butyl bromide are −2.23 and −2.19 V,[18] but for *n*-pentyl and *tert*-pentyl chloride are −2.79 and −2.64 V.[19] The chloride reduction shows a large effect of structure which is consonant with the view that the transition state occurs later.

Finally this work bears in part on the recent work that has beendone on the mechanism of the Grignard reagent. Whitesides concludes, from the structural effect on the rate of formation of Grignard reagents, that reaction involves rate-determining formation of organic halide radical anion.[20] His work used bromides, and our results are supportive of his conclusions. Additionally, the observation of significant structural effects when the thermodynamics of reaction are less favorable, raises the possibility of a radical-like mechanism for Grignard formation from less easily reducible halides.[21]

Experimental Section

Materials. Naphthalene was obtained from Eastman Organic Chemical (No. 168) or Matheson Coleman and Bell (No. NX5). Anthracene (No. AX 1590) and fluoroanthrene (No. 1214) were obtained from Matheson Coleman and Bell. Biphenyl (No. 721) was obtained from Eastman Organic Chemicals. Samples of pyrene and perylene were donated by Professor W. D. Closson. Alkyl and aryl halides were obtained either from Eastman Organic Chemicals or Matheson Coleman and Bell. The halides were distilled from calcium hydride and stored over calcium hydride. Purity of halides was determined by vapor phase chromatography. Tetrahydrofuran, chromoquality from Matheson Coleman and Bell, was distilled from benzophenone sodium ketyl prior to use.

Solutions of sodium biphenyl and sodium naphthalene were prepared from sodium metal, and the aromatics are described previously.[5] The other radical anions were prepared by electron transfer from sodium naphthalene to THF solutions of the corresponding aromatic in large excess.

Kinetic Procedures. Kinetic measurements were made on a rapid-mixing stopped-flow spectrophotometer as described previously.[5] The wavelengths that were used to monitor reaction for the various aromatic radical anions were in nm; biphenyl, 630; naphthalene, 775; pyrene, 730; anthracene, 720; fluoranthane, 510; and perylene, 577. All kinetic data reported are the averages of a minimum of their determinations at each concentration.

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An Alternative Mechanism for the Formation of 1,4-Disilacyclohexa-2,5-dienes from Acetylenes and Silylenes[1]

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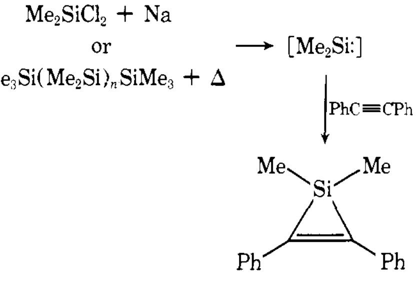
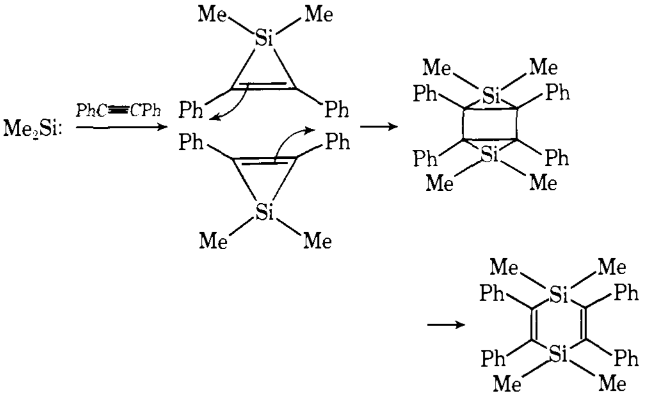
Abstract: To account for the formation of 1,4-disilacyclohexa-2,5-dienes (disilins) from the reaction of silylenes and acetylenes, a mechanism involving a Diels–Alder addition of an acetylene to a 1,4-disila-1,3-butadiene is proposed. This novel diene could arise from opening of a 3,4-disilacyclobutene, and, indeed, the permethyldisilacyclobutene is found to react with acetylenes to afford the predicted disilacyclohexadienes. Experiments are described which indicate that under static pyrolysis conditions the disilacyclobutenes arise from silylene and not disilene reactions with the acetylenes. While tetramethyldisilene does react with 2-butyne to produce the permethyldisilin, attempted crossover experiments rule out dissociation of the disilene to two molecules of silylene. Thus it is concluded that the two mechanisms, silylene and disilene, merge at a disilacyclobutene intermediate. The combined experiments do not rule out a σ-dimerization of an initially formed silacyclopropene but do provide an alternate mechanism which is consistent with all known facts.

One of the best known and certainly most perplexing problems in organosilicon chemistry is the nature of the reaction between silylenes (R_2Si:) and acetylenes. In 1961 Vol'pin and co-workers initiated a series of experiments designed to synthesize a silacyclopropene.[2–4] It was predicted that this system would be stabilized by π-delocalization through an empty 3d orbital of silicon and thus be analogous to the cyclopropenium cation. Dimethylsilylene was generated from the reaction of dimethyldichlorosilane and sodium and from pyrolysis of polydimethylsilanes, in the presence of diphenylacetylene to produce what was thought to be silacyclopropene **1**.



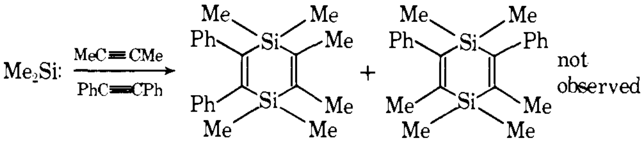
1

The proposed structure, **1**, was soon discovered to be incorrect, with the actual product being the 1,4-disilacyclohexa-2,5-diene (**2**) (a disilin).[5-7] A π-dimerization mechanism for the conversion of presumed intermediate **1** to disilin **2** was later proposed.[8] This proposal gained support from findings of Skell and Goldstein[9] that the ground state for dimethylsilylene is a singlet, and thus the silylene might be expected to react with an acetylene in much the same manner as a singlet carbene.[10]

