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# Distinctly different reactivity of bis(silylenyl)- versus phosphanyl-silylenyl-substituted *o*-dicarborane towards O<sub>2</sub>, N<sub>2</sub>O and CO<sub>2</sub>†

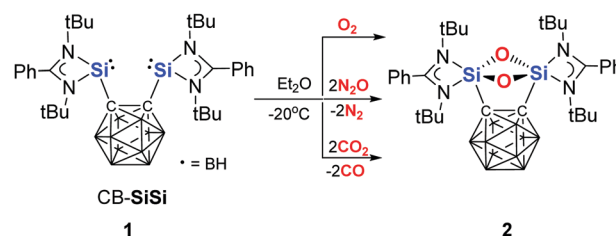
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In stark contrast to the reactivity of the bis-silylenyl dicarborane CB–Si<sub>2</sub> (**1**) [CB = *ortho*-C,C′-C<sub>2</sub>B<sub>10</sub>H<sub>10</sub>, Si = PhC(tBuN)<sub>2</sub>Si] towards O<sub>2</sub>, N<sub>2</sub>O, and CO<sub>2</sub>, yielding the same dioxygenation product CB–Si<sub>2</sub>O<sub>2</sub> (**2**) with a four-membered 1,3,2,4-disiladioxetane ring, the activation of the latter small molecules with the phosphanyl-silylenyl-functionalised CB–SiP (**3**) {P=[N(tBu)CH<sub>2</sub>]<sub>2</sub>} affords with O<sub>2</sub> the CB–Si(=O)P(=O) silanone-phosphine oxide (**4**), with N<sub>2</sub>O the CB–Si(=O)P silanone-phosphine (**5**), and with CO<sub>2</sub> the CB–Si(O<sub>2</sub>C=O)P silicon carbonate-phosphine (**6**) and CB–C(=O)OSiOP ester (**7**), respectively.

For many decades, the activation of ubiquitous small molecules such as H<sub>2</sub>, N<sub>2</sub>, O<sub>2</sub>, CO, CO<sub>2</sub>, N<sub>2</sub>O, *etc.* has been considered to be a domain of transition-metal chemistry and metalloenzymes, including their low molecular-weight functional models. However, recent advances in low-valent non- and semi-metal chemistry have provided a plethora of impressive evidence with transition-metal-like reactivity of main-group elements in small molecule activation.<sup>1–6</sup> This is in part due to the availability of reactive lone pair electrons and relatively low-lying empty acceptor orbitals of main-group elements in unusual low oxidation states, which can mimic the electronic situation of transition-metal centres and even mediate chemical bond cleavage of unactivated small molecules. Striking examples comprise the activation of dihydrogen by acyclic silylenes with a highly reactive silicon(II) centre<sup>7–10</sup> and the fixation of dinitrogen by a borylene as a carbene analogue.<sup>11,12</sup> In recent years,

we have been interested in the chemistry of chelating N-heterocyclic silylenes (NHSis) that feature two adjacent divalent silicon atoms as highly reactive sites.<sup>13–15</sup> Such bis-NHSis not only can serve as steering ligands for coordination of main-group elements in unusual low oxidation states and transition metals for catalysis,<sup>13–15</sup> they can also mediate cooperative small molecule activation through sufficiently close proximity of the two silicon(II) centres.<sup>16,17</sup> For instance, the bis-NHSis with a Si···Si distances between 2.6 and 4.5 Å are capable reacting with CO at ambient temperature, affording disilaketenes.<sup>16–18</sup> Featuring a Si···Si distance of about 3.3 Å, the two Si(II) centres in the *ortho*-dicarborane-based bis-NHSis CB–SiSi (**1**)<sup>19</sup> (Scheme 1) are in a predestinate position to coordinate and subsequently activate CO.<sup>17</sup> Moreover, the bis-NHSis **1** has been employed to stabilise a single zero-valent Si atom,<sup>20</sup> monovalent boron,<sup>21</sup> and serves in nickel-mediated catalytic transformations.<sup>19</sup> More recently we succeeded in the synthesis of the isolobal phosphanyl-silylenyl-functionalised *o*-dicarborane CB–SiP (**3**) where one silylenyl group in **1** is replaced by a phosphanyl moiety.<sup>22</sup> Compound **3** enabled the formation of new classes of C,C′-dicarborandiyl-silylene supported Ge<sub>2</sub> and Ge<sub>4</sub> species which could not be realised with **1**.<sup>22</sup> Herein, we wish to report the markedly different reactivity of **1** and **3** towards O<sub>2</sub>, N<sub>2</sub>O, and CO<sub>2</sub>, respectively.

