

# The first intramolecular silene Diels–Alder reactions†

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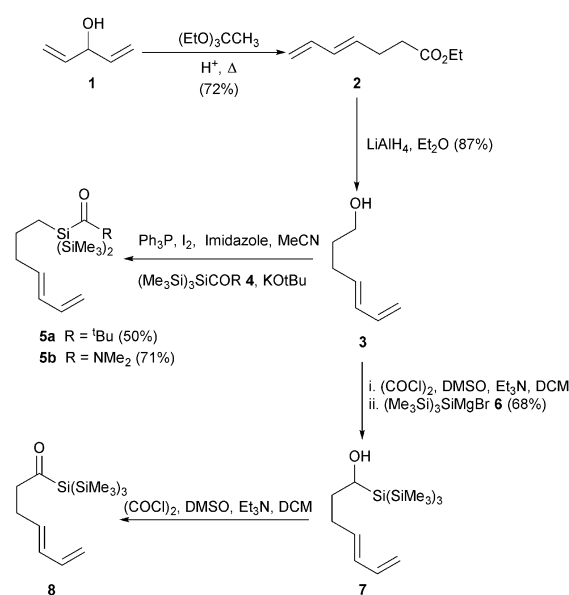
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**The synthesis of silaheterocycles through the first examples of an intramolecular silene Diels–Alder reaction is described.**

As evidenced by the vast range of transformations mediated by silyl hydrides, ethers and enol ethers and vinyl, aryl and allyl silanes, organosilicon compounds play an important role in organic synthesis. Moreover, although formally isostructural, the replacement of a carbon atom by a silicon atom can have profound effects on molecular properties. For example, this “silicon-switch” has been exploited in the design of new odors,<sup>1</sup> pharmaceutical compounds<sup>2</sup> and organic materials. The challenge for the continued development of these reagents is that there are relatively limited methods for the preparation of functionalised silanes, particularly when the silicon centre is contained within a ring structure.<sup>3</sup> One option that remains largely unexplored is the application of low-coordinate silicon compounds. Such compounds, silenes (and disilenes), silynes and silylenes which represent the organosilicon equivalents of alkenes, alkynes and carbenes respectively, display a fascinating array of chemistry that has much to offer synthetic chemistry.<sup>4</sup> We and others have begun to explore this area and have demonstrated that such reagents can provide ready access to a variety of functionalised organosilanes that would be difficult to achieve using classical synthetic methodology.<sup>5–7</sup> The challenges in this reside in the high electrophilicity of a low-coordinate silicon centre and the relatively weak nature of the silicon–carbon multiple bond. For example, silenes are highly reactive, most commonly transient, species that in the absence of a suitable trapping molecule readily dimerise or oligomerise.<sup>8</sup> Consequently, they have largely been the subject of fundamental studies into reactivity, structure and bonding

with a particular emphasis on preparation of examples that are kinetically stabilised with respect to dimerisation through the incorporation of bulky substituents.<sup>4a,9</sup> In this respect it is surprising to note that intramolecular reactions of silenes beyond simple rearrangements have not been described.<sup>10,11</sup> To explore this option we initiated a programme to study the structural requirements for such a process and in this communication describe the first examples of intramolecular silene cycloadditions that provide access to novel heterocyclic silanes.

Building on our earlier experience for the generation of silenes through either a thermal 1,3-silyl shift of an acyl polysilane<sup>12</sup> or a sila-Peterson reaction,<sup>13a</sup> initial attempts focused on simple acyclic substrates combining silene precursor and dienyl fragments (Scheme 1). Hepta-4,6-dienol **1** could be readily generated through a sequence involving the Claisen *ortho* ester rearrangement of divinyl carbinol **1** and reduction of the resultant ester **2**. Following



