Organic Magnetic Resonance, 1976, Vol. 8, pp. 40 to 44.

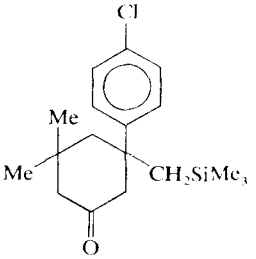
Concerning some Unusual Trimethylsilyl Proton Chemical Shifts†

B. L. Shapiro* and T. W. Proulx§
Department of Chemistry, Texas A & M University, College Station, Texas 77843, USA

(Received in the U.K. 10 August 1975; accepted in the U.K. 9 September 1975)

Abstract—Proton and ^{13}C NMR data are presented for six different compounds containing the fragment C_6H_5—C—CH_2SiMe_3. In a number of instances it was observed that, in the ^1H NMR spectrum, the $SiMe_3$ groups had a chemical shift significantly upfield from internal tetramethylsilane ($\delta = -0{\cdot}14$ to $-0{\cdot}36$). These unexpected upfield chemical shifts of the $SiMe_3$ groups are suggested to result from the predominance, on a time averaged basis, of conformations which place the methyl groups attached to silicon in the face of an aromatic ring. The preference for such conformations is, in turn, the result of rotational preferences exhibited by the 'flat' aromatic ring. These results suggest that conformational analysis of systems containing a phenyl ring should take more explicit account of the fact that the preferred orientation of this phenyl ring can have a profound influence on the conformation adopted by the remainder of the molecule. In addition, the preferred conformation of the phenyl ring can have a significant effect upon the observed ^1H NMR chemical shifts, while the ^{13}C chemical shifts are relatively insensitive to conformational factors and can be explained by well-known substituent effects previously delineated for all-carbon systems.

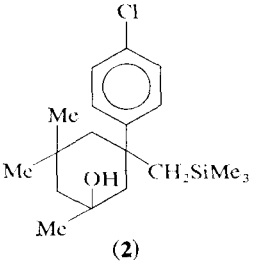
IN THE course of some investigations concerned with the use of lanthanide shift reagents in the conformational analysis of some highly substituted cyclohexanones,[1] compound **1** was prepared and its ^1H NMR spectrum was examined.



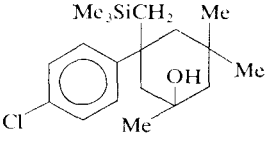
(1)

Unexpectedly, the chemical shift observed for the $SiMe_3$ group was found to be $\delta = -0{\cdot}29$. The initial observation of this unusual chemical shift was made for the compound analogous to **1** with a phenyl ring in place of the *p*-chlorophenyl group.[2] In subsequent studies the *p*-chlorophenyl group was employed, since this group has a greatly simplified ^1H NMR spectrum. In addition, the two alcohols **2** and **3**, formed by the addition of methylmagnesium bromide to ketone **1**, also show chemical shifts for the $SiMe_3$ groups of $\delta = -0{\cdot}32$ and $-0{\cdot}36$, respectively.

These observations were not anticipated since, in general, the chemical shifts of $SiMe_3$ groups bonded to



(2)

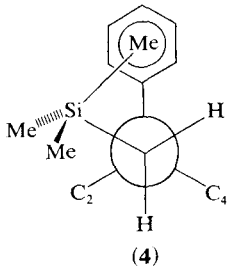


(3)

sp^3 carbon atoms occur in the range $0 \leq \delta < 1{\cdot}0$.[3] In fact, for $SiMe_3$ groups bonded to a CH_2 fragment the chemical shifts are invariably in the narrow range $\delta = 0{\cdot}15$ to $-0{\cdot}05$. In hydrocarbon-type systems then, a chemical shift for an $SiMe_3$ group occurring very much upfield of tetramethylsilane (TMS) cannot be accommodated by bonded substituent effects alone and other factors such as molecular conformation must be considered.

In both **1** and **2** the aromatic rings occupy axial positions, as expected by analogy to the preferred conformations observed for a variety of 3,5,5-trimethyl-3-arylcyclohexane systems.[1,4] As a consequence of this, the axial methyl at C-5 is held in the shielding region of the aromatic ring and its chemical shift occurs at much higher field (typically $\delta = 0{\cdot}3$ $-0{\cdot}5$)[4] than might otherwise be expected.