Exposure of solutions of **1** in diethyl ether at –20 °C to O<sub>2</sub> gas leads to immediate disappearance of the yellow color and formation of the 1,3,2,4-disiladioxetane **2** (Scheme 1).



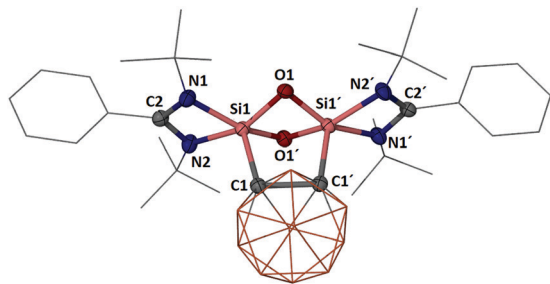
Scheme 1 Reactions of **1** with O<sub>2</sub>, N<sub>2</sub>O, and CO<sub>2</sub> to yield **2**.

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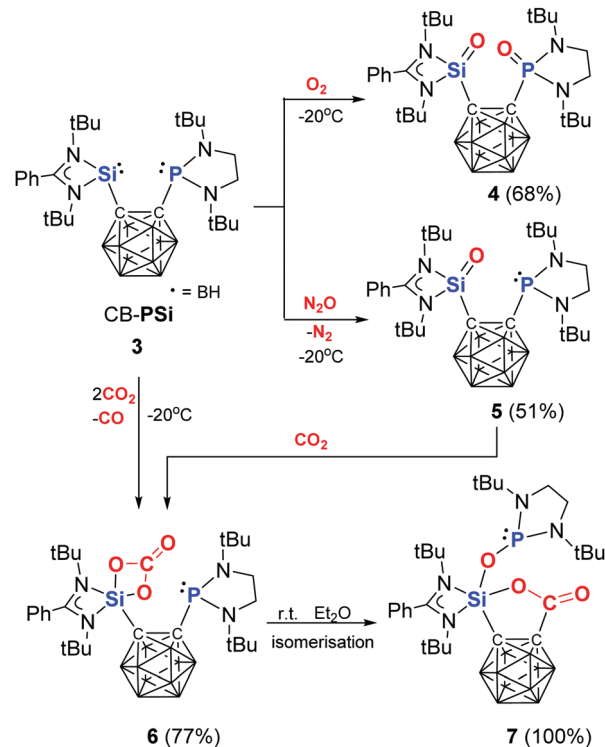


**Fig. 1** Molecular structure of **2**. Thermal ellipsoids are drawn at 50% probability level. Hydrogen atoms and one toluene molecule are omitted for clarity. Selected bond distances (Å) and angles (°): Si1–O1 1.695(1), Si1–O1' 1.708(1), Si1–C1 1.961(2), Si1–N1 1.861(1), Si1–N2 1.884(1), Si1–Si1' 2.403(1); O1–Si1–O1' 83.4(1), Si1–O1–Si1' 89.8(1), O1–Si1–C1 96.6(1), O1'–Si1–C1 96.1(1).