Scheme 1

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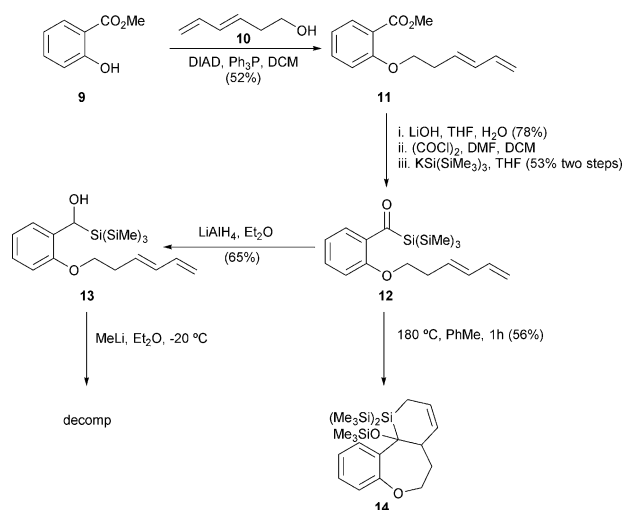
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phosphine mediated halogenation, reaction of the resulting dienyl iodide with the silenolate generated from acyl silanes **4a** and **4b** afforded acyl polysilane **5a** and carbamoyl silane **5b**, respectively.<sup>14</sup> Initial attempts to generate the silene followed protocols established in our groups based on the thermal 1,3-silicon shift to generate Brook-type silenes. Disappointingly all such attempts led to extensive decomposition of the starting diene with no evidence for the formation of the desired cycloadduct. Disappointed by these results we then turned to low temperature silene generation based on our previously described methods using a sila-modified Peterson reaction. The precursors for this could simply be accessed by oxidation of the alcohol **3** to the aldehyde and reaction with the hypersilyl Grignard reagent **6** derived from tetrakis(trimethylsilyl)silane to afford silyl alcohol **7**. Despite our earlier success exploring intermolecular reactions with closely related silenes,<sup>13</sup> none of these approaches afforded evidence of the desired cycloadducts. Similarly, attempts to generate the corresponding silenolate, by treatment of acylpolysilane **8** with KO<sup>t</sup>Bu,<sup>14</sup> only led to extensive oligomerisation and a complex mixture of other products arising from the formation of a transient silene *e.g.* dimers or ene type products. Speculating that difficulties in attaining the necessary reactive conformations within the short life-time of the silene were inhibiting the intramolecular cycloaddition we modified the substrate to enhance this pathway. This could most simply be achieved by incorporating an aromatic ring into the tether for cyclisation. Initial attempts to couple a diene unit to salicyl-aldehyde using simple Mitsunobu chemistry proved to be surprisingly challenging giving only low yields of the desired ether. Consequently, we turned to a more linear approach from methyl salicylate **9** (Scheme 2). Coupling with hexadienol **10**, prepared by deconjugation of ethyl sorbate and reduction, followed by hydrolysis, conversion to the acid chloride and reaction with KSi(SiMe<sub>3</sub>)<sub>3</sub> afforded the acyl silane **12**. Pleasingly, heating a toluene solution of this afforded the desired cycloadduct **14** in 56% isolated yield. After some experimentation optimum conversion was realised by heating at 180 °C for 1 h affording a 2.7:1 mixture of diastereoisomers.<sup>15</sup> Attempts to enhance selectivity by conducting reactions at lower temperatures were not successful with the longer reaction times

**Table 1** Thermal cycloaddition reactions of transient silenes generated from acylpolysilanes

Entry	Acylpolysilane	Time <sup>a</sup> (min)	Silacycloadduct	Yield <sup>b</sup> (%; ds)
1		15		— <sup>c</sup> (2.0:1)
2		75		60 (2.7:1)
3		90		87 (3.7:1)
4		75		75 (2.2:1)
5		60		— <sup>e</sup> (—)

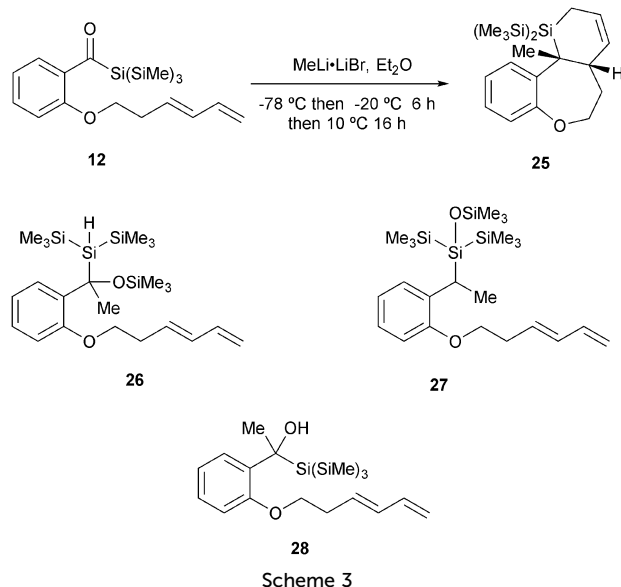
<sup>a</sup> Time required for complete conversion of acylpolysilane. <sup>b</sup> Yield of purified cycloadduct, diastereoselectivity determined from <sup>1</sup>H NMR spectra (see ref. 15). <sup>c</sup> Decomposed on attempted purification. <sup>d</sup> EZ and EE isomers. <sup>e</sup> No cycloadduct obtained.