It is attractive to invoke a similar conformational argument in the case of the methyl groups on silicon, especially since these methyl groups are separated from the aromatic ring by the same number and types of bonds as is the *syn*-axial methyl at C-5. It appears that the high field chemical shifts observed for the $SiMe_3$ groups of compounds **1**, **2** and **3** result from the greater importance, on a time averaged basis, of a conformation such as that shown below:



(4)

When one realizes that the observed chemical shift for the methyl groups on silicon is the average not only of rotation of the trimethylsilyl group itself, but also of rotation about the bond joining the $-CH_2SiMe_3$ group to the cyclohexane ring, the observed upfield shift of

* Author to whom correspondence should be addressed.

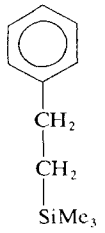
† Taken, in part, from the PhD Dissertation of Thomas W. Proulx, Texas A & M University, 1975.

§ Predoctoral Fellow of The Robert A. Welch Foundation, Houston, Texas.

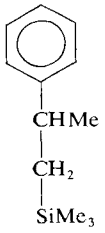
c. 0·3 ppm is remarkably large. It is our view that this must bespeak a very substantial preference for a molecular conformation such as **4**.

There is not a large amount of data available on the preferred conformations of organosilane compounds[5] and, although it would be expected that the same factors which affect the conformations of hydrocarbons would be operable in organosilanes, the increased length of the C—Si bond (*c.* 1·85 Å) could result in some unusual conformational effects. Therefore, a determination of the factors which affect the stabilities of the various rotational isomers of the $-CH_2SiMe_3$ group in compounds **1**, **2** and **3** would be useful in an attempt to delineate the major factors involved in the conformational features of organosilanes.

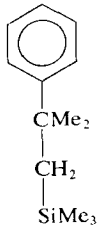
In this paper, NMR studies, both ^1H and ^{13}C, will be reported for compounds **1**, **2** and **3** as well as three acyclic model compounds, **5**, **6** and **7**.



(5)



(6)



(7)

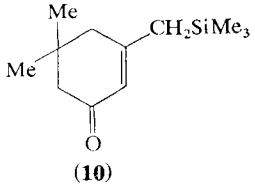
Compounds **5**, **6** and **7** were prepared in an effort to determine whether the suspected conformational preference exhibited by the trimethylsilylmethyl group in compounds **1**, **2** and **3** is some consequence of the highly substituted cyclohexyl system, or instead, is the result of a more basic conformational preference deriving from acyclic factors.

SYNTHESIS OF COMPOUNDS 1, 2 AND 3

The synthetic route to compounds **1**, **2** and **3** is outlined in Scheme 1.

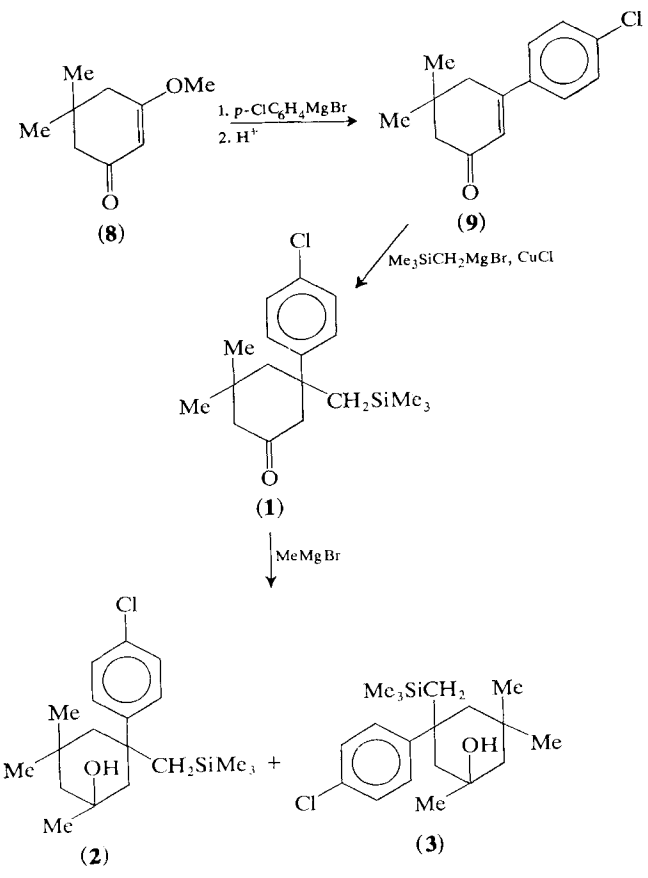
Enone **9** was prepared from dimedone methyl ether (**8**) in excellent yield by standard methods.[6] However, the conjugate Grignard additions of trimethylsilylmethylmagnesium bromide to enone **9** to give ketone **1** proceeds in very poor yield (4%). This is clearly a consequence of the reduced positive character at C-3 owing to the increased conjugation with the phenyl substituent, for, under the same conditions, trimethylsilylmethylmagnesium bromide will add to isophorone to give the conjugate addition product in quantitative yield (unpublished results, this laboratory).