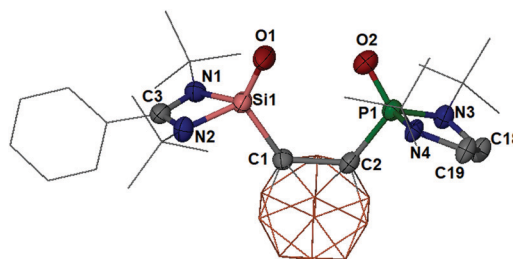
Interestingly, **2** is also formed as single product through exposure of **1** towards  $\text{N}_2\text{O}$  and  $\text{CO}_2$  under the same reaction conditions. After workup, **2** has been isolated as a colorless solid; it crystallises in the monoclinic space group  $C2/c$ . The two Si centres are five-coordinated and bridged by two oxygen atoms (Fig. 1). The Si atoms adopt a distorted square-pyramidal coordination geometry with the carborane–C atom at the apical position. The Si1–O1 [1.695(1) Å] and Si1–O1' [1.708(1) Å] distances in **2** are slightly longer than the Si–O length in octamethyl cyclotetrasiloxane (*ca.* 1.65 Å).<sup>23</sup> As expected, the five-coordinate  $^{29}\text{Si}$  nuclei exhibit a drastic up-field shift in the  $^{29}\text{Si}\{^1\text{H}\}$  NMR spectrum ( $\delta = -98.6$  ppm) when compared with the precursor **1** ( $\delta = 18.9$  ppm).<sup>19</sup>

The reactions of  $\text{O}_2$ ,  $\text{N}_2\text{O}$ , and  $\text{CO}_2$  with various stable silylenes to give  $\text{Si}=\text{O}$ -containing compounds or further oxygenated Si–O-containing species are well-documented.<sup>5,9,24–30</sup> We wondered whether a transient or even isolable  $\text{Si}=\text{O}$  species could be detected if one silylenyl moiety in **1** is replaced by a isoelectronic phosphanyl group; thus we employed the phosphanyl-silylenyl-functionalised carborane CB–SiP (**3**). Indeed, under the same reaction conditions, exposure of **3** to dioxygen gas at  $-20^\circ\text{C}$  resulted in the formation of the CB–Si(=O)P(=O) silanone-phosphine oxide (**4**) (Scheme 2 and Fig. 2), in which both P and Si atoms are mono-oxygenated. Compound **4** was isolated at  $-20^\circ\text{C}$  as a colorless solid in 68% yields. It is sparingly soluble in  $\text{Et}_2\text{O}$ , but well soluble in THF. Solutions of **4** in ethereal solvents are only stable below  $-20^\circ\text{C}$ ; its decomposition affords a mixture of unidentified products. In the solid state, however, **4** is stable at room temperature and decomposes above  $153^\circ\text{C}$ .

The  $^{31}\text{P}\{^1\text{H}\}$  NMR spectrum of **4** (measured at  $-20^\circ\text{C}$  in  $d_8$ -THF) exhibits a singlet at  $\delta = 26.4$  ppm, which is significantly up-field shifted relative to that of the precursor **3** ( $\delta = 102.9$  ppm).<sup>22</sup> A similar up-field shift is observed for the  $^{29}\text{Si}\{^1\text{H}\}$  NMR resonance of **4** ( $\delta = -52.8$  vs.  $17.5$  ppm for **3**).<sup>22</sup> The IR spectrum of **4** shows a very strong stretching vibration mode at  $\nu = 1193\text{ cm}^{-1}$  for the  $\text{Si}=\text{O}$  bond, which is slightly larger than the value observed for the  $\text{Si}=\text{O}$  bond in a C=O-supported silanone ( $1153\text{ cm}^{-1}$ ).<sup>27</sup> A single-crystal X-ray diffraction analysis confirmed the presence of  $\text{Si}=\text{O}$  and  $\text{P}=\text{O}$



**Scheme 2** Reactions of CB–Psi **3** with  $\text{N}_2\text{O}$ ,  $\text{O}_2$ , and  $\text{CO}_2$  to give **4**, **5**, **6** and **7**.