**Scheme 2**

required leading to extensive decomposition. A range of other substrates **15–19** varying the nature of the arene tether and diene substitution pattern were then investigated to explore the scope and limitation of this cycloaddition (Table 1). The desired precursors could be prepared in an identical fashion to that described above. Intriguingly for the preparation of **19** deconjugation of methyl hepta-2,4-dienoate in an analogous fashion to that employed for ethyl sorbate followed by reduction afforded the desired hepta-3,5-dienol favouring the EZ isomer (EZ:EE 84:16). Presumably, this reflects the kinetic protonation of an “endo W”<sup>16</sup> shaped tri-enolate anion as treatment of the EZ dienylester with a catalytic amount of iodine resulted in isomerisation to the corresponding E,E diene.

Mirroring earlier work exploring intermolecular silene cycloaddition in which steric hindrance proved to be a critical parameter 1,4-disubstituted dienes proved not to be viable substrates (entry 5). However, substitution on the aromatic tether was tolerated with a 3-methyl substituent leading to isolation of the silacycle **22** in 87% yield, possibly reflecting a degree of conformational constraint in the precursor. Introduction of a *para*-methoxy group was predicted to enhance the stability of the silene facilitating its generation. Consistent with this complete consumption of starting material was observed within 15 minutes to afford a mixture of diastereomeric cycloadducts (entry 1). However, these proved to be highly unstable and attempts to isolate them were unsuccessful. We then turned to



explore low-temperature methods for silene generation. Initial attempts to generate the silene by deprotonation of silyl alcohol **13** to initiate a sila-Peterson reaction were not successful. Consequently, we adopted the Ishikawa protocol for silene generation in which an acyl polysilane is treated with an alkyl lithium reagent to initiate the sila-Peterson olefination and afford the silene at much lower reaction temperatures (Scheme 3).<sup>16</sup> In earlier studies of the sila-Peterson reaction we demonstrated that the presence of  $\text{LiBr}$  promotes elimination of  $\text{LiOSiMe}$  and enhances the formation of silene. Consequently, initial attempts explored the use of  $\text{MeLi-LiBr}$  complex at  $-78^\circ\text{C}$ . However this only afforded the addition product **28** with no evidence for silene generation suggesting that with these substrates higher temperatures were required to promote the elimination step. Following some optimisation of the reaction temperature involving addition of  $\text{MeLi-LiBr}$  at  $-78^\circ\text{C}$ , ageing at  $-20^\circ\text{C}$  for 6 h followed by stirring at  $10^\circ\text{C}$  for a further 16 h afforded the desired cycloadduct **25** in 57% yield (major diastereoisomer of a 2.5:1 mixture)<sup>15</sup> accompanied by small amounts of the silanes **26** and **27** arising from incomplete silene generation and competing trapping of the silene with  $\text{LiOSiMe}_3$ , respectively. The formation of the cycloadduct in this approach is particularly noteworthy when contrasted with the analogous reaction of benzoyl polysilane which, even in the presence of a large excess of a diene, afforded only silene dimers.<sup>17</sup> Whilst this approach to silene generation provided considerably simpler access to the cycloadducts none of these variations provided significantly enhanced stereoselectivity and we speculate that when the reactivity of the silene is taken into account the difference between *endo* and *exo* transition state barriers is relatively small.

In conclusion, we have described the first examples of intramolecular silene Diels-Alder reactions. These provide access to a range of polycyclic and heterocyclic organosilanes. Such complex cyclic organosilanes have potential both as novel building blocks and as structural entities in their own right. Work to explore these and develop more efficient cycloaddition strategies are in progress.

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