analogous mechanism involving radical[11] rather than ionic intermediates cannot be ruled out at this time.

1,1-Diphenyl-2-methoxyethylene reacted at low temperature also with TPPO and with triethylsilyl hydrotrioxide to produce benzophenone in 28% and 57% yields, respectively.[16,17] Even vinyl aromatics not activated by methoxyl substituents were converted by triethylsilyl hydrotrioxide into the corresponding 1,2-dioxetanes; TPPO did not react detectably (^{1}H NMR) with simple 1-arylalkenes at −60 °C even after 3 days. For example, 25–40 mg each of 1-vinylpyrene, 1-vinylnaphthalene,[18] and 2-vinylnaphthalene reacted with 1.8 equiv of triethylsilyl hydrotrioxide in methylene chloride (0.04 M),[7] slowly warmed during several hours from −78 → 25 °C and then kept at 25 °C for 12 h, to form the corresponding aromatic aldehydes (accompanied by CL during formation of 1-pyrenecarboxaldehyde) isolated by preparative TLC in 35%, 9%, and 23% yields (37%, 58%, and 59% yields based on recovered starting material), respectively. These results have both mechanistic and synthetic implications.

We are studying further the mechanism and the scope and limitations of these dioxetane-forming chemical reactions as well as biological applications.

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(17) Ozonolysis of 1,1-diphenyl-2-methoxyethylene apparently leads to dimerization and rearrangement: Nakamura, N.; Nojima, M.; Kusabayashi, S. *J. Am. Chem. Soc.* **1986**, *108*, 4671 and references therein.

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First Isolation of a Stable Aliphatic Thioaldehyde, Tris(trimethylsilyl)ethanethial

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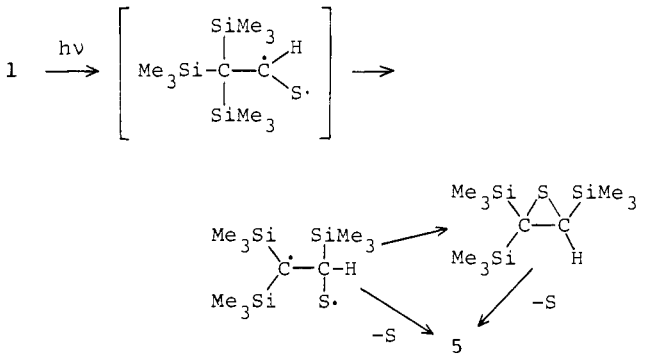
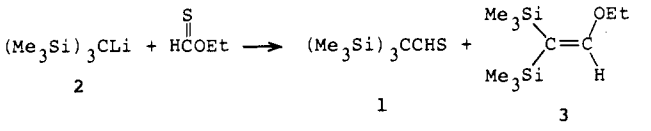
The chemistry of thioaldehydes has been of current interest.[1-9] Although many stable thioketones have been synthesized and relatively well studied in recent years, thioaldehydes have eluded isolation until very recently because of their extremely high tendency toward oligomerization.[10] We recently reported the first isolation of a stable aromatic thioaldehyde, 2,4,6-tri-*tert*-butylthiobenzaldehyde.[1] No aliphatic thioaldehyde, however, has been isolated so far although Vedejs and his co-workers have reported that thiopivaldehyde is relatively long-lived in solution (the half-life in chloroform at room temperature is 16 h).[2a,b] We now report the first isolation of a stable, crystalline, aliphatic thioaldehyde, tris(trimethylsilyl)ethanethial (**1**) and its interesting reactivities.

Scheme I



The reaction of tris(trimethylsilyl)methyllithium (**2**),[11] obtained from tris(trimethylsilyl)methane[12] and methyllithium, with *O*-ethyl thioformate gave the thioaldehyde **1** (16%)[13] and vinyl ether **3** (25%).[14,15]



Thioaldehyde **1** is a pink-red crystalline compound (mp 129–131 °C[16]) and can be purified by chromatography and recrystallization. It can be stored in a refrigerator for a long time without any decomposition and is stable at room temperature in the air at least for a week. Some spectral data of **1** are listed in Table I.

