Published in final edited form as:

Organometallics. 2010 February 22; 29(4): 1041–1044. doi:10.1021/om901114q.

Formation of silicon-carbon bonds by photochemical irradiation of $(\eta^5\text{-C}_5\text{H}_5)\text{Fe}(\text{CO})_2\text{SiR}_3$ and $(\eta^5\text{-C}_5\text{H}_5)\text{Fe}(\text{CO})_2\text{Me}$ to obtain R_3SiMe

Skye Fortier, Yongqiang Zhang, Hemant K. Sharma, and Keith H. Pannell

Department of Chemistry, University of Texas at El Paso, El Paso, Texas, 79968-0513, USA

Abstract

Photochemical irradiation of an equimolar mixture of $(\eta^5\text{-C}_5\text{H}_5)\text{Fe}(\text{CO})_2\text{SiR}_3$, FpSiR_3 , and FpMe leads to the efficient formation of the silicon-carbon coupled product R_3SiMe , $\text{R}_3 = \text{Me}_3$, Me_2Ph , MePh_2 , Ph_3 , ClMe_2 , Cl_2Me , Cl_3 , Me_2Ar ($\text{Ar} = \text{C}_6\text{H}_4\text{X}$, $\text{X} = \text{F}$, OMe , CF_3 , NMe_2). Similar chemistry occurs with related germyl and stannyl complexes at slower rates, $\text{Si} > \text{Ge} > \text{Sn}$. Substitution of an aryl hydrogen in $\text{FpSiMe}_2\text{C}_6\text{H}_4\text{R}'$ has little effect upon the rate of the reaction whereas progressive substitution of methyl groups on silicon by Cl slows the process. Also changing FpMe to $\text{FpCH}_2\text{SiMe}_3$ dramatically slows the reaction as does the use of $(\eta^5\text{-C}_5\text{Me}_5)\text{Fe}(\text{CO})_2$ derivatives. A mechanism involving the initial formation of the $16e^-$ intermediate $(\eta^5\text{-C}_5\text{H}_5)\text{Fe}(\text{CO})\text{Me}$ followed by oxidative addition of the Fe-Si bond, accounts for the experimental results obtained.

Introduction

Silicon-carbon bond formation is not only very well-established but continues to be well-studied and many distinct routes are available, including *inter alia* (a) the Rochow-direct process, (b) salt-elimination reactions, and (c) hydrosilylation.¹ Interestingly both a and b generally need the use of a transition metal catalyst illustrating the importance and widespread chemistry involving silicon-transition metal interactions. Such interactions often involving oxidative addition reactions of the organosilicon species to the metal center and the capacity of the Si-H,² Si-C,³ Si-Cl,⁴ and Si-Si,⁵ bonds to oxidatively add to a transition metal center is well-known.

We have reported that photochemical irradiation of $\text{Fp-SiMe}_2\text{SiMe}_2\text{CH}_2\text{-Fp}$, [$\text{Fp} = (\eta^5\text{-C}_5\text{H}_5)\text{Fe}(\text{CO})_2$] led to the quantitative formation of the β -elimination rearrangement product $\text{Fp-SiMe}_2\text{CH}_2\text{SiMe}_2\text{-Fp}$ rather than the silylene α -elimination product $\text{FpSiMe}_2\text{CH}_2\text{Fp}$.^{6a} Since both α - and β -elimination processes are preceded by CO elimination we concluded that the carbonyl groups at the Fe-C end of the molecule were more labile than those at the Fe-Si end. Furthermore, using this knowledge we later suggested that the unexpected and quantitative photochemical elimination of 1,3-tetramethyldisilacyclobutane from $\text{FpSiMe}_2\text{CH}_2\text{SiMe}_2\text{CH}_2\text{Fp}$ resulted from an unprecedented intramolecular oxidative-addition reaction initiated by CO elimination at the Fe-C end of the molecule.^{6b}

We now report a study of the reactions between FpSiR_3 and FpMe where upon photochemical irradiation the high-yield formation of Fp_2 and R_3SiMe is observed, consistent with a related intermolecular oxidative addition mechanism.