Attempts were made to synthesize enone **10** in the hope that the addition of a phenyl Grignard reagent would proceed in better yield, following results obtained in systems without the trimethylsilyl groups.[1]



(10)

However, attempts to prepare this enone failed, owing to the lability of the trimethylsilyl group[7] to



SCHEME 1

reaction and/or work-up conditions. In fact, the addition of trimethylsilylmethylmagnesium bromide to dimedone methyl ether (**8**) is a rather expensive method for the preparation of isophorone and hexamethyldisiloxane, both in excellent yield. Since the starting materials necessary to prepare enone **8** and the trimethylsilylmethyl Grignard reagent are inexpensive and readily available, the route outlined in Scheme 1 was followed.

The addition of methylmagnesium bromide to ketone **1** resulted in an 85% yield of the *cis*-isomer (**2**) and a 15% yield of the *trans*-isomer (**3**), readily separated by column chromatography on silica gel.

Compounds **5**, **6** and **7** were prepared in standard fashion (see Experimental).

EXPERIMENTAL

Capillary melting points were determined on a Mel-Temp melting point apparatus. All boiling points and melting points reported are uncorrected. Mass spectral data were obtained with a Consolidated Electronics Corp. Model 21-110B mass spectrometer operated by Mr G. Gable of the Department of Biochemistry, Texas A & M University.

All ^1H NMR data were obtained on a Varian Associates HA-100 spectrometer operating in the frequency sweep mode, at an ambient probe temperature of 31 °C.

^{13}C NMR spectra were obtained in the Fourier transform mode on a JEOL PFT-100 spectrometer system operating at 25·034 MHz (proton resonance frequency 99·539 MHz) and equipped with a Nicolet 1085 data system.

All chemical shifts (^1H and ^{13}C) are reported on the usual δ scale (i.e. ppm downfield from internal TMS).

Preparation of compounds

5,5-Dimethyl-3-(p-chlorophenyl)-2-cyclohexen-1-one (**9**). This compound was prepared by the method of Woods[6] from *p*-chlorophenylmagnesium bromide and 3-methoxy-2-cyclohexen-1-one

in 75% yield. The compound is a pale yellow crystalline solid with m.p. 84 – 85 °C (*ex* ethanol). NMR: $\delta = 1{\cdot}01$ (Me), 6·16 (=CH). Exact mass analysis: calc. for $C_{14}H_{15}ClO$: 234·081731; Found: 234·081135 (3·0 ppm error).

5,5-Dimethyl-3-(p-chlorophenyl)-3-trimethylsilylmethylcyclohexanone (**1**). This compound was prepared by standard, copper catalyzed, conjugate addition[1] of 28·7 gm (0·15 mol) of trimethylsilylmethylmagnesium bromide to 23·4 gm (0·1 mol) of 5,5-dimethyl-3-(*p*-chlorophenyl)-2-cyclohexen-1-one. The crude reaction product was purified by chromatography on alumina using hexane–benzene mixtures as the eluents, followed by reduced pressure distillation to yield the ketone **1** as a colorless liquid, b.p. = 120 °C at 0·1 Torr. Yield = 1·4 g (4·3%). NMR: $\delta =$ 0·99, 0·25 (Me); −0·29 ($SiMe_3$). Exact mass analysis: calc. for $C_{18}H_{27}ClOSi$: 322·151955; Found: 322·150661 (4·9 ppm error).