Although **1** is stable at room temperature, it undergoes Brook-type rearrangement[17] upon heating around 80 °C to give

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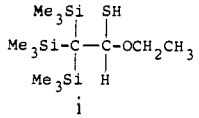
(13) A typical procedure of the synthesis of **1** follows. *O*-Ethyl thioformate (0.76 g, 8.5 mmol) was added to **2**, prepared from tris(trimethylsilyl)methane[12] (1.65 g, 7.08 mmol) and methyllithium (0.829 M solution of ether, 10.5 mL, 8.5 mmol) in THF (28 mL), at −78 °C. The pale yellow reaction solution was stirred for 10 min at −78 °C and for 1.5 h at room temperature. To the dark red solution were added aqueous ammonium chloride and ether. The dark red organic layer was separated, washed with brine 3 times, dried over anhydrous $MgSO_4$, and evaporated under reduced pressure. Residual dark red liquid was subjected to chromatography (silica gel, hexane–dichloromethane 20:1). The first fraction was 694 mg of a mixture of tris(trimethylsilyl)methane (19%) and **5** (25%). The second fraction was **1** (306 mg, 1.10 mmol, 16%), which was recrystallized from pentane (0.4 mL) at −78 °C to give pink-red crystals. Exact mass for $C_{11}H_{28}Si_3S$: 276.1219. Found: 276.1209. For spectra data, see Table I.

(14) The vinyl ether **3** is most probably produced by Peterson type reaction of **i** on silica gel.



(15) All new compounds gave satisfactory spectral data including exact mass analysis. For the details, see the supplementary material.

(16) Decolorization due to the isomerization into **3** began gradually at ca. 70 °C on measuring the melting point.

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Table I. Some Spectral Data of **1**

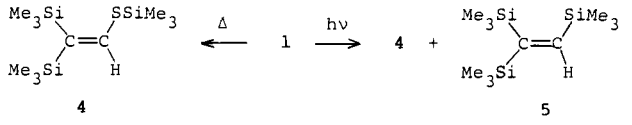
electronic spectrum/λ_{max}/nm (ϵ)		^{1}H NMR, δ		^{13}C NMR,	^{29}Si NMR,	
hexane	CH_3CN	$CDCl_3$	C_6D_6	δ, $CDCl_3$	δ, $CDCl_3$	IR, cm^{-1}, KBr
518 (15)	503 (14)	0.26 (s, 27 H)	0.16 (s, 27 H)	2.6	-0.22	1120 (C=S)
272 (9940)	277 (8720)	11.45 (s, 1 H, C*H*S)	11.45 (s, 1 H, C*H*S)	59.0		
212 (4320)	211 (5330)			248.2 (*C*HS)		

Table II. Thermodynamic Parameters of the Thermolysis of **1** and **5**[a]

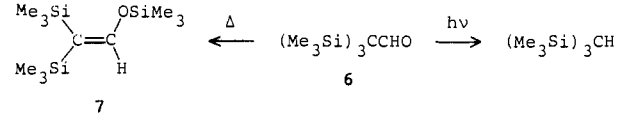
entry	compound	$\Delta H^{\ddagger}$/kcal mol^{-1}	$\Delta S^{\ddagger}$/eu	$\tau_{1/2}$ (70 °C)/h
1	1	28.0 ± 0.7	0.4 ± 2.1	16
2	6	24.2 ± 1.6	-6.1 ± 4.9	1.7
3[b]	$R_3SiCH_2C(=O)R'$	26-33[c]	-4.2 to -16.9	

[a] The thermolyses were carried out in toluene-d_8 at 70-90 °C for **1** and at 56-70 °C for **6**. [b] Reference 17. [c] E_a values.

vinyl sulfide **4** quantitatively.[15] It is noteworthy that **1** does not undergo oligomerization but isomerization upon heating. In contrast to the thermolysis, the photolysis of **1** (medium-pressure Hg lamp, benzene, 5 °C, 17 h) afforded **5** (33%)[18] in addition to **4** (66%).



For comparison, the corresponding aldehyde **6**,[15] prepared from **2** and ethyl formate, was also subjected to the thermolysis and photolysis under similar conditions to give silyl enol ether **7**[19] (100%) and tris(trimethylsilyl)methane[12] (90%), respectively.