Experimental

All reactions involved the use of pure materials synthesized by published methods in dry deoxygenated solvents. Two photochemical set ups were used to irradiate the samples in 5 mm Pyrex NMR tubes; either use of a water-cooled, medium pressure Hg lamp at a distance of 5 cm from the NMR tubes, or a Luzchem LSZ-5 UV photoreactor with a merry-go-round containing 8 UV lamps (350 nm, of 0.3 mW/cm²). The photoreactor was more conducive to the relative rate study, but either method resulted in the same chemistry.

In a general procedure an equimolar amount of FpSiR₃ and FpMe (1 – 0.1 mmol) were charged into an NMR tube with solvent (typically C₆D₆ unless noted), degassed, and flame sealed *in vacuo*. The samples were irradiated over a period of ~20 hrs and monitored using ¹³C and ²⁹Si NMR spectroscopy every ~1 hr. Irradiation caused the solution to turn from yellow to dark purple reflecting the generation of the Fp₂ dimer. NMR monitoring illustrated the disappearance of the starting materials and generation of the R₃SiMe product. Trace amounts of ferrocene could be detected in experiments with prolonged irradiation times.

The ²⁹Si and ¹³C NMR resonances for the silyl portions of selected reactants and products are recorded in Tables 1 and 2, respectively; all values are in accord with published data as referenced.⁶⁻¹³ Additionally mass spectral data for Me₃SiC₆H₄-*p*- X, X = MeO, CF₃, F, Me₂N are in total accord with literature values.¹⁴

Photochemical reaction of FpSiPh₃ and FpMe in C₆D₆

A 9" long 5 mm Pyrex NMR tube was charged with 0.12 g (0.27 mmol) of FpSiPh₃ and 0.052 g (0.27 mmol) of FpMe in 1.0 mL of degassed C₆D₆ and the tube was flame-sealed *in vacuo*. The tube was irradiated in the Luzchem LSZ-5 UV photoreactor and the progress of the photoreaction was periodically monitored by ¹³C and ²⁹Si NMR spectroscopy. The starting materials were 90 % consumed after 60 h of irradiation with clean formation of *only* two products Ph₃SiMe and Fp₂. The photolysis was stopped and the solution was placed on a 2.5 × 10 cm silica gel column and a colorless band was eluted with hexane. Upon removal of the solvents *in vacuo*, this band produced 0.06 g (0.22 mmol, 81 % yield) of Ph₃SiMe as a white solid (m.p. 66-67 °C; (lit. m.p. 67-69 °C)).¹⁵ A second, dark red, band was eluted with a 50:50 hexane/CH₂Cl₂ solvent mixture that after evaporation of the solvents yielded 0.08 g (0.22 mmol, 81 % yield) of Fp₂ as a dark purple solid. The spectral data for Ph₃SiMe: ¹H NMR (CDCl₃): δ 0.77 (s, 3H, Me), 7.30, 7.45 (m, 15H, Ph). ¹³C NMR (CDCl₃): δ -3.39 (Me), 127.82, 129.36, 135.25, 136.07 (ipso) (Ph). ²⁹Si NMR (CDCl₃): δ -10.5; (lit. ²⁹SiNMR, C₆D₆, -10.4 ppm).¹⁷

Photochemical reaction of FpGePh₃ and FpMe in C₆D₆

The reaction was performed in exactly the same manner as that above using 0.10 g (0.21 mmol) of FpGePh₃ and 0.04 g (0.21 mmol) of FpMe. The irradiation was longer than for the Si analog, ~ 81 hrs by which time the reagents had been consumed to ~ 90%. and *only* two products Ph₃GeMe and Fp₂ were observed. Upon opening the tube the solution was placed directly on a 2.5 × 10 cm silica gel column and first a colorless band was eluted with 90:10 hexane/CH₂Cl₂ solvent mixture. Upon removal of the solvents *in vacuo*, 0.055 g (0.17 mmol, 81 % yield) of Ph₃GeMe was obtained as a white solid, (m.p. 65-66 °C; (lit. m.p. 66-67 °C)).¹⁸ A second, dark red, band was eluted with a 50:50 hexane/CH₂Cl₂ mixture that after evaporation of the solvents yielded Fp₂ as a purple solid (0.059 g, 0.167 mmol, 79 % yield). The spectral data for Ph₃GeMe: ¹H NMR (CDCl₃): δ 0.85 (s, 3H, Me), 7.32, 7.43 (m, 15H, Ph). ¹³C NMR (CDCl₃): δ -4.18 (Me), 128.15, 128.85, 134.51, 137.96 (ipso) (Ph).

Results and discussion

In all cases studied the general photoreaction between $(\eta^5\text{-C}_5\text{H}_5)\text{Fe}(\text{CO})_2\text{Me}$, FpMe , (**1a**) and a corresponding FpSiR_3 , e.g. FpSiMe_3 (**2**), in hydrocarbon solvents resulted in the smooth formation of only two products, Fp_2 and R_3SiMe , equation 1.

The reactions were performed in pyrex NMR tubes and monitored by ^{13}C and ^{29}Si NMR spectroscopy. A typical reaction sequence between **1a** and **2** is illustrated in Figure 1.

The spectral changes observed in Figure 1 clearly demonstrate the progressive replacement of the ^{29}Si resonance for **2** at 40.5 ppm by a resonance at 0.0 ppm associated with SiMe_4 . At the same time the ^{13}C NMR spectra exhibit the progressive disappearance of the resonances at -20.5 ppm (FpMe) and 5.3 ppm (FpSiMe_3) and the appearance of the resonance at 0.0 ppm associated with SiMe_4 . The two $(\eta^5\text{-C}_5\text{H}_5)$ resonances for **1** and **2** also disappear and are replaced by a single resonance at 88.5 ppm associated with the concurrent formation of Fp_2 . The spectral sequence is extremely clean and illustrates the efficiency of the process. Monitoring by ^1H NMR was also feasible, but line broadening was often noted; however, a typical monitoring sequence of the reaction between **1** and **2a** is available as supporting information and confirms the clean nature of the reaction. In general the rate of the reactions slows with time predominantly due to the reduction in transmission of the solutions associated with the formation of Fp_2 .

We propose a mechanism for this process involving an initial formation of the $16e^- [(\eta^5\text{-C}_5\text{H}_5)\text{Fe}(\text{CO})\text{Me}]$ species followed by oxidative addition of the Fe-Si bond. Subsequent reductive elimination of the Si-C bonded species, a well-established step,¹⁹ leads to the observed products, Scheme 2.

We have studied this unprecedented chemistry from the point of view of variation of the R groups on silicon, replacement of Si by Ge and Sn, and by modification of the structure of the Fp-C complex.

In terms of the quantitative nature of the reaction, as suggested by the data in Figure 1, we observed that the reaction between **1a** and FpSiPh_3 resulted in the isolation of Ph_3SiMe in > 90% yield. A similar almost quantitative result was obtained from the reaction of **1a** and FpGePh_3 stopping the reaction prior to total transformation for the sake of time. The reactions were performed at higher concentrations and required longer time periods to go to completion due to the reduced transmission of the sample as a result of the build-up of Fp_2 . Full details are presented in the experimental section.

To ascertain both the generality of the process and to determine what, if any, factors effect the efficiency and rate of the process we studied a large range of FpER_3 complexes; $\text{R}_3 = \text{Me}_3$, $\text{E} = \text{Si}$ (**2**), Ge (**3**), Sn (**4**); $\text{E} = \text{Si}$, $\text{R}_3 = \text{Me}_2\text{Ph}$ (**5**), $\text{Me}_2\text{C}_6\text{H}_4\text{-p-X}$, [$\text{X} = \text{CF}_3$ (**5a**), F (**5b**), OMe (**5c**), NMe_2 (**5d**)], MePh_2 (**6**), Ph_3 (**7a** $\text{E} = \text{Si}$, **7b**, $\text{E} = \text{Ge}$), Me_2Cl (**8**), MeCl_2 (**9**), and Cl_3 (**10**). In all cases spectroscopic monitoring data obtained during the reaction were in accord with the clean chemistry noted in equation 1. The ^{29}Si and ^{13}C spectroscopic data for the various reactants and products are recorded in Tables 1 and 2, respectively, and are in accord with the published data. Furthermore, analysis of the final products by GC/MS spectroscopy also confirmed the products and each set of data were in accord with all literature values.

We investigated the rate variations of the transformation as a function of FpER_3 by normalizing the time for 50% completion based upon the reaction described above between **1a** and **2**. Variation of the of the group 14 element, i.e. **2**, **3** and **4**, led to the formation of the expected Me_3EMe , $\text{E} = \text{Si}, \text{Ge}, \text{Sn}$ product. Substituting the silicon atom by a germanium atom, i.e. **2** to **3**, had a moderately negative impact upon the rate of the reaction, an almost doubling the time required for completion. However, the reaction with FpSnMe_3 was very slow and indeed never went to completion even after >240 h irradiation (under the same reaction conditions the transformation of **2** was 100% complete after 16h and that of the Ge analog **3** was complete after 25h).

For the series of $\text{Me}_n\text{Ph}_{3-n}\text{SiFp}$ ($n = 3, 2, 1, 0$) complexes there was little variation in rate, with the relative rates for $\text{Me}_3 : \text{Me}_2\text{Ph} : \text{MePh}_2 : \text{Ph}_3$ of 1.0 : 1.2 : 1.3 : 1.2, respectively. Also, in the case of the various dimethylarylsilyl complexes **5**, $\text{FpSiMe}_2\text{C}_6\text{H}_4\text{-}p\text{-X}$, varying the electronic properties of the *para*-X substituent had only minor impact with relative rates in the series $\text{CF}_3, \text{F}, \text{H}, \text{OMe}, \text{NMe}_2$: 0.5 : 1.0 : 1.0 : 1.1; 1.2, respectively. The impact of the electron-withdrawing CF_3 group suggested that a substituent closer to the silicon atom might have a greater impact. Thus, the series $\text{FpSiMe}_n\text{Cl}_{3-n}$ was studied, $n = 3$ (**2**); $n = 2$ (**8**); $n = 1$ (**9**); $n = 0$ (**10**). The relative rates of the transformations (which again were clean) illustrated a regular slowing of the reaction rate as a function of increasing electron-withdrawing substituent on the silicon atom, **2** : **8** : **9** : **10** = 1.0 : 0.8 : 0.5 : 0.3. However, these rate differences are marginal.

In terms of bond energy changes during the process, outlined in equation 2, the major distinctions between the reactions of the Fe-E ($\text{E} = \text{Si}, \text{Ge}, \text{Sn}$) and the Fp-Me resolve into the differences between the C-E and Fe-E bond strengths.

Typical bond energies for the E-CH_3 bonds, in kJ/m, are in the general order of Si-C (318) > Ge-C (238) > Sn-C (192) and the corresponding Fe-E bond energies have the same trend, Fe-Si (174.5) > Fe-Ge (163 (estimated)) > Fe-Sn (151.9).²⁰ With published data of the Fe-C and Fe-Fe bonds of 113 and 87 kJ/m, respectively, these data suggest that the transformations reported herein tend to be exothermic in the case of Si and Ge, but endothermic for the very slow Sn chemistry. Based upon similar reasoning, the small rate decrease in the sequence $\text{FpSiMe}_3 < \text{FpSiMe}_2\text{Cl} < \text{FpSiMeCl}_2 < \text{FpSiCl}_3$ can be interpreted by the greater Fe-Si bond energies upon increasing retrodonative π -bonding between Fe and Si with increasing chloro-substituents.²¹ This feature apparently outweighs the general trend of increasing the Si-C bond energy in systems with increasingly electronegative substituents on silicon.²²

Selected substituted-Fp compounds with significant steric features were also investigated. Thus Fp^*CH_3 (**11**) and Fp^*SiMe_3 (**12**), $\text{Fp}^* = (\eta^5\text{-C}_5\text{Me}_5)\text{Fe}(\text{CO})_2$, were used. The resulting order, again normalized to the reaction of $\text{FpMe} + \text{FpSiMe}_3$, was (**11** + **2**) = 0.3; (**12** + **1**) = 0.6 and (**11** + **12**) = <0.01. Coupling this data to the dramatic slowdown when reacting $\text{FpCH}_2\text{SiMe}_3$ and **2** (relative rate = 0.02) indicates a very significant steric impediment to the reaction which is compatible with an oxidative addition process.

As in all photochemical reactions the possibility of radical processes can be suggested. However, in the present case irradiation of the starting materials by themselves under the identical conditions and concentrations resulted in no significant chemistry. Only after the longest time periods (> 30 h, when all reactions except the higher concentration preparative reactions were essentially complete) were traces of Fp_2 and ferrocene observed. In addition, zero evidence for any R_3SiMe , $(\text{R}_3\text{Si})_2$, MeH(D) , $\text{R}_3\text{SiH(D)}$, or C_2H_6 was obtained suggesting

that a radical process involving cleavage of the Fe-C or Fe-Si bonds are not at work in this new methyl transfer reaction.

A sigma bond metathesis process is possible, however, such mechanisms are generally associated with early transition metal complexes where the formation of 16e⁻ systems (and oxidation) is not so facile (or possible). Many previous reports have concluded that the (η⁵-C₅H₅)Fe(CO)CH₃ species is often involved in oxidative addition chemistry.²³ A more intriguing alternative to the simple oxidative addition mechanism we suggest is the possibility that direct “binuclear reductive elimination” chemistry is involved.²⁴ This would involve a concerted direct bridging of either the methyl or silyl group²⁵ between two Fe atoms with transformation of a terminal to bridging CO and subsequent elimination of the R₃SiMe product. We have no evidence to propose bridging silyl groups in the Fp and related systems, however, we are studying the possibility of such chemistry.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This research was supported by the Welch Foundation (Grant AH-546) and an NIH MARC U*STAR undergraduate scholarship to SF (Grant # 2T34GM 008048) who also thanks the American Chemical Society for an ACS Scholars Award.

References

1. (a) Eaborn, C. *Organosilicon Compounds*. Butterworth Scientific Publications; London: 1960. (b) Brook, MA. *Silicon in Organic, Organometallic, and Polymer Chemistry*. J Wiley & Sons; NY: 2000.
2. (a) Harrod JF, Gilson DFR, Charles R. *Can J Chem* 1969;47:2205. (b) Chatt J, Eaborn C, Kapoor PN. *J Chem Soc [Section] A* 1970:881. (c) Corey JY, Braddock-Wilking J. *Chem Rev* 1999;99:175. [PubMed: 11848982]
3. (a) Huang D, Heyn RH, Bollinger JC, Caulton KG. *Organometallics* 1997;16:292. (b) Hua R, Akita M, Moro-oka Y. *J Chem Soc Chem Commun* 1996:541. (c) Gilges H, Schubert U. *Organometallics* 1998;17:4760. (d) Suresh CH, Koga N. *J Theor Comp Chem* 2005;4:59.
4. (a) Zlota AA, Frolov F, Milstein D. *J Chem Soc Chem Commun* 1989:1826. (b) Yamashita H, Tanaka M, Goto M. *Organometallics* 1997;16:4696. (c) Sturmayer D, Schubert U. *Eur J Inorg Chem* 2004:776.
5. (a) Gilges H, Kickelbick G, Schubert U. *J Organomet Chem* 1997;548:57. (b) Murakami M, Yoshida T, Ito Y. *Chem Lett* 1996:13. (c) Sugimoto M, Oike H, Shuff PH, Ito Y. *J Organomet Chem* 1996;521:405.
6. (a) Pannell KH, Kobayashi T, Cervantes-Lee F, Zhang Y. *Organometallics* 2000;19:1. (b) Zhang Y, Cervantes-Lee F, Pannell KH. *Organometallics* 2002;21:5859.
7. (a) Nguyen DC, Chvalovsky V, Schraml J, Magi M, Lippmaa E. *Coll of Czech Chem Comm* 1975;40:875. (b) Cragg RH, Lane RD. *J Organomet Chem* 1984;277:199.
8. Williams EA, Gargioli JD. *Annual Reports on NMR Spectroscopy* 1979;9:221.
9. (a) Pannell KH, Rozell JM Jr, Hernandez C. *J Amer Chem Soc* 1989;111:4482. (b) Jones KL, Pannell KH. *J Amer Chem Soc* 1993;115:11336.
10. van Walree CA, Lauteslager XY, van Wageningen AMA, Zwikker JW, Jenneskens LsW. *J Organometal Chem* 1995;496:117.
11. Krentz R, Pomeroy R. *Inorg Chem* 1985;24:2976.
12. Van den Berghe EV, Van der Kelen GP. *J Organomet Chem* 1973;59:175.
13. Rakita PE, Worsham LS. *Inorg Nucl Chem Lett* 1977;13:547.
14. Freeburger ME, Hughes BM, Buell GR, Tiernan TO, Spialter L. *J Org Chem* 1971;36:933.
15. Gilman H, Trepka WJ. *J Org Chem* 1962;27:1414.

16. Nguyen, Duc-Chuy; Chvalovský, V.; Schraml, J.; Mägi, M.; Lippmaa, E. Collect Czech Chem Commun 1975;40:875.
17. Tsuji H, Inoue T, Kaneta Y, Sase S, Kawachi A, Tamao K. Organometallics 2006;25:6142.
18. Brook AG, Peddle GJD. J Am Chem Soc 1963;85:1869.
19. (a) Brinkman KC, Blakeney AJ, Krone-Schmidt W, Gladysz JA. Organometallics 1984;3:1325. (b) Schubert U. Angew Chem 1994;106:435.
20. Suresh CH, Koga N. Organometallics 2001;20:4333.
21. Lichtenberger DL, Rai-Chaudhuri A. J Am Chem Soc 1991;113:2923.
22. Gusel'nikov LE, Avakyan VG, Gusel'nikov SL. Russ J Gen Chem 2001;71:1933.
23. (a) Kazlauskas RJ, Wrighton MS. Organometallics 1982;1:602. (b) Hooker RH, Rest AJ, Whitwell I. J Organomet Chem 1984;266:C27. (c) Mohamed BAS, Kikuchi M, Hashimoto H, Ueno K, Tobita H, Ogino H. Chem Lett 2004;33:112. (d) Adam W, Azzena U, Prechtel F, Hindahl K, Malisch W. Chem Ber 1992;125:1409.
24. Stockland RA, Anderson GK, Rath NP. J Am Chem Soc 1999;121:7945.
25. Osakada K, Koizumi T, Yamamoto T. Angew Chem Int Ed 1998;37:349.

Figure 1.
²⁹Si and ¹³C NMR monitoring of the reaction between **1** and **2**

Scheme 1.
Intermolecular photochemical formation of Si-C bond

Table 1
Observed ^{29}Si Silicon Shift (ppm) for reagents and products

Starting Material	^{29}Si (δ)		Product
FpSiPh ₃ ^{9a}	36.07	-10.69	MeSiPh ₃ ⁷
FpSiMePh ₂ ^{9a}	35.18	-7.97	Me ₂ SiPh ₂ ⁸
FpSiMe ₂ Ph ^{9a}	36.37	-4.71	Me ₃ SiPh ⁸
FpSiMe ₂ C ₆ H ₄ F ^{9b}	36.43	-4.07	Me ₃ SiC ₆ H ₄ F ^{9b,10}
FpSiMe ₂ C ₆ H ₄ NMe ₂ ^{9b}	36.06	-4.6	Me ₃ SiC ₆ H ₄ NMe ₂ ^{9b,10}
FpSiMe ₂ C ₆ H ₄ OMe ^{9b}	35.49	-4.80	Me ₃ SiC ₆ H ₄ OMe ^{9b,10}
FpSiMe ₂ C ₆ H ₄ CF ₃ ^{9b}	36.00	-3.35	Me ₃ SiC ₆ H ₄ CF ₃ ^{9b,10}
FpSiMe ₃ ¹¹	41.82	-0.15	Me ₄ Si ⁸
FpSiMe ₂ Cl ¹¹	86.36	30.69	Me ₃ SiCl ^{8,12}

Table 2
Observed ^{13}C Shift (ppm) for methyl group of reagents and products

Starting Material	^{13}C (δ)SiCH _n		Product
FpSiPh ₃ ⁶	-	-3.23	MeSiPh ₃ ⁶
FpSiMePh ₂ ⁶	5.11	-2.31	Me ₂ SiPh ₂ ⁶
FpSiMe ₂ Ph ⁹	5.29	-1.13	Me ₃ SiPh ⁶
FpSiMe ₂ PhF ⁹	5.50	-1.12	Me ₃ Si C ₆ H ₄ F ^{9b,10}
FpSiMe ₂ C ₆ H ₄ OMe ^{9b}	5.84	-0.81	Me ₃ SiC ₆ H ₄ OMe ^{9b,10}
FpSiMe ₂ PhCF ₃ ^{9b}	5.18	-1.55	Me ₃ SiC ₆ H ₄ CF ₃ ^{9b,10}
FpSiMe ₃ ⁶	7.39	0.04	Me ₄ Si
FpSiMe ₂ Cl ¹¹	12.63	3.04	Me ₃ SiCl ¹³
FpSiMeCl ₂ ¹¹	17.9	6.67	Me ₂ SiCl ₂ ¹³
FpSiCl ₃ ¹¹		9.17	MeSiCl ₃ ¹³