chem. Soc.* **1974**, *96*, 7503. (b) Mukaiyama, T. *Org. React.* **1982**, *28*, 203.

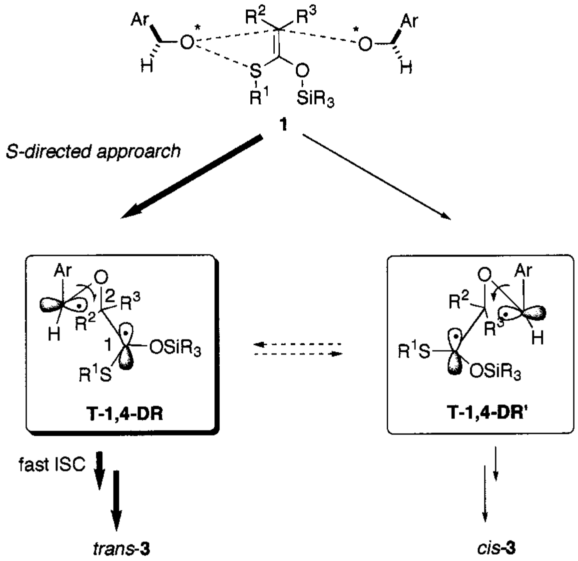


1b

	HOMO
C1	+0.32
C2	+0.54
S	-0.64

Figure 2.

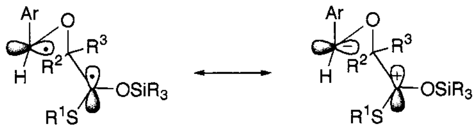
Scheme 6



As judged by the above considerations, the regioselective formation of oxetanes **3** may arise from these two points.[16]

***Trans*-Selective Formation of 3-Siloxyoxetanes 3.** Judging from the substrate-dependent formation of 3-siloxyoxetanes **3fb** depicted in eq 2 and Table 3, the *trans*-selective formation of 3-siloxyoxetanes **3** is not controlled by the thermodynamic preference of the trans-isomer.[11] Thus, we propose the hypothetical mechanism for the *trans*-selective formation of 3-siloxyoxetanes **3** as shown in Scheme 6.

Namely, the perpendicular approach[12a,17,18] of the electrophilic oxygen of the triplet excited state of **2** preferentially occurred from the sulfur-atom side of the O,S-SKA **1** to give the triplet 1,4 diradical **T-1,4-DR**. The sulfur (S)-directed approach of the electrophilic oxygen is reasonably explained by the electrostatic attraction between the sulfur atom and the electrophilic oxygen (see the large HOMO coefficients at the sulfur atom (Figure 2)). Then, the intersystem crossing (ISC) to the singlet state **S-1,4-DR** quickly occurred to afford the *trans*-isomer of 3-siloxyoxetane **3**. The *S-directed approach* can be reasonably supported by the fact that much higher diastereoselectivity (*trans,trans*-/*cis,trans*-**3fb** = 96/4) than the β,β-dimethyl substituted case, *e.g. trans*-/*cis*-**3ab** = 80/20, was observed. Namely, the direction of the *S-directed approach* of the carbonyl oxygen for *E*-**1f** (R^2 = H, R^3 = Et) is also sterically favored. The combined electrostatic and steric effects may increase the diastereoselectivity derived from O,S-SKA *E*-**1f**.



S-1,4-DR **ZI-1,4-DR**

Figure 3.

If our hypothesis as shown in Scheme 6 is right, the ISC from the triplet state **T-1,4-DR** to its singlet state **S-1,4-DR** should be faster than both the C1−C2 and C2−O bond rotations (Scheme 6). The situation is unusual since, in general, the rate constant of C−C bond rotation in ethane derivatives is around 10^{10-12} s^{-1},[19] while the rate constant for the spin-forbidden ISC process is reported to be 10^{6-8} s^{-1} for carbon chained 1,3- and 1,4-diradicals.[20] Thus, a C−C bond rotation should be much faster than the ISC process, which is a reason for stereo-random formation of oxetanes via triplet diradicals.[21] However, the general consideration may not be applied to our case, if the spin−orbit coupling (SOC) mechanism[22] for the ISC process is crucial for our system. The SOC mechanism has been reasonably accepted for short distance 1,*n*-diradicals, i.e. n = 3, 4. Salem and Rowland have addressed theoretically the following points expected to influence the SOC mechanism: (1) the perpendicularity of two singly occupied orbitals, (2) the distance between the radical cites, and (3) ionic contributions to the singlet wave function.[23] These factors may accelerate the ISC process.[24]