The difference in photochemical behavior between **1** and **6** is noteworthy. The formation of **5** from **1** is especially interesting since this type of reaction, i.e., 1,2-shift of a group from the α-position to the thiocarbonyl carbon with a concomitant loss of sulfur, is a new mode of photoreaction for thiocarbonyl compounds. This reaction most likely proceeds as shown in Scheme I. The vinyl sulfide **4** cannot be an intermediate of **5** since **4** is inactive under the reaction conditions.

Interestingly, **1** is thermally more stable than the corresponding aldehyde **6**. The thermolyses of **1** and **6** obey first-order kinetics, and the half-lives of **1** and **6** in toluene-d_8 at 70 °C are 16 and 1.7 h, respectively. The thermodynamic parameters for these reactions are shown in Table II along with those obtained for α-silyl ketones by Brook,[17] which are in good agreement with those for **6**. Comparison of the parameters for **1** and **6** shows that the stability of **1** compared with **6** results mainly from an enthalpic factor, i.e., the much smaller bond energy of Si-S than that of Si-O.

The thioaldehyde **1** was reduced with sodium borohydride to give the corresponding thiol, $(Me_3Si)_3CCH_2SH$ (**8**),[15] quantitatively.

When **1** was treated with methyllithium and *tert*-butyllithium, the olefin **5** was formed in 79% and 34% yields, respectively, although in the latter reaction the thiol **8** (35%) and $(Me_3Si)_3CCH_2S$-*t*-Bu (**9**) (10%) were also produced. The corresponding Grignard reagents react with **1** in a similar manner but with a much slower rate.

Acknowledgment. We thank Shin-etsu Chemical Co. Ltd. for the gift of chlorosilanes. The financial support of the Ministry of Education, Science and Culture of Japan is gratefully acknowledged.

Supplementary Material Available: Spectral data and exact mass analyses for new compounds (2 pages). Ordering information is given on any current masthead page.

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Dehydrogenase Inactivation by an Enzyme-Generated Acetylenic Ketone: Identification of a Lysyl Enaminone by ^{13}C NMR

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Mechanism-based inactivation[1] by enzyme-generated acetylenic ketones[2] has been assumed to occur by Michael addition of an enzymic nucleophile to these potent electrophiles. No structural information has been presented, however, that supports the presumed inactivation mechanism. Recently, we have extended our studies of acetylenic steroid inhibitors of estrogen biosynthesis to human placental estradiol dehydrogenase (E_2-HSD),[2a] an enzyme that catalyzes the interconversion of estrone and estradiol. We now present evidence that Michael addition of the ϵ-amino group of a lysine residue accompanies inactivation of E_2-HSD by enzyme-generated 3-hydroxy-14,15-secoestra-1,3,5(10)-trien-15-yn-17-one[3] (**2**) (Scheme I).

Incubation of 40 μM [15,16-$^{13}C_2$]-14,15-secoestra-1,3,5-(10)-trien-15-yne-3,17β-diol[4] ([$^{13}C_2$]-**1**) with 100 μM NAD^+ and E_2-HSD[5] for 18 h at pH 9.2 produced >90% loss of initial enzymatic activity.[6] The ^{13}C NMR spectrum of the inactivated enzyme did not reveal any major features not present in the spectrum of enzyme inactivated with natural-abundance steroid (Figure 1a,b). We attribute our inability to observe the steroidal ^{13}C resonances to the large molecular weight of the enzyme (M_r = 68 000) and its tendency to form aggregates in the absence of glycerol,[7] affording relatively long correlation times and line

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(4) Prepared as in ref 3 except using [$^{13}C_2$]HC≡CLi in the last step (from 99% [$^{13}C_2$]HC≡CH and *n*-BuLi in THF/-78 °C[15]).
(5) Purified from human term placenta by the method of Murdock et al. (Murdock, G. L.; Chin, C.-C.; Warren, J. C. *Biochemistry* **1986**, *25*, 641-646) except that a second ammonium sulfate precipitation was added after the heat step and that Reactive Red 120-Agarose was used in place of Reactive Blue 2-Agarose (Sigma Chemical Co., St. Louis, MO).
(6) Inactivated enzyme was concentrated by ultrafiltration and dialyzed vs. four changes of 10 mM KPO_4, pH 7.0, containing 1 g/L bovine serum albumin in the first two changes, both at 4 °C. The dialyzed protein was filtered, further concentrated to ~1.5 mL by suction ultrafiltration, and diluted with D_2O to ~1.7 mL in a 10-mm NMR tube.

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