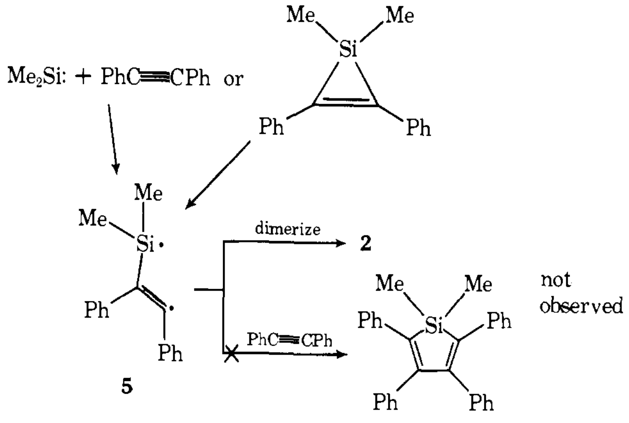


2

The π-dimerization mechanism was ruled out when Atwell and Weyenberg[11] generated dimethylsilyene in the presence of a mixture of 2-butyne and diphenylacetylene to obtain disilin **3** but none of the expected disilin **4**. Dimerization of the 1,3-diradical **5** was considered highly unlikely since it was felt that in the presence of excess diphenylacetylene this diradical should react to yield silacyclopentadiene **6** and none of **6** was formed. Thus it has been assumed that "the formation of the disilacyclohexadienes proceeds by a rather specific dimerization of silacyclopropene intermediates with rupture of the carbon-silicon ring bonds".[11]

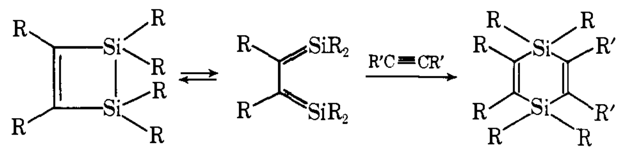


3 **4**

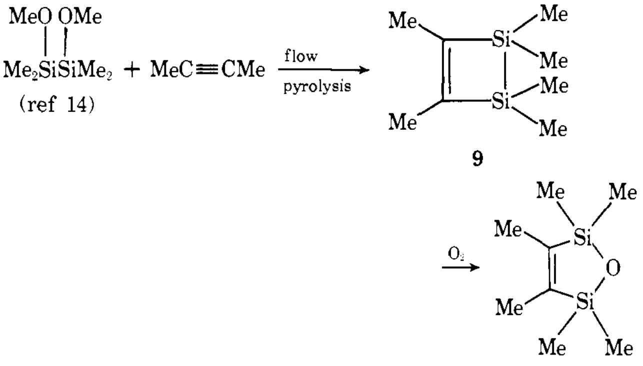


5 **6**

Our interest in molecules containing the silicon-carbon (p-p)π double bond (silenes) produced the suggestion that disilin formation might arise from the Diels-Alder reaction between a 1,4-disila-1,3-butadiene (**7**) and an acetylene. Diene **7** could be reversibly formed from the opening of a 1,2-disilacyclobutene (**8**), and if $R \neq R'$ this would account for the exclusive formation of mixed isomer **3** in the work of Atwell and Weyenberg.[11] While compounds containing the carbon-silicon (p-p)π bond were long thought incapable of existence, considerable evidence has accrued in recent years for at least their transient existence.[12] Recently 2-methyl-2-silabut-2-ene has been observed by infrared at 8 K in an argon matrix.[13] Recently Atwell[14] has reported that the gas phase, flow copyrolysis of the dimethylsilylene generator, 1,2-dimethoxytetramethyldisilane, and 2-butyne produces the permethyl-3,4-disilacyclobutene **9**, thus making possible a test of this mechanism.



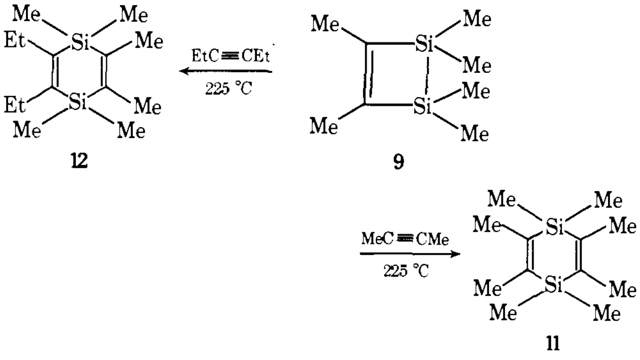
8 **7**



9

10

Copyrolysis of **9** and 2-butyne was accomplished under the usual conditions for silylene additions to acetylenes (sealed tube, 225 °C, 18 h). The isolated products were hexamethyl-3,5-disila-4-oxycyclopentene (**10**), the known product of oxygen insertion into **9**,[14] and 3,6-disilacyclohexa-1,4-diene (**11**) (31%). Perhaps more importantly, copyrolysis of **9** and 3-hexyne produces one isomer of hexamethyldiethyldisilin. The structure of this isomer as **12** can be deduced from its mass

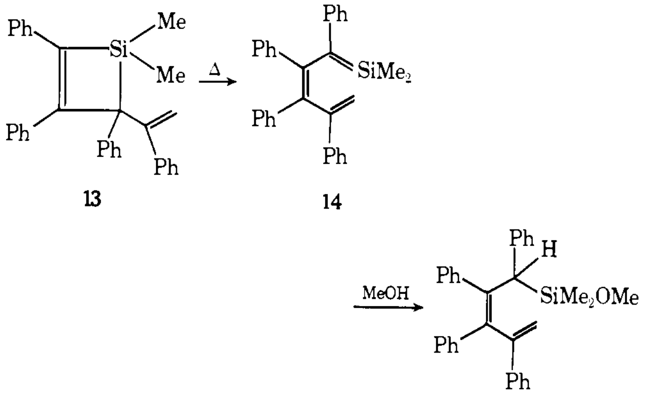


12 **9**

11

spectrum. Atwell and Weyenberg[15] have shown that disilins fragment in the mass spectrometer by first a loss of methyl radical and next an extrusion of an acetylene. Working with a series of substituted disilins it was shown that the integrity of all carbon–carbon bonds is maintained in this fragmentation. Thus the exclusive losses of 2-butyne and 3-hexyne with no loss of 2-pentyne establishes the structure of **12**. This result is in keeping with a Diels–Alder route to the disilins. It should be noted that this latter experiment rules out the possibility that **9** extrudes dimethylsilylene and then disilin formation arises from a mechanism involving a silacyclopropene. Since the reaction is run with a fourfold excess of 3-hexyne, such a route would generate both permethyldisilin **11** and a tetraethyldisilin, neither of which is observed.

