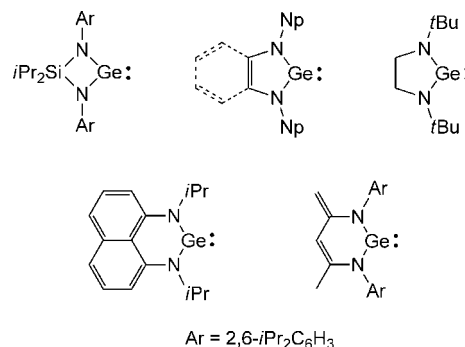


# Low-Coordinate Germanium(II) Centers Within Distorted Axially Chiral Seven-Membered Chelates: Stereo- and Enantioselective Cycloadditions\*\*

Hidekazu Arai, Taiyo Amari, Junji Kobayashi, Kunio Mochida,\* and Takayuki Kawashima

The heavier group 14 analogues of carbenes ( $R_2E:$ ) have attractive structures and interesting reactivity toward unsaturated compounds.<sup>[1]</sup>  $R_2E:$  compounds have two covalent bonds with high p character, a single electron lone pair with high s character, and a single vacant p orbital in the singlet ground state. The intrinsic ambiphilic nature of  $R_2E:$  compounds allows their participation in a variety of cycloaddition reactions with compounds containing unsaturated bonds.<sup>[2,3]</sup> (2 + 2 + 1) Cycloaddition reactions of divalent group 14 element species provide one of the most interesting ways for synthesizing a heterocycle in one step but have been limited to a number of transient silylenes and  $[Si(Cp^*)_2]$  ( $Cp^*$  = pentamethylcyclopentadienyl).<sup>[4,5]</sup> The reactions of these silylenes with a ketone or an aldehyde afforded the corresponding 1:2 cycloadducts, although different reaction intermediates were proposed for the used silylenes. In both cases, the high Lewis acidity of the group 14 element atom was believed to be an essential factor in promoting the formation of these intermediates.

Since the appearance of a report on diaminogermylene by Harris and Lappert,<sup>[6]</sup> most germynes have been synthesized by taking advantage of the thermodynamic stabilization achieved through their binding with  $\pi$ -donor atoms (Scheme 1); in this stabilized form, their Lewis acidity is presumed to be relatively low.<sup>[7–9]</sup> We envisioned that a seven-membered N-heterocyclic germylene containing an *N,N'*-bis(trimethylsilyl)-2,2'-diamino-6,6'-dimethylbiphenyl ( $LH_2$ ) unit would engender a germanium center with relatively high Lewis acidity. We expected that the seven-membered chelate would exhibit significantly lower  $\pi$  donation from the nitrogen atoms to the vacant p orbitals of the germanium center than planar five- or six-membered chelates because of the twisted conformation of the seven-membered chelate. Indeed, a number of N- and O-heterocyclic germynes of larger ring size form adducts with Lewis donors,<sup>[10,11]</sup>



Scheme 1. Two-coordinate N-heterocyclic germynes.

however, their reactivity was not explored. On the other hand, seven-membered N-heterocyclic carbenes, such as 1,3-disubstituted 1,3-diazacycloheptane-2-ylidenes and dibenzo-1,3-diazazepine-2-ylidenes, have been reported.<sup>[12]</sup> Palladium complexes containing these carbenes were reported to be very useful catalysts for Mizoroki–Heck coupling reactions.<sup>[12d]</sup> However, there has been no discussion on the Lewis acidity of the divalent carbon centers, although there has been discussion about the influence of ring size and steric hindrance of the carbenes on catalytic performance. Herein, we describe the synthesis and characterization of  $[GeL]$  (**1**) and a stereoselective cycloaddition reaction of an in situ generated carbonyl germylide derived from the reaction of **1** with benzaldehyde.