**Fig. 2** Molecular structure of **4** (There are two molecules in the asymmetric unit, only one is depicted). Thermal ellipsoids are drawn at 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond distances (Å) and angles (°) for molecule 1: Si1–O1 1.524(3), Si1–C1 1.943(4), Si1–N1 1.820(3), Si1–N2 1.814(3), P1–O2 1.456(3), P1–C2 1.899(4), P1–N3 1.638(3), P1–N4 1.656(3); O1–Si1–C1 122.5(2), O2–P1–C2 109.2(2).

bonds in **4** with a O1–Si1–P1–O2 torsion angle of  $36.8^\circ$  (Fig. 2). In **4** both silicon and phosphorus atoms adopt a distorted tetrahedral coordination environment. In line with the IR spectroscopic data, the Si–O distance of 1.524(3) Å in **4** is slightly shorter than that in the aforementioned keto-supported silanone adduct [1.532(2) Å],<sup>27</sup> indicating a more pronounced  $\text{Si}=\text{O}$  bond character.

As mentioned above, the reaction of silylenes with dioxygen usually affords disiladioxetanes or related Si–O single bond containing products. The formation of **4** as an isolable  $\text{Si}=\text{O}$  species is apparently due to the presence of the phosphanyl



moiety, acting as an oxygen atom acceptor in close proximity to the silicon atom. In order to figure out whether **3** is capable of N<sub>2</sub>O activation to furnish a Si=O-(and/or P=O)-containing product, we exposed solutions of **3** in Et<sub>2</sub>O to N<sub>2</sub>O gas at −20 °C. To our surprise, the oxygenation took place only at the silicon centre to form the CB-(Si=O)P silanone-phosphine (**5**), which could be isolated in 51% yields (Scheme 2). This is consistent with the fact, that such substituted phosphines are inert toward N<sub>2</sub>O. Akin to **4**, compound **5** is labile in Et<sub>2</sub>O and THF solutions above −20 °C and decomposes to an unidentified mixture of products. However, **5** is indefinitely stable in the solid state at ambient temperature and decomposes above 176 °C.

The molecular structure of **5** established by a single-crystal X-ray diffraction analysis revealed a four-coordinate silicon atom with a distorted tetrahedral coordination geometry (Fig. 3), while the phosphorus atom remains unchanged with respect to the precursor **3**. The Si=O distance of 1.524(1) Å in **5** is identical to that in **4**. In line with that, the IR spectrum of **5** exhibits a Si=O stretching frequency of 1187 cm<sup>−1</sup>, which is very close to the value observed for **4** ( $\nu$  = 1193 cm<sup>−1</sup>). The four-coordinate Si atom in **5** shows a resonance at  $\delta$  = −51.9 ppm in the <sup>29</sup>Si{<sup>1</sup>H} NMR spectrum (measured at −30 °C in *d*<sub>8</sub>-THF), matching well with that for **4** ( $\delta$  = −52.8 ppm). In contrast, the marginally different chemical shift at  $\delta$  = 114.2 ppm in the <sup>31</sup>P{<sup>1</sup>H} NMR spectrum of **5** (vs.  $\delta$  = 102.9 ppm of its precursor **3**)<sup>22</sup> confirms the presence of the unchanged phosphine moiety.

As aforementioned, previous studies on CO<sub>2</sub> activation toward silylenes revealed mono-oxygen transfer and liberation of CO to form either Si=O<sup>26,28–30</sup> or dimeric disiladioxetane species.<sup>29,31</sup> In less cases, silicon carbonates<sup>31–34</sup> could be isolated which resulted from trapping reaction of Si=O intermediate with CO<sub>2</sub>. Similar to the reactivity of **3** towards N<sub>2</sub>O, **3** reacts with CO<sub>2</sub> in diethyl ether at −20 °C only at the Si(III) site to yield the CB-(SiO<sub>2</sub>C=O)P silicon carbonate-phosphine (**6**) (Scheme 2). The latter product was isolated in 77% yields after workup at low temperature. The <sup>31</sup>P{<sup>1</sup>H} NMR spectrum of **6** shows a signal at  $\delta$  = 115.5 ppm (measured at −10 °C in *d*<sub>8</sub>-THF), indicating the presence of the unchanged phosphine