Since publication of the preliminary account of our work,[1] indirect support for the thermal ring opening of **9** has appeared. Sakurai[16] has presented evidence that silacyclobutene **13** upon heating opens to silabutadiene **14** which was trapped by alcohol.

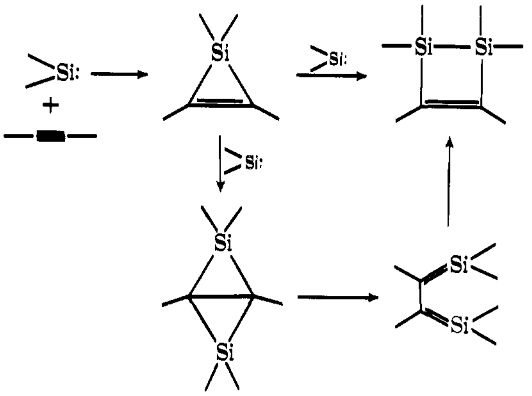


13 **14**

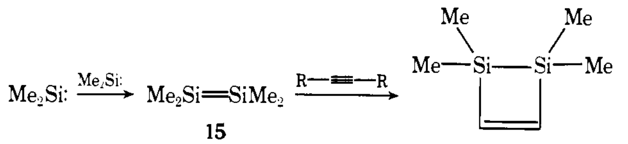
(ref 16)

Thus, since (1) a disilacyclobutene has been shown to be formed in a reaction between a silylene and an acetylene which also produces a disilin,[17] (2) a disilacyclobutene has been shown to react with an acetylene to produce a disilin, and (3) only the substitution isomer of disilin was formed which is consistent with addition across the silicon–silicon bond, the Diels–Alder route must be considered a viable mechanism. However, this probably holds true only for disilin formation at elevated temperatures as we find that **9** fails to react with 2-butyne at room temperature for 24 h. It should be clearly stated that until time when it can be demonstrated whether or not silacyclopropenes (unknown to date) undergo dimerization across a silicon–carbon bond, that mechanism must receive equal consideration.

Several possibilities exist for the origin of a disilacyclobutene in a silylene/acetylene reaction. Atwell[14] made the reasonable suggestion that this might arise from silylene insertion into a silicon–carbon bond of an initially formed silacyclopropene. However, it is also possible that the silylene inserts into the π bond to form a 2,4-disilabicyclo[1.1.0]butane which rearranges to the disilacyclobutene. We see no obvious method of distinguishing between these pathways short of the synthesis of the bicyclic material.

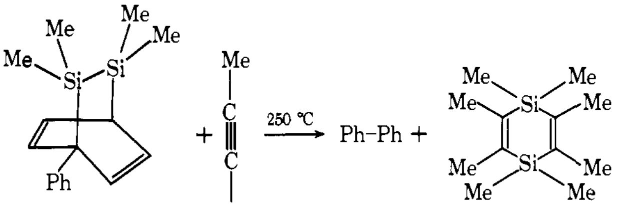


Another possible route to disilacyclobutene would involve initial dimerization of dimethylsilylene to form tetramethyldisilene (**15**). Margrave[18] has provided evidence that difluorosilylene dimerizes in the condensed state to a triplet diradical which adds to acetylenes to form 3,4-disilacyclobutenes. Quite recently Gaspar[19] has shown that dimethylsilylene does indeed dimerize in the gas phase (600–700 °C), as he has isolated the known rearrangement products from the corresponding disilene. Therefore silylene dimerization followed by disilene (**15**) addition across the triple bond must be considered as a route to the disilacyclobutene.

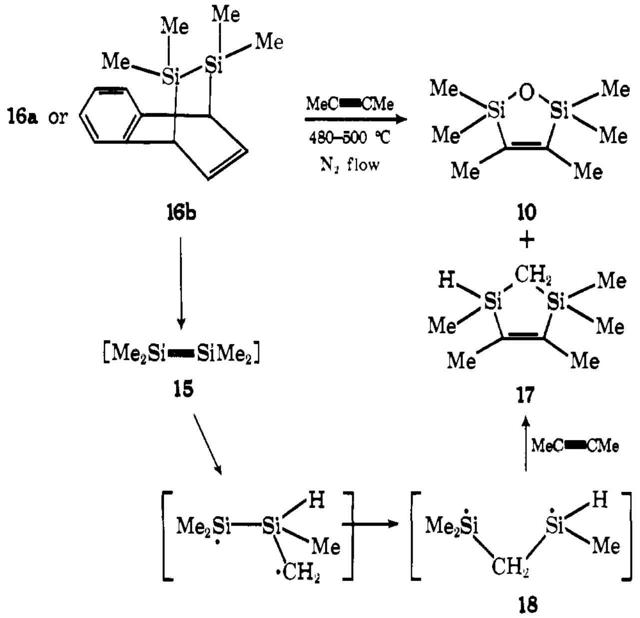


15

A method for testing this proposal exists as Peddle[20] has presented strong evidence that 7,8-disilabicyclo[2.2.2]octa-2,5-dienes **16a** and **16b** thermally extrude disilene **15** as a reactive intermediate which will add in a Diels–Alder fashion to 1,4-diphenyl-1,3-butadiene. Thus disilene generator **16a** was copyrolyzed with an excess of 2-butyne in a sealed tube at 250 °C for 18 h. Two major products were identified—biphenyl and disilin **11** (20%). However, when either **16a** or **16b** was copyrolyzed with 2-butyne in a flow system at 480 °C, the isolated products were **10** (4–8%) and 1,2,3,3,5-pentamethyl-3,5-disilacyclopentene (**17**) (26–28%). Disilacyclopentene **17** is assumed to arise from addition of the disilene rearrangement intermediate **18** across the triple bond of 2-butyne. Diradical **18** has been previously proposed[20] to explain the rearrangement products of **15**.