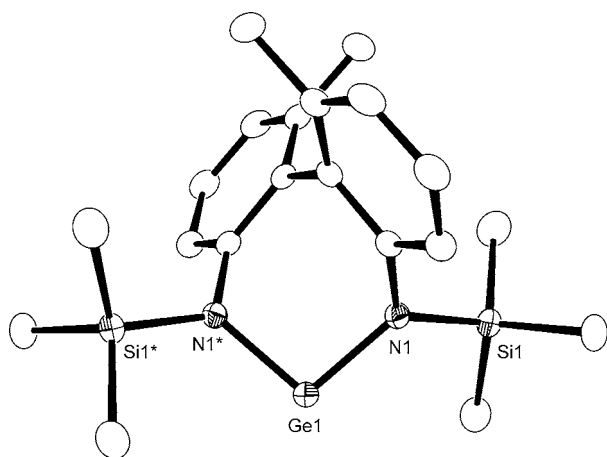
The reaction of dilithio derivative  $[LLi_2]$  and  $GeCl_2$ -dioxane in THF at  $-80^\circ C$  under Ar afforded the corresponding germylene **1** as yellow crystals in a 19% yield upon isolation. The crystal structure of **1** (Figure 1)<sup>[13]</sup> revealed that a twofold rotation axis exists through the germanium center and the midpoint of the C(1)–C(1') bond and that the distance between germanium atoms on neighboring molecules is approximately 6.6 Å, thus indicating that there are no intermolecular  $Ge \cdots Ge$  interactions (Figure 1). The divalent germanium species has a bent geometry, thus indicating the presence of a vacant p orbital and a lone pair of electrons on the germanium center. The Ge–N bonds (1.8651(13) Å) of **1** are slightly longer than those of the previously reported planar five-membered N-heterocyclic germynes; this difference can be attributed to the twisted geometry of the seven-membered chelate, wherein there is weak  $\pi$  donation from the nitrogen atoms to the germanium center. The large N–Ge–N bond angle (98.13(8)°) indicates that the Ge–N bond has higher s character and thus a lone pair of higher p character than that of typical non-distorted

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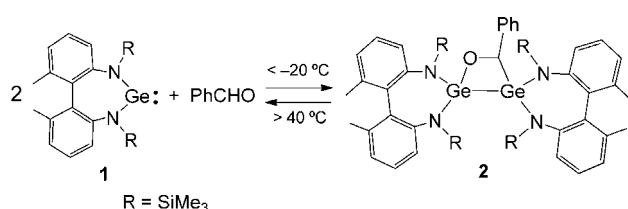
Supporting information for this article is available on the WWW under <http://dx.doi.org/10.1002/ange.201201566>.



**Figure 1.** Crystal structure of **1**. Thermal ellipsoids are shown at 50% probability and hydrogen atoms are omitted for clarity.

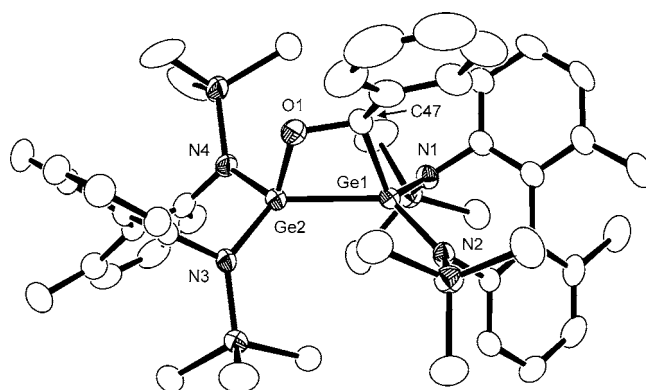
germylenes. The dihedral angle of the biphenyl backbone (approximately  $62^\circ$ ) is similar to that of the binaphthyl moiety in the previously reported *O*-substituted germylene, despite the steric repulsion between the methyl groups on 6 and 6' positions of the biphenyl moiety.<sup>[10a]</sup> In accordance with the results of the X-ray diffraction (XRD) analysis, the  $^1\text{H}$  and  $^{13}\text{C}$  NMR spectra of a solution of **1** in  $\text{C}_6\text{D}_6$  showed two equivalent sets of signals that are characteristic of a  $C_2$ -symmetric molecule.

Treatment of germylene **1** with one equivalent of benzaldehyde in toluene at  $-30^\circ\text{C}$  gave a (2 + 1 + 1) cycloadduct, 1,2,3-oxadigermetane **2** (Scheme 2), which has one stereogenic carbon atom and two axes of chirality. The addition of



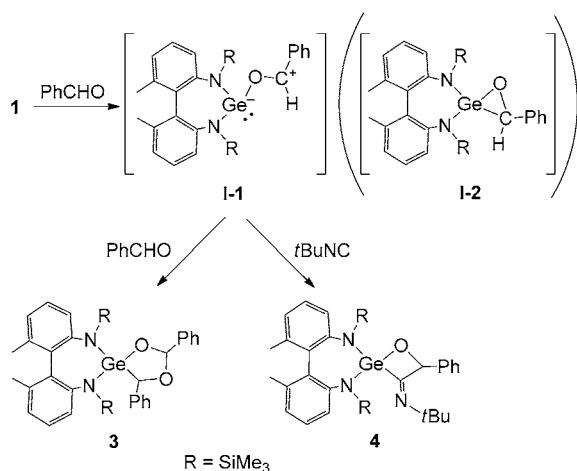
**Scheme 2.** Equilibrium reaction involving **1** (two mole equivalents), benzaldehyde, and **2**.