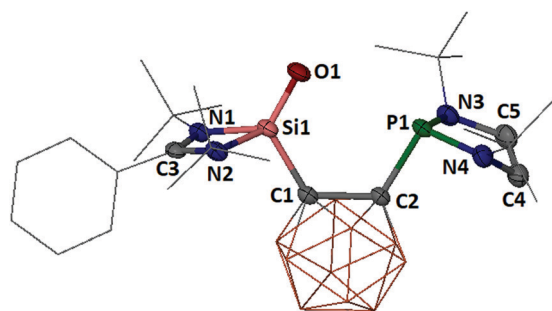


Fig. 3 Molecular structure of **5**. Thermal ellipsoids are drawn at 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond distances (Å) and angles (°): Si1–O1 1.524(1), Si1–C1 1.930(2), Si1–N1 1.827(2), Si1–N2 1.814(2), P1–C2 1.949(1), P1–N3 1.717(2), P1–N4 1.677(2); O1–Si1–C1 120.2(1).

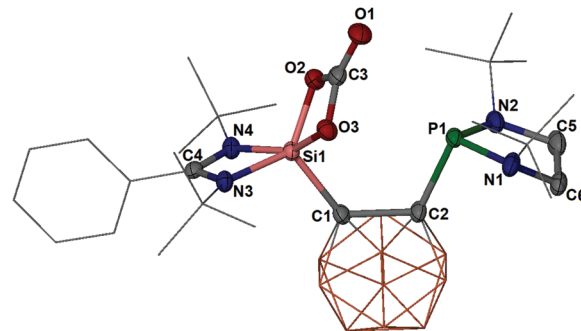


Fig. 4 Molecular structure of **6**. Thermal ellipsoids are drawn at 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond distances (Å) and angles (°): Si1–O2 1.718(1), Si1–O3 1.770(1), Si1–C1 1.939(2), Si1–N3 1.811(2), Si1–N4 1.874(2), P1–C2 1.932(2), P1–N1 1.684(2), P1–N2 1.708(2), C3–O1 1.194(2), C3–O2 1.362(2), C3–O3 1.340(2), C1–C2 1.738(3); O2–Si1–C1 117.5(1), O3–Si1–C1 102.1(1), N3–Si1–C1 109.8(1), N4–Si1–C1 103.2(1), O2–Si1–O3 75.0(1), O1–C3–O2 126.9(2), O1–C3–O3 129.3(2), O2–C3–O3 103.7(2).

moiety, whereas the <sup>29</sup>Si{<sup>1</sup>H} NMR spectrum shows a resonance at  $\delta$  = −93.1 ppm, reminiscent of the five-coordinate <sup>29</sup>Si nuclei attached to a ferrocene spacer ( $\delta$  = −92.1 ppm).<sup>29</sup> The IR spectrum of **6** exhibits a stretching vibration mode at  $\nu$  = 1813 cm<sup>−1</sup> for the C=O group, comparable to that observed in a bis-NHC-supported silicon dicarbonate (1746 cm<sup>−1</sup>).<sup>35</sup> A single-crystal X-ray diffraction analysis confirmed the molecular structure of **6** (Fig. 4), which features a five-coordinate silicon atom in a strongly distorted square-pyramidal coordination geometry with the carbaborane–C atom at the apical position. The Si–O distances of 1.718(1) and 1.770(1) Å in **6** are significantly longer than the Si=O lengths in **4** and **5**, respectively, but close to the Si–O bonds in **2** [1.695(1), 1.708(1) Å]. The C3–O1 distance of 1.194(2) Å is considerably shorter than those of C3–O2 (1.362(2) Å) and C3–O3 (1.340(2) Å), implying a C=O bond between C3 and O1.