On the basis of theoretical considerations, the ISC process of our 2-oxatetramethyene 1,4-diradicals (**T-1,4-DR**) should be much faster than that of pure hydrocarbon 1,4-diradicals for the following reasons: (1) the spatial orientation, perpendicular geometry,[2e,25] of the two singly occupied orbitals in **T-1,4-DR** is already the best for the ISC process by the spin−orbit coupling (SOC) mechanism and (2) the ISC process may be accelerated by the zwitterionic character (**ZI**) of the singlet diradical **S-1,4-DR** (Figure 3), which may be induced by the adjacent substituents (SR, $OSiR_3$, Ar).

The significantly short lifetime, ca. 1−5 ns,[26] of 2-oxatetramethylene-1,4-diyls has been reported in comparison with that of the tetramethylene-1,4-diradicals, ca. 500 ns[20b] by flash photolysis studies. Caldwell has suggested that a 10^2−10^3 acceleration for 2-oxatetramethylene-1,4-diradicals relative to pure hydrocarbon biradicals would be expected in the ISC process.[20c] He has also mentioned that the large rate acceleration

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(16) For the regioselective formation of oxetanes from methyl vinylsulfides, see; (a) Morris, T. H.; Smith, E. H.; Walsh, R. *J. Chem. Soc., Chem. Commun.* **1987**, 964. (b) Khan, N.; Morris, T. H.; Smith, E. H.; Walsh, R. *J. Chem. Soc., Perkin Trans. 1* **1991**, 865.

(17) For the electrophilic attack, perpendicular approach, of excited carbonyl to electron-rich alkenes, see; (a) Salem, L. *J. Am. Chem. Soc.* **1974**, *96*, 3486. (b) Bigot, B.; Devaquet, A.; Turro, N. J. *J. Am. Chem. Soc.* **1981**, *103*, 6. (c) Palmer, I. J.; Ragazos, I. N.; Bernardi, F.; Olivucci, M.; Robb, M. A. *J. Am. Chem. Soc.* **1994**, *116*, 2121.

(18) Griesbeck, A. G. In *CRC Handbook of Organic Photochemistry and Photobiology*; Horspool, W. M., Song, P.-S., Eds.; CRC Press: New York, 1995; p 550.

(19) Horn, B. A.; Herek, J. L.; Zeweil, A. H. *J. Am. Chem. Soc.* **1996**, *118*, 8755.

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(21) For stereo-random formation of oxetanes, see; Turro, N. J.; Wriede, P. A. *J. Am. Chem. Soc.* **1970**, *92*, 320.

(22) (a) Bonacic-Koutecky, V.; Koutecky, J.; Michl, J. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*, 170. (b) Zimmerman, H. E.; Kutateladze, A. G.; Maekawa, Y.; Mangette, J. E. *J. Am. Chem. Soc.* **1994**, *116*, 995. (c) Minaev, B. F.; Jonsson, D.; Norman, P.; Agren, H. *Chem. Phys.* **1995**, *194*, 19.

(23) Salem, L.; Rowland, C. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 92.

(24) For the semiempirical formula for the magnitude of SOC, see; (a) Furlani, T. R.; King, H. F. *J. Chem. Phys.* **1985**, *82*, 5577. (b) Carlacci, L.; Doubleday, C., Jr.; Furlani, T. R.; King, H. F.; Mclever, J. W., Jr. *J. Am. Chem. Soc.* **1987**, *109*, 5323.

(25) (a) Griesbeck, A. G.; Stadtmüller, *J. Am. Chem. Soc.* **1990**, *112*, 1281. (b) Griesbeck, A. G.; Stadtmüller, S. *Chem. Ber.* **1990**, *123*, 357.

(26) (a) Freilich, S. C.; Peters, K. S. *J. Am. Chem. Soc.* **1981**, *103*, 6255. (b) Caldwell, R. A.; Majima, T.; Pac, C. *J. Am. Chem. Soc.* **1982**, *104*, 629.