excess benzaldehyde was required to shift the equilibrium to the formation of **2**. Among the four racemic forms that are possible, **2** crystallized as a single racemate (*M,M,R*)-**2**/(*P,P,S*)-**2**, wherein the two biphenyl moieties of each molecule have the same absolute configurations (Figure 2).<sup>[13]</sup> Each of the germanium centers has a tetrahedral geometry, and the length of the Ge(1)–Ge(2) and C(47)–O(1) bonds in the four-membered ring were 2.4613(13) and 1.431(8) Å, respectively, both of which correspond to single bonds.<sup>[14]</sup> The  $^1\text{H}$  NMR spectrum of a solution of **2** in  $[\text{D}_8]\text{toluene}$  at  $-40^\circ\text{C}$ , indicated that the structure of **2** in the crystal form was maintained in solution. The NMR signal associated with the methine proton was observed at 5.95 ppm as only one singlet, thus ruling out the presence of other diastereomers. However, when the solution of **2** in  $[\text{D}_8]\text{toluene}$  was warmed to  $40^\circ\text{C}$ , the resulting

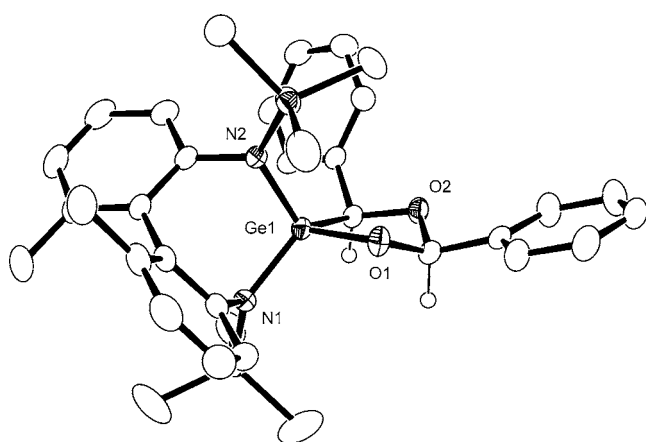


**Figure 2.** Crystal structure of **2**. Thermal ellipsoids are shown at 50% probability and hydrogen atoms are omitted for clarity.

$^1\text{H}$  NMR spectrum showed that **2** had completely transformed into **1** and free benzaldehyde in a molar ratio of 2:1. Interestingly, this temperature-dependent spectral change was reversible between  $-40$  and  $20^\circ\text{C}$ , thus indicating that **2** is in equilibrium with two mole equivalents of **1** and one mole equivalent of benzaldehyde. The thermodynamic parameters of the equilibrium were  $\Delta H = -114(5) \text{ kJ mol}^{-1}$  and  $\Delta S = -302(17) \text{ J K}^{-1} \text{ mol}^{-1}$ , as estimated using the van't Hoff equation (see the Supporting Information, Figure S5).<sup>[15]</sup> At high temperatures, the large negative entropy of formation governs the equilibrium and **1** and benzaldehyde predominate. The report on an N-heterocyclic silylene by Lappert and co-workers suggests that it is unlikely that a digermene, which could form by a dimerization of **1**, is an intermediate in the reaction pathway toward **2**.<sup>[16]</sup> We believe that **1** reacts with benzaldehyde to give an adduct, that is, carbonyl germaylide **I-1** or 1,2-oxagermirane **I-2**; either of these potential intermediates could then react rapidly with a second equivalent of **1** to afford **2**. These results prompted us to investigate the reaction in the presence of excess benzaldehyde to determine whether benzaldehyde could compete with **1** as a reactant in the further transformation of the potential intermediates **I-1** and **I-2**. The reaction of **1** with three equivalents of benzaldehyde at  $60^\circ\text{C}$  in benzene gave the expected adduct derived from a (2 + 2 + 1) cycloaddition, 1,3,4-dioxagermolane **3**, in a yield of 88%, as determined by NMR experiments (Scheme 3).<sup>[17]</sup> The  $^1\text{H}$  NMR spectrum of the reaction mixture showed that **1** was completely consumed resulting in the formation of one major product together with several minor products. The major product **3** crystallized from hexane solution and colorless crystals were obtained in a yield of 27% upon isolation. Compound **3** crystallized as the racemate (*M,R,S*)-**3**/(*P,S,R*)-**3**, in which the two phenyl groups are *cis* to each other (Figure 3).<sup>[13]</sup> It is considered that **3** forms through a regio- and stereoselective cycloaddition via a 1,3-dipolar intermediate, that is, a carbonyl germaylide **I-1**. The  $^1\text{H}$  NMR spectrum of a solution of **3** in  $[\text{D}_6]\text{benzene}$  showed two singlets at 5.16 and 6.24 ppm, which were assigned to the aliphatic methine protons. In the  $^{13}\text{C}$  NMR spectrum of **3**, the aliphatic methine carbon nuclei resonated at 73.9 and 100.2 ppm. In contrast to the equilibrium associated with **2**,