cis- *and* trans-*1,5,5-Trimethyl-3-(p-chlorophenyl)-3-trimethylsilylmethylcyclohexanols* (**2**, **3**). The addition of methylmagnesium bromide to 3·4 g (0·01 mol) of **1** followed by isomer separation by column chromatography on silica gel (Woelm, Act. 1) using hexane–acetone mixtures (1 to 10% acetone) as the eluents gave 0·5 g of **3** (15%) and 2·8 g of **2** (85%).

(**2**). NMR: $\delta = 0{\cdot}86$, 0·61, 1·24 (Me); −0·32 ($SiMe_3$). Exact mass analysis: calc. for $C_{19}H_{31}ClOSi$: 338·183260; Found: 338·184088 (2·4 ppm error).

(**3**). NMR: $\delta = 1{\cdot}29$, 0·85, 1·22 (Me); −0·36 ($SiMe_3$). Exact mass analysis: calc. for $C_{18}H_{28}ClOSi$ [M − 15]: 323·159800; Found: 323·160651 (3 ppm error). The calculations were performed for the [M − 15] peak since the intensity of the molecular ion peak was very small.

(β-Phenethyl)trimethylsilane (**5**), *(β-cumyl)trimethylsilane* (**6**) *and neophyltrimethylsilane* (**7**). These compounds were all prepared by the coupling of the appropriate Grignard† reagent with trimethylchlorosilane. The coupling was effected by refluxing the two components in tetrahydrofuran for 48 h, followed by standard work-up with saturated ammonium chloride solution. Yields = **5**, 75%; **6**, 70%; **7**, 5%. Compounds **5** and **6** are known compounds,[8] and were characterized by NMR and appropriate physical constants. Compound **7** has not been reported previously and was characterized by mode of preparation and NMR spectra.

(**5**). NMR: $\delta = 0{\cdot}00$ ($SiMe_3$); 2·61 ($CH_2C_6H_5$); 0·86 (CH_2Si).

(**6**). NMR: $\delta = 1{\cdot}26$ (Me); 2·85 (CHC_6H_5); 0·88, 0·98 (CH_2Si); −0·14 ($SiMe_3$).

(**7**). NMR: $\delta = 1{\cdot}38$ (Me); 1·16 (CH_2Si); −0·21 ($SiMe_3$).

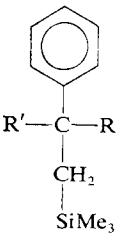
RESULTS AND DISCUSSION

Proton NMR

For convenience, structure **11** below will be used for the following discussions.

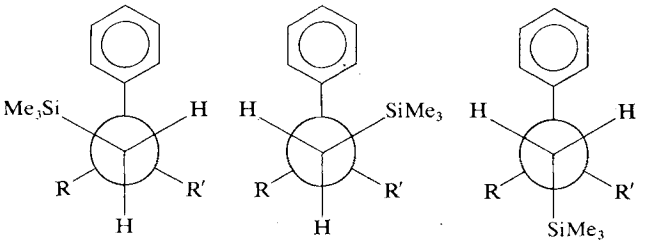
The proton chemical shifts for the trimethylsilylmethyl groups of compounds **1**, **2** and **3** and for all of the protons of compounds **5**, **6** and **7** are presented in Table 1.

† β-Phenethyl bromide and β-cumyl bromide are commercially available, and neophyl chloride was prepared by the method of W. T. Smith, Jr and J. T. Stellas, *Org. Syn*, Coll. Vol. IV, Wiley, New York, 1973, p. 702.