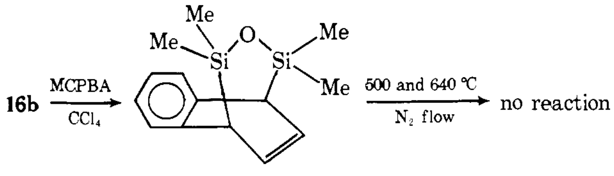


16a **11**



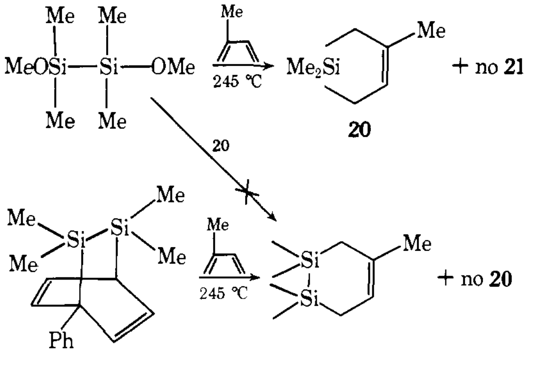
16b **10** **15** **17** **18**

Although Atwell[14] had already established that the atmospheric conversion of **9** to **10** is a rapid, exothermic reaction (something we accidentally confirmed several times), it was necessary to establish that **10** did not arise from a route where oxygen insertion had occurred on the starting material. Toward this end the 2,4-disila-3-oxybicyclo[3.2.2]nona-6,8-diene **19** was synthesized by treatment of **16b** with *m*-chloroperbenzoic acid (MCPBA) in CCl_4 and subjected to flow pyrolysis at both 500 and 640 °C. In both cases the only isolated material was unchanged **19**.



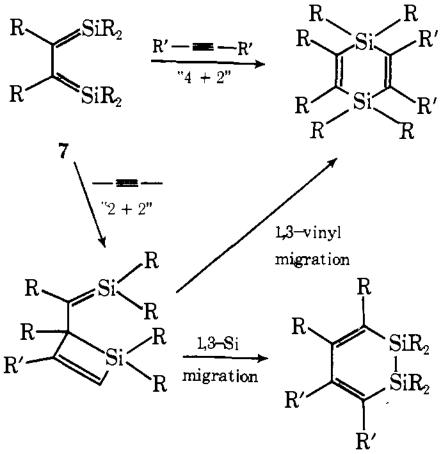
19

From these divergent results of static and gas-flow copyrolyses of **16** and 2-butyne we conclude that in the gas phase the disilene will cycloadd across the triple bond, but our conditions are not appropriate for the subsequent ring opening and Diels–Alder addition. Since these are physical conditions where we have obtained disilin from dimethylsilylene and 2-butyne, it seems reasonable to suggest that silacyclopropene σ-dimerization accounts for most, if not all, of the disilin products from the gas phase, flow silylene/acetylene reactions. We therefore must conclude that dimethylsilylene reacts with 2-butyne to form a silacyclopropene. However, dimethylsilylene has recently been shown to undergo gas-phase dimerization[19] (at 600 °C in the absence of acetylene trap or at 700 °C in the presence of an acetylene trap), and it is entirely reasonable that conditions can be found where a mechanism involving silylene dimerization, disilene cycloaddition to an acetylene, ring opening, and Diels–Alder addition becomes operative in the formation of disilins. However, in our static pyrolyses both silylene and disilene generators react with 2-butyne to afford disilin **11**. Therefore the questions of either silylene dimerization or disilene monomerization under these conditions must still be answered. To this end we have carefully examined two known reactions—the addition of dimethylsilylene and tetramethyldisilene to isoprene. 1,1,2,2-Tetramethyl-1,2-dimethoxy-1,2-disilane was pyrolyzed with excess isoprene in a sealed tube at 245 °C for 18 h to yield 1,4,4-trimethyl-4-silacyclopentene (**20**) (18.9%), and no evidence (<1%) of 1,4,4,5,5-pentamethyl-4,5-disilacyclohexene (**21**) was found. Likewise **16a** and excess isoprene were copyrolyzed under the same conditions to yield **21** (22%) and no evidence (<1%) of **20** was observed. To conclusively demonstrate that **21** was not a product of silylene insertion into **20** the dimethoxydisilane was copyrolyzed with **20** under the same conditions. No **21** was formed, and **20** was unchanged. Thus under the usual static conditions we conclude that there is no significant interconversion of silylene and disilene. Therefore under these conditions disilin formation from silylenes or disilenes arises from two different mechanisms which may merge at a disilacyclobutene intermediate.[23]



16a **21**

Lastly, a comment about the addition of an acetylene to a disilacyclobutene is in order. If the premise that this reaction proceeds through a 1,4-disila-1,3-butadiene is accepted, one still might ask whether or not this is a stepwise reaction. An alternative to the "4 + 2" cycloaddition would be addition of the acetylene across one silicon–carbon double bond followed by a 1,3 shift. The absence of 1,2-disilacyclohexadiene formation appears to argue against this stepwise route since silicon is well known to undergo facile 1,3-migration.[21]



Experimental Section

Infrared spectra (ir) were recorded on a Beckman 18A spectrophotometer. Routine NMR spectra were determined on a Varian Model A-60 or Hitachi R20-B spectrometer, and chemical shifts are reported as parts per million (δ scale) from tetramethylsilane as an internal standard. Routine mass spectra were obtained on an Atlas CH-4 spectrometer and an MS-902 spectrometer. High resolution mass spectra were run on the MS-902. Gas chromatographic/mass spectral (GCMS) analysis was done on a Perkin-Elmer 270 mass spectrometer. Routine analytical and preparative gas chromatography (GC) was done with an F & M 500 gas chromatograph.