**Scheme 3.** Cycloaddition involving a 1,3 dipole derived from **1**.



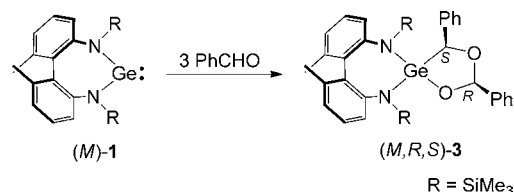
**Figure 3.** Crystal structure of **3**. Thermal ellipsoids are shown at 50% probability and hydrogen atoms are omitted for clarity.

the formation of **3** was exergonic. To our knowledge, a (2+2+1) cycloaddition involving a germylene and a carbonyl compound is unprecedented, although Banaszak Holl et al. reported that germylene [Ge{CH(SiMe<sub>3</sub>)<sub>2</sub>}<sub>2</sub>] reacts with benzophenone to give an adduct derived from a concerted (4+1) cycloaddition.<sup>[3b]</sup> In the reaction with carbonyl compounds, when a transient silylene was generated in the presence of Ag<sup>I</sup>, which is thought to act as an electrophile by the authors, the (2+2+1) cycloadducts were formed through a regio- and stereoselective cycloaddition via a carbonyl silaylide. On the other hand, when isolable [Si(Cp\*)<sub>2</sub>] and silylenoides, which are thought to act as nucleophiles, were used, the (2+2+1) cycloadducts involving C–C bond formation were obtained via oxasirilanes.<sup>[4d,5]</sup> Taking the relatively high Lewis acidity of germylene **1** into consideration,<sup>[18]</sup> it is most likely that an intermediate is the carbonyl germylide **I-1**, which could form through the electrophilic attack of **1** on the carbonyl oxygen atom.

When benzaldehyde and *tert*-butyl isocyanide were added to a benzene solution of **1** at 60 °C, a (2+1+1) cycloadduct, 3-imino-1,2-oxagermetane **4**, was obtained as a mixture of two diastereomers, (*M,R*)-**4**/(*P,S*)-**4** and (*M,S*)-**4**/(*P,R*)-**4**, in yields

of 59% and 15%, respectively, as determined by NMR spectroscopy (Scheme 3). The use of three equivalents of *tert*-butyl isocyanide was sufficient for preventing the competing reaction that yields **3**. The diastereoselectivity for the cycloaddition of **4** was slightly lower than that of **3**, with respect to a three-component system. The isolated crystals of adduct **4** were composed of only the racemate (*M,R*)-**4**/(*P,S*)-**4**, as determined by XRD (see the Supporting Information, Figure S1)<sup>[13]</sup> and NMR spectroscopy (see the Supporting Information, Figure S7).

Optically active (*M*)-**1**, which was prepared by using the same method as that used to prepare racemic **1**, crystallizes in the asymmetric space group *P*2<sub>1</sub>2<sub>1</sub>2<sub>1</sub>.<sup>[13]</sup> The distance between neighboring germanium centers Ge...Ge in (*M*)-**1** is 2.6102(5) Å, which is much shorter than that of racemic **1**, but significantly longer than that of typical Ge–Ge single bonds (2.42–2.45 Å);<sup>[19]</sup> this difference probably has its origin in the crystal-packing forces in the crystal. The <sup>1</sup>H NMR spectrum of (*M*)-**1** is identical to that of racemic **1**, thus indicating that (*M*)-**1** behaves as a monomer in solution. The reaction of optically active germylene (*M*)-**1** with benzaldehyde afforded the optically active (*M,R,S*)-**3** in a yield of 78% together with traces of other diastereomers as determined by NMR spectroscopy (Scheme 4 and see the Supporting Information, Figure S8). Thus, it was shown that (*M*)-**1** can be used as a chiral source in the enantiospecific cycloaddition to give the heterocycle.



**Scheme 4.** Enantiospecific cycloaddition of (*M*)-**1**.

In conclusion, we designed and synthesized a divalent N-heterocyclic germylene **1** representing a seven-membered chelate containing an axially chiral biphenyl backbone. In situ generation of a 1,3 dipole, that is, a carbonyl germylide, by electrophilic attack of **1** on benzaldehyde, followed by its stereoselective cycloaddition with benzaldehyde or *tert*-butyl isocyanide, gave the corresponding cycloadducts **3** and **4**. (*M,R,S*)-**3** was obtained by the diastereoselective cycloaddition involving enantiomerically pure (*M*)-**1**. The incorporation of a germylene moiety within a seven-membered chelate was demonstrated to be a very effective way of engendering a germanium center of high Lewis acidity, thus allowing its involvement in several types of cycloadditions.

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