(**11**)

Consider first the chemical shifts of the protons in the model systems, **5**, **6** and **7**. The data presented in Table 1 indicate that beginning with compound **5** and progressively replacing a benzylic proton by a methyl group, the conformations with the phenyl ring *gauche* to the $SiMe_3$ become more important contributors to the time averaged rotational state. Newman projections of the three rotamers follow:



(**12a**) (**12b**) (**12c**)

The 'normal' methyl (on silicon) chemical shift, $\delta = 0$, for the groups in **5** (R = R′ = H) must be the result of the dominance of an *anti* conformation **12c**, as would be expected on steric grounds. Replacing one of the benzylic protons by a methyl to give **6** (R = Me, R′ = H) results in an upfield shift of 0·14 ppm for the $SiMe_3$ resonance. This implies that conformations **12a** and **12b** must be more important to the time averaged structure. It is reasonable to rule out **12a** (R = Me) on steric grounds, and to consider that **12b** must be the major contributor to the observed effect. Finally, replacing the second benzylic proton by a methyl group results in an additional 0·07 ppm upfield shift for **7** (R = R′ = Me) relative to **6**. In this case rotamers **12a** and **12b** are identical, and clearly must be the preferred conformations of this compound.

TABLE 1. PROTON CHEMICAL SHIFTS[a] (δ_H)

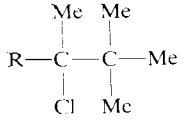
Compound	R	R′	CH_2Si		$SiMe_3$	Phenyl[b]
(1)	—	—	0·97,	1·33	−0·29	—
(2)	—	—	0·78,	1·03	−0·32	—
(3)	—	—	1·30,	1·77	−0·36	—
(5) R = R′ = H	2·61[b]	2·61[b]	0·86[b]		0·00	~7·14 (~14)
(6) R = Me, R′ = H	1·26	2·85	0·88,[c]	0·98[c]	−0·14	~7·15 (~14)
(7) R = R′ = Me	1·38	1·38	1·16		−0·21	~7·25 (~41)

[a] 0·15 M solutions in carbon tetrachloride.

[b] Approximate center of a complex multiplet. Numbers in parentheses are the widths of the patterns in Hz at 100 MHz.

[c] Obtained from the analysis of these protons as the AB portion of an ABX system. The linewidths of the peaks (*c.* 1 Hz) of this pattern confirm that coupling to the methyl group is very small (<0·1 Hz), as expected, so that this approximation is valid.

Although it is not immediately obvious, the above results are quite reasonable when the effect of rotation of the phenyl ring is taken into account. A recent study by Anderson and Pearson[9] on compounds of structure **13** (see below) demonstrated that the barrier to rotation of the *t*-butyl group in **13** is lower for R = phenyl than for R = methyl.



(13)

The authors ascribe this observation to the preference of the phenyl ring for a 'parallel' conformation in which the plane of the aromatic ring is parallel to either a C—CH_3 or C—Cl bond rather than the 'perpendicular' conformation in which the plane of the aromatic ring is perpendicular to the C—$C(CH_3)_3$ bond.

The analogous parallel and perpendicular orientations of the phenyl ring for compound **6** are shown in Fig. 1. The results of Anderson and Pearson suggest that the phenyl ring should prefer the parallel conformation with the C—H bond nearly eclipsed by the phenyl ring.

In this conformation, should the $SiMe_3$ group be *gauche* to phenyl (and hydrogen), viz. conformation **12b**, there will be no significant steric interactions between the $SiMe_3$ group and the *gauche* groups. However, should the $SiMe_3$ group be *gauche* to methyl (and hydrogen), viz. conformation **12c**, then there can be significant steric interactions between the protons of the methyl group and the $SiMe_3$ group. The effect of the phenyl preference for the parallel conformation is to rotate the *ortho* carbon of the phenyl ring (and its hydrogen) away from the *gauche* $SiMe_3$ group, thereby reducing or eliminating any unfavorable steric interactions.

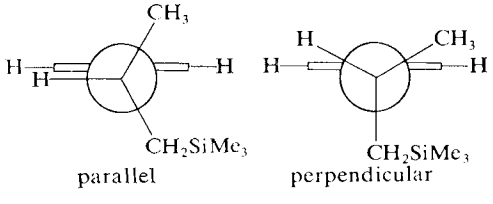


Fig. 1

It should be noted that if the phenyl ring would prefer the perpendicular conformation, then any conformations having *gauche* phenyl–trimethylsilyl groups should be very much disfavored owing to the introduction of