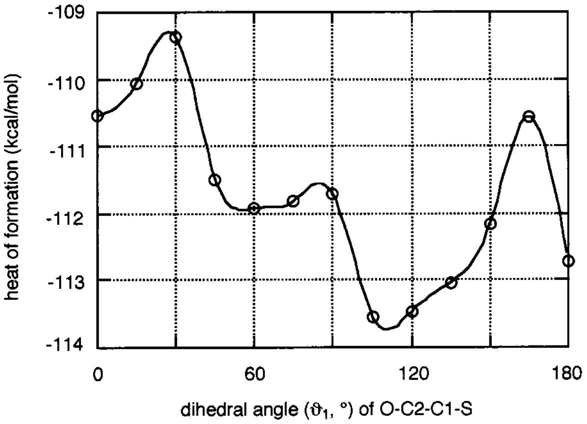


Figure 4. Conformational search around O−C2−C1−S (ϑ_1) in **T-1,4-DR-1**.

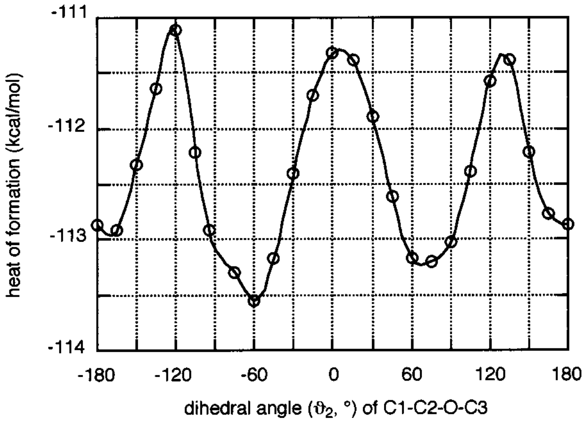
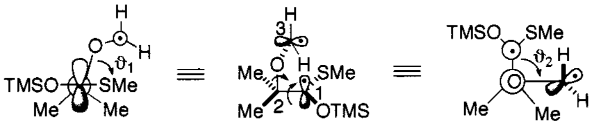


Figure 5. Conformational search around O−C2−C1−C3 (ϑ_2) in **T-1,4-DR-1**.



T-1,4-DR-1

may be due to the significant mixing of the oxygen lone pairs and p orbitals at both radical termini. In our diradicals **T-1,4-DR**, sulfur substituent also exists at radical termini. Thus, the additional rate acceleration would be expected.

Next, we should be concerned with the conformational stability of our diradicals **T-1,4-DR** with the perpendicular orientation of the two p orbitals. If the conformation does not exist as an energy minimum structure, our discussion seems to make no sense. Thus, the triplet 2-oxatetramethylene 1,4-diradical **T-1,4-DR-1** has been chosen as a model compound and calculated to estimate the relative stability in the possible conformations by using the semiempirical MO method (PM3/UHF).[27] The conformational searches around ϑ_1 (O−C2−C1−S) and ϑ_2 (C1−C2−O−C3) dihedral angles are shown in Figures 4 and 5. In reality, the optimized structure is closely similar to the structure **T-1,4-DR** depicted in Scheme 6. Namely, the structure with (1) parallel alignment ($\vartheta_1 =$ ca. $+100°$) between the C−O bond and the radical p orbital and (2) gauche geometry ($\vartheta_2 =$ ca. $\pm 60°$) was found to exist as an energy minimum, with a rotational energy barrier of ca. 3−4 kcal/mol at this level of theory. The stereoelectronic effect, i.e. the interaction between the SOMO of the alkoxyalkyl radical and the adjacent C−O σ^* orbital, can explain the parallel alignment of the C−O bond with the p orbital.[28] The results clearly suggest that the conformation of diradicals **T-1,4-DR** depicted in Scheme 6 has a lifetime. From these considerations, our hypothesis, i.e. the rate of ISC process > C1−C2 and O−C2 bond rotations, may be possible.

Summary

We have examined the Paternò−Büchi photocycloaddition of O,S-SKA **1** and aromatic aldehydes **2** in detail. The regioselective formation of 3-siloxyoxetanes **3** has been reasonably explained by both the stability of the 1,4-diradical involved and the interaction between the electrophilic oxygen of the triplet $n\pi^*$ aldehydes and the nucleophilic C2 carbon of the O,S-SKA. The *S-directed approach* of the excited state of the aldehydes and the successive ISC process have been proposed for the trans-selective formation of 3-siloxyoxetanes **3**. The notable sulfur atom effects on the regio- and stereoselectivity in the formation of siloxyoxetanes have been discovered for the first time. We believe that our finding will open up the new concept of the stereoselective formation of oxetanes.

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Supporting Information Available: Experimental procedure and spectral data (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(27) Excellent spin expectation $\langle S^2 \rangle$ values of 2.04 were obtained for the spin densities of these diradicals.

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