Although the mechanism of **6** from **3** with CO<sub>2</sub> is still unknown, we propose that the initial step of the reaction is the formation of **5** with a Si=O moiety under release of CO. To prove this, we conducted the reaction of **5**, obtained from **3** and N<sub>2</sub>O, with CO<sub>2</sub> at −20 °C (Scheme 2). Indeed, a clean formation of **6** confirmed this by multinuclear NMR spectroscopy measurements.

While **6** is stable at room temperature in the solid state, it isomerises quantitatively at room temperature in ethereal solvents to give **7** in the course of 24 hours (Scheme 2). Its molecular structure has been established by a single-crystal X-ray diffraction analysis. As depicted in Fig. 5, the silicon atom in **7** is five-coordinate and in a distorted trigonal-bipyramidal coordination environment with the N1 and O2 atoms in the axial positions. Thus, the Si1–O2 distance of 1.773(2) Å is longer than that of Si1–O3 (1.624(2) Å). The driving force of the isomerization of **6** to **7** is attributed to the oxygen affinity of phosphorus that induces CB C–P bond scission and CB C–CO bond formation. In addition, the steric congestion in **6** between the phosphine group and the CB cage is released after migration of the phosphine moiety from the carbaborane–C2 to the



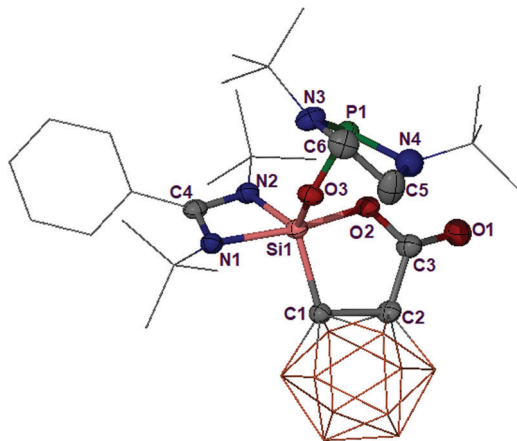


Fig. 5 Molecular structure of **7**. Thermal ellipsoids are drawn at 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond distances (Å) and angles (°): Si1–O2 1.773(2), Si1–O3 1.624(2), Si1–C1 1.937(3), O3–P1 1.666(2), O2–C3 1.314(3), O1–C3 1.200(3), C2–C3 1.515(4), C1–C2 1.652(3); O3–Si1–O2 94.2(1), O3–Si1–N2 120.2(1), N2–Si1–C1 118.3(1), O3–Si1–C1 120.6(1), N1–Si1–O2 167.8(1), Si1–O3–P1 134.7(1), O2–C3–O1 125.5(2), O1–C3–C2 122.4(2), O2–C3–C2 112.1(2).

O3 atom. As a result, the C1–C2 distance of 1.652(3) Å in **7** is significantly shorter than that in **6** (1.738(3) Å). In accordance with the molecular structure of **7**, its  $^{29}\text{Si}\{^1\text{H}\}$  NMR spectrum shows a doublet at  $\delta = -110.4$  ppm ( $^2J_{(\text{Si},\text{P})} = 9.4$  Hz) comparable to that of **6** ( $\delta = -93.1$  ppm), and the  $^{31}\text{P}$  nucleus resonates at  $\delta = 119.6$  ppm in the  $^{31}\text{P}\{^1\text{H}\}$  NMR spectrum reminiscent of that for **6** ( $\delta = 115.5$  ppm).

In summary, we have described the markedly different reactivity of the bis-NHSi dicarborane **1** and its isolobal phosphanyl-NHSi-functionalised dicarborane analogue **3** towards  $\text{O}_2$ ,  $\text{N}_2\text{O}$ , and  $\text{CO}_2$ . While all reactions of **1** with  $\text{O}_2$ ,  $\text{N}_2\text{O}$ , and  $\text{CO}_2$  let to the same dioxygenation product CB–Si( $\mu\text{-O}$ ) $_2$ Si **2**, the activation products with **3** turned out to furnish different products featuring Si=O, P=O, or C=O functionalities.

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## Conflicts of interest

There are no conflicts to declare.

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