Yields, unless otherwise indicated, were done by GC analysis. A known amount of a standard was added to the reaction mixture and used to calculate yield. The exception to this procedure was for reactions of the disilene generators. In these cases the yield of naphthalene or biphenyl was assumed quantitative and yields based on them. In all cases, corrections were made for differences in thermal conductivities.

Flow pyrolysis was done by dripping the desired solution through a vertical tube (10 m × 30 cm) packed with quartz chips. The solutions were dripped through the tube at a rate of 0.33 ml/min. The reactions were done under a nitrogen flow at 1 ml/s. The products were trapped in a liquid nitrogen cooled trap for analysis and separation.

Flow Pyrolysis of 1,2-Dimethoxy-1,1,2,2-tetramethyldisilane with 2-Butyne. The procedure and quantities used were those of Atwell and Uhlman.[14] 1,2,3,3,4,4-Hexamethyl-3,4-disilacyclobutene (**9**) was isolated by distillation: bp 55–65 °C (25 mm); NMR (CCl_4) δ 0.15 (s, 12 H), 1.66 (s, 6 H); mass spectrum (70 eV) *m/e* (rel intensity), 170 (65), 155 (100), 116 (50), 73 (82); mass spectrum calculated for $C_8H_{18}Si_2$, *m/e* = 170.0947; found: *m/e* = 170.0942 ± 0.001 (85). After distillation, a solid crystallized from the residue, and 3.2 grams (25.5%) of octamethyl-3,6-disilacyclohexa-1,4-diene was isolated and identified by GC retention time, NMR, and mass spectral comparison with an authentic sample.

Reaction of Hexamethyl-3,4-disilacyclobutene (9) with Oxygen. Hexamethyl-3,4-disilacyclobutene (**9**) was dissolved in carbon tetrachloride. Oxygen was bubbled through the solution. The solution became hot and gave a quantitative yield of 1,2,3,3,5,5-hexamethyl-3,5-disila-4-oxycyclopentene (**10**): NMR (CCl_4) δ 0.08 (s, 12 H), 1.70 (s, 6 H). The carbon tetrachloride was distilled off: mass spectrum (70 eV) *m/e* (rel intensity) 180 (61), 165 (100, 116 (18), 73 (30), 58

(13); mass spectrum calculated for $C_8H_{18}Si_2O$, *m/e* = 186.0896; found, *m/e* = 186.0902 ± 0.002 (85).

Pyrolysis of 1,2-Dimethoxy-1,1,2,2-tetramethyldisilane with 2-Butyne and 3-Hexyne. The procedure was that of Atwell and Weyenberg.[15] A solution of 0.162 g (0.91 mmol) of 1,2-dimethoxy-1,1,2,2-tetramethyldisilane, 0.108 g (2.0 mmol) of 2-butyne, and 0.178 g (2.0 mmol) of 3-hexyne was degassed in a tube. The tube was sealed under a vacuum and heated to 225 °C for 18 h. The tube was opened, and the products were analyzed and separated by gas chromatography. The products were octamethyl-3,6-disilacyclohexa-1,4-diene (**11**) (17.9%) (identified by comparison of GC retention time, NMR, and mass spectral comparison with authentic sample[15]), 1,2,3,3,6,6-hexamethyl-4,5-diethyl-3,6-disilacyclohexa-1,4-diene (**12**) (19.5%), and 1,2,4,5-tetraethyl-3,3,6,6-tetramethyl-3,6-disilacyclohexa-1,4-diene (8.7%).

1,2,3,3,4,5,6,6-Octamethyl-3,6-disilacyclohexa-1,4-diene was identified (**11**): NMR (CCl_4) δ 0.10 (s, 12 H), 1.80 (s, 12 H) (82); mass spectrum (70 eV) *m/e* (rel intensity), 224* (65), 209 (100), 155 (73), 97 (22), 73 (31); mass spectrum calculated for $C_{12}H_{24}Si_2$, *m/e* = 224.1417; found, *m/e* = 224.1419 ± 0.0012. 1,2,4,5-Tetraethyl-3,3,6,6-tetramethyl-3,6-disilacyclohexa-1,4-diene was identified: NMR (CCl_4) δ 0.10 (s, 12 H), 1.00 (t, 12 H), 2.26 (q, 8 H); mass spectrum (70 eV) *m/e* (rel intensity), 280 (100), 265 (37), 251 (96), 183 (55), 111 (16), 97 (18), 73 (49), 58 (30); mass spectrum calculated for $C_{16}H_{32}Si_2$, *m/e* = 280.0243; found, *m/e* = 280.0243 ± 0.0014. 1,2,3,3,6,6-Hexamethyl-4,5-diethyl-3,6-disilacyclohexa-1,4-diene was identified (**12**): NMR (CCl_4) δ 0.10 (s, 12 H), 1.00 (t, 6 H), 2.26 (q, 4 H); mass spectrum *m/e* (rel intensity), 252 (100), 237 (85), 223 (68), 183 (40), 155 (75), 111 (35), 97 (37), 73 (44), 58 (40); mass spectrum calculated for $C_{12}H_{24}Si_2$, *m/e* = 252.1730; found, *m/e* = 252.1726 ± 0.0013.

Reaction of Hexamethyl-3,4-disilacyclobutene (9) with 2-Butyne. 2-Butyne (0.22 g, 4 mmol) was degassed in a tube. Hexamethyl-3,4-disilacyclobutene (**9**) (0.17 g, 1 mmol) was added under nitrogen. The tube was degassed and sealed. The solution was heated for 18 h at 225 °C. The products was analyzed and isolated by gas chromatography. No starting material was found. The products were hexamethyl-3,5-disila-4-oxycyclopentene (**10**) (81.4%) (identified by GC retention time and NMR comparison with authentic samples[14]) and (31.4%—corrected for presence of **10**) octamethyl-3,6-disilacyclohexa-1,4-diene (identified by GC retention time, NMR spectrum, mass spectrum, and exact mass comparison with an authentic sample[15]).

Reaction of Hexamethyl-3,4-disilacyclobutene (9) with 3-Hexyne. 3-Hexyne (0.33 g, 4 mmol) was degassed in a tube. Hexamethyl-3,4-disilacyclobutene (**9**) (0.17 g) was added under nitrogen. The tube was degassed again, sealed, and heated for 18 h at 225 °C. Analysis and isolation was done by gas chromatography. No starting material was found. Compounds isolated were hexamethyl-3,5-disila-4-oxycyclopentene (**10**) (86%) (identified by GC retention time and NMR comparison with authentic samples[14]) and (39%—corrected for presence of **10**) 1,2-diethyl-3,3,4,5,6,6-hexamethyl-3,6-disilacyclohexa-1,4-diene (**12**) (identified by GC retention time, NMR spectrum, mass spectrum, and exact mass comparison with authentic samples). No octamethyl-3,6-disilacyclohexa-1,4-diene or 1,2,4,5-tetraethyl-3,3,6,6-tetramethyl-3,6-disilacyclohexa-1,4-diene was found.

1-Phenyl-7,7,8,8-tetramethyl-7,8-disilabicyclo[2.2.2]octa-2,5-diene (16a). 1-Phenyl-7,7,8,8-tetramethyl-7,8-disilabicyclo[2.2.2]octa-2,5-diene was prepared according to the method of Roark and Peddle[20] with sodium used in place of lithium.

2,3-Benzo-7,7,8,8-tetramethyl-7,8-disilabicyclo[2.2.2]octa-2,5-diene (16b). 2,3-Benzo-7,7,8,8-tetramethyl-7,8-disilabicyclo[2.2.2]octa-2,5-diene was prepared according to the method of Roark and Peddle.[20] This procedure was sometimes modified to use sodium in place of lithium.

Reaction of 1-Phenyl-7,7,8,8-tetramethyl-7,8-disilabicyclo-[2.2.2]octa-2,5-diene (16a) with 2-Butyne. 1-Phenyl-7,7,8,8-tetramethyl-7,8-disilabicyclo[2.2.2]octa-2,5-diene (**16a**) (1.08 g, 4 mmol) was dissolved in 0.69 g (13 mmol) of 2-butyne in a sealing tube. The tube was sealed and heated at 250 °C for 18 h. The products were biphenyl (identified by GC retention time, NMR, and GCMS comparison with authentic samples) and 20% octamethyl-3,6-disilacyclohexa-1,4-diene (**11**) (identified by GC retention time, NMR, and mass spectral comparison with an authentic sample).

Flow Pyrolysis of 2,3-Benzo-7,7,8,8-tetramethyl-7,8-disilabicyclo[2.2.2]octa-2,5-diene (16b) with 2-Butyne. 2,3-Benzo-7,7,8,8-tetramethyl-7,8-disilabicyclo[2.2.2]octa-2,5-diene (1.22 g, 5 mmol) was dissolved in 1.35 g (25 mmol) of 2-butyne. The solution was pyrolyzed in a nitrogen flow system at 500 °C. The product was analyzed and separated by gas chromatography. The isolated products were 1,2,3,3,5,5-hexamethyl-3,5-disila-4-oxycyclopentene (**10**) (4.1%) (identified by GC retention time, NMR, and mass spectral comparison of a known sample) and 1,2,3,3,5-pentamethyl-3,5-disilacyclopentene (**17**) (26.3%); NMR (CCl_4) δ −0.52 (d of d, 1 H), −0.08 (d of d, 1 H) 0.11 (s, 6 H), 0.17 (d, 3 H), 4.25 (m, 1 H); infrared (CCl_4) 2945 (s), 2890 (m), 2840 (m), 2085 (s), 1248 (s) cm^{-1}; mass spectrum (70 eV) *m/e* (rel intensity) 170 (20), 155 (100), 128 (56), 44 (42); mass spectrum calculated for $C_8H_{18}Si$, *m/e* = 170.0947; found, *m/e* = 170.0947 ± 0.001.

Flow Pyrolysis of 1-Phenyl-7,7,8,8-tetramethyl-7,8-disilabicyclo[2.2.2]octa-2,5-diene (16a) with 2-Butyne. 1-Phenyl-7,7,8,8-tetramethyl-7,8-disilabicyclo[2.2.2]octa-2,5-diene (**16a**) (0.54 g, 2 mmol) was dissolved in 3.24 g (60 mmol) of 2-butyne. The solution was pyrolyzed in a nitrogen flow system at 480 °C. The solution was analyzed and separated by gas chromatography. 1,2,3,3,5-Pentamethyl-3,5-disilacyclopentene (**17**) (28.3%) and 1,2,3,3,5,5-hexamethyl-3,5-disila-4-oxycyclopentene (**10**) (8.5%) were isolated. Products were identified by GC retention time, NMR, and mass spectral comparison with known samples.

Preparation of 6,7-Benzo-2,2,4,4-tetramethyl-2,4-disila-3-oxybicyclo[3.2.2]nona-6,8-diene (19). 2,3-Benzo-7,7,8,8-tetramethyl-7,8-disilabicyclo[2.2.2]octa-2,5-diene (**16b**) (1.0 g, 4.1 mmol) was dissolved in carbon tetrachloride. *m*-Chloroperbenzoic acid (0.71 g, 4.1 mmol) was added and the reaction followed by NMR. After 1 h of stirring at room temperature, the solution was extracted with an aqueous solution of sodium bicarbonate and then dried. The carbon tetrachloride was removed via rotoevaporation to isolate the 6,7-benzo-2,2,4,4-tetramethyl-2,4-disila-3-oxybicyclo[3,2.2]nona-6,8-diene (**19**): NMR (CCl_4) δ 0.11 (s, 6 H), 0.37 (s, 6 H), 2.85 (d of d, 2 H), 6.16 (d of d, 2 H), 7.00–7.40 (m, 4 H).

Pyrolysis of 6,7-Benzo-2,2,4,4-tetramethyl-2,4-disila-3-oxybicyclo[3.2.2]nona-6,8-diene (19) with 2-Butyne. 6,7-Benzo-2,2,4,4-tetramethyl-2,4-disila-3-oxybicyclo[3.2.2]nona-6,8-diene (**19**) (0.5 g, 1.92 mmol) was dissolved in 2.1 g (39 mmol) of 2-butyne. The solution was pyrolyzed in the flow pyrolysis system under nitrogen at 500 °C. NMR and gas chromatographic analysis showed no evidence of 1,1,3,3,4,5-hexamethyl-1,3-disila-2-oxycyclopent-4-ene (**10**). The butyne was distilled off, and NMR and gas chromatography analyses were repeated with only negative results. An NMR analysis indicated 95% recovery of starting **19**. The reaction was repeated with negative results (78% recovery of **19**, 11% benzene, and 4% biphenyl) at 640 °C.

Preparation of 1,1,2,2,4-Pentamethyl-1,2-disilacyclohex-4-ene (21). Isoprene (5.1 g, 75 mmol) was added to 9.31 g (50 mmol) of 1,2-dichloro-1,1,2,2-tetramethyldisilane in 100 ml of dry hexamethylphosphoramide. Magnesium (2.43 g, 0.1 mmol) was added, and the solution was heated (80 °C) for 3 days. Hexane was added and extracted several times with water. After drying with magnesium sulfate, the majority of hexane was removed by rotoevaporation. The residue was analyzed and separated by GC. The products were 1,1,3-trimethyl-1-silacyclopent-3-ene (5.35%) (identified by GC and NMR comparison with an authentic sample) and 1,1,2,2,4-pentamethyl-1,2-disilacyclohex-4-ene (**21**) (11.8%): NMR (CCl_4) δ 0.7 (s, 12 H), 1.36 (m, 4 H), 1.7 (m, 3 H), and 5.27 (t, 1 H); infrared 2960 (b), 1440 (w), 1250 (s), 1150 (w), and 1042 (m); mass spectrum 70 eV) *m/e* (rel intensity) 184 (56), 179 (42), 116 (100), 73 (48), and 45 (62); mass spectrum calculated for $C_9H_{20}Si_2$, *m/e* = 184.1103; found, *m/e* = 184.1114 ± 0.0018.

Preparation of 1,1,3-Trimethyl-1-silacyclopent-3-ene (20). 1,1,3-Trimethyl-1-silacyclopent-3-ene was prepared according to the method of Weyenberg and co-workers:[22] NMR (CCl_4) δ 0.15 (s, 6 H), 1.20 (m, 4 H), 1.72 (m, 3 H), and 5.38 (m, 1 H); and bp 55–65 °C (20 mm).

Pyrolysis of 1-Phenyl-7,7,8,8-tetramethyl-7,8-disilabicyclo-[2.2.2]octa-2,5-diene (16a) with Isoprene. Disilabicyclo[2.2.2]octadiene (**16a**) (1.35 g, 1.0 mmol) was added to 0.73 g (10.7 mmol) of isoprene in a tube. The solution was degassed and the tube sealed. The tube was heated for 18 h at 245 °C. The tube was opened and the products analyzed and separated by GC. The products were biphenyl and 1,1,2,2,4-pentamethyl-1,2-disilacyclohex-4-ene (**21**) (22.0%). Both products were identified by GC, NMR, and mass spectral (including exact mass of the disilacyclohexene) comparison with authentic samples.

Pyrolysis of 1,2-Dimethoxy-1,1,2,2-tetramethyldisilane and Isoprene. 1,2-Dimethoxy-1,1,2,2-tetramethyldisilane (1.2 g, 6.75 mmol) was added to 0.93 g (1.35 mmol) of isoprene in a tube. The solution was degassed and the tube sealed. The tube was heated for 18 h at 245 °C. The tube was opened, and the products were analyzed and separated by GC. The products were dimethyldimethoxysilane and 1,1,3-trimethyl-1-silacyclopent-3-ene (**20**) (18.9%) (identified by GC, NMR, and mass spectral comparison with authentic samples). No evidence was found for 1,1,2,2,4-pentamethyl-1,2-disilacyclohex-4-ene (**21**) (<1%).

Pyrolysis of 1,1,3-Trimethyl-1-silacyclopent-3-ene (20) with 1,2-Dimethoxy-1,1,2,2-tetramethyldisilane. 1,1,3-Trimethyl-1-silacyclopent-3-ene (**20**) (0.57 g, 4.5 mmol) was added to 0.53 g of 1,2-dimethoxytetramethyldisilane in a tube. The solution was degassed and sealed. The tube was heated for 18 h at 245 °C. The 1,1,3-trimethyl-1-silacyclopent-3-ene was recovered (98%), and no evidence was found for 1,1,2,2,4-pentamethyl-1,2-disilacyclohex-4-ene (**21**) (<1%).

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(23) NOTE ADDED IN PROOF. Professor P. P. Gaspar [*J. Am. Chem. Soc.*, **98**, 3715 (1976)] has now reported the first isolable silacyclopropene. Professor D. Seyferth recently reported (172d National Meeting of the American Chemical Society, San Francisco, Calif., Aug 29–Sept 3, 1976, Abstracts, No. ORGN-73) that disilin formation is *not* observed upon heating silacyclopropenes in solution. Thus a mechanistic decision may soon be available.

The Kinetics and Mechanisms of 1,5-Dihydroflavin Reduction of Carbonyl Compounds and Flavin Oxidation of Alcohols. 2. Ethyl Pyruvate, Pyruvamide, and Pyruvic Acid

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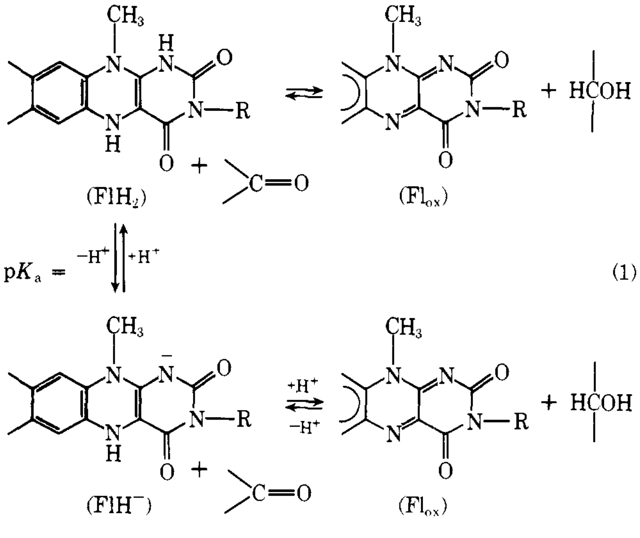
Abstract: The time courses for the appearance of lumiflavin-3-acetate (Fl_{ox}) on reaction of 1,5-dihydrolumiflavin-3-acetate (FlH_2) and its N(1) anion (FlH^-) with pyruvamide, ethyl pyruvate, pyruvic acid, and pyruvate anion are quantitatively explained by the reactions of Scheme I. In competitive reactions FlH_2 and FlH^- (FlH_{2T}) react with the carbonyl substrate to yield Fl_{ox} and the *N*(5)-carbinolamine (CA) which goes on to the corresponding imine (Im). This initial process ($Fl_{ox} \leftarrow FlH_{2T} \rightleftarrows CA_T \rightleftarrows Im_T$) may be characterized by an initial burst of Fl_{ox} production dependent upon pH and carbonyl substrate. Following this initial phase, Fl_{ox} continues to be formed by two pathways. Return of CA to FlH_{2T} contributes but the principal production of Fl_{ox} occurs via the comproportionation of Fl_{ox} with CA [which is an *N*(5)-alkyl-1,5-dihydroflavin]. Formation of CA and Im during the course of the reaction is supported by their spectral identification (at 355–360 and 500 nm, respectively) and by the quantitative reductive trapping with sodium cyanoborohydride and subsequent conversion of the resultant *N*-alkyl-1,5-dihydroflavin to its aminium cation radical (λ_{max} ~585 nm). The concentration of FlH_{2T} remaining in solution, following the initial burst reaction, has been determined via its rapid conversion to Fl_{ox} by addition of CH_2O or additional substrate. An extended kinetic study was deemed feasible only for pyruvic acid and pyruvate due to the competing hydrolysis of ethyl pyruvate and the observed dimerization of pyruvamide during the time of reaction with FlH_{2T}. The time courses for formation of Fl_{ox} from the reaction of pyruvic acid + pyruvate with FlH_{2T} have been simulated by analog computations employing the differential expressions for the reactions of Scheme II. The rate constants obtained from the analog simulation have been fit to log k_{rate} vs. pH profiles and k_{rate} vs. substrate concentration plots. For ethyl pyruvate and pyruvamide, selective analog simulation of the time courses for Fl_{ox} production suffice to support the mechanism of Scheme I. The direct reaction of ethyl pyruvate with FlH_{2T} to yield ethyl lactate and Fl_{ox} is first order in reactants. At pH 1 the reduction of pyruvic acid + pyruvate is first order in [pyruvic acid + pyruvate] and [H_3O^+], while at pH 3.3 the reaction is second order in [pyruvic acid + pyruvate] and is [H_3O^+] independent. Mechanisms involving 1e⁻ transfer from 1,5-dihydroflavin species to the carbonyl group of the substrate which involve proton transfer to substrate carbonyl oxygen or its derived anion radical are considered. The reasonableness of radical pair intermediates (e.g., $FlH\cdot_T \cdot C{-}O^-$ and $FlH\cdot_T \cdot C{-}OH$) along the reaction path is established from the observation that the computed standard free energies of formation for these species in the pH range of investigation are less positive by 9 to 14 kcal M^{-1} than $\Delta G^{\ddagger}_{expl}$. At alkaline pH values the standard free energy for pyruvate + $FlH^- \rightarrow$ lactate + Fl_{ox} is positive, and it has been shown that lactamide at pH 11.6 and lactate at pH 10 reduces Fl_{ox} to FlH^-. The kinetics and mechanism for CA and Im formation and the comproportionation of CA and Fl_{ox} are discussed.

Introduction

An understanding of the mechanisms of flavin mediated redox reactions is of singular importance to the comprehension of the mechanisms of flavoenzyme catalysis.[2] The reduction of carbonyl compounds by 1,5-dihydroflavins (FlH_2 and FlH^-) and the retrograde oxidation of alcohols by oxidized flavins (Fl_{ox}) serve as important examples of reactions for mechanistic elucidation (eq 1). This manuscript, the second of a series dealing with this topic,[3] describes a detailed kinetic study of the 1,5-dihydroflavin reduction of biochemically important pyruvic acid, its amide, and ethyl ester. The results of this study are significant with regard to the mechanistic understanding of lactic acid oxidase. The kinetic findings are discussed in terms of covalent vs. radical mechanisms.[2,4]



(1)

Experimental Section

Materials. 3-Carboxymethyl-7,8,10-trimethylisoalloxazine (I; lumiflavin-3-acetate) was synthesized utilizing the method of Hemmerich[5] and purified by silica column chromatography. The purity of the lumiflavin-3-acetate was checked by thin-layer chromatography on silica employing two solvent systems (acetic acid/1-butanol/H_2O 1:2:1 and chloroform/methanol/acetic acid 18:1:1); mp 300 °C dec.

Pyruvic acid (II) was purchased from Aldrich Chemical Co. (Gold Label Lot No. 041647) and carefully purified by distillation at 8 mm Hg. The fraction distilling at 59.0–59.1 °C was collected and stored frozen at −20 °C under nitrogen (lit. bp 65 °C at 10 mm Hg).[6] **Ethyl pyruvate** (III) from Aldrich (Lot No. 072647) was purified by vacuum distillation at 68.5 °C at 40 mm Hg (lit. bp 69–71 °C at 42 mm Hg)[6] and stored at −20 °C. **DL-Lactamide** (IV) was purchased from Sigma Chemical Co. (Lot No. 54C-0222) and purified by two recrystallizations from ethyl acetate to yield a solid melting at 74.5 °C (lit. mp 75.5 °C).[6] This solid was stored at −20 °C. **Ethyl lactate** (V) from Aldrich was distilled at 153.1–153.9 °C (lit. mp 154 °C)[6] and stored at −20 °C. **Pyruvamide** (IV) was synthesized by first converting acetyl chloride to pyruvonitrile according to the procedure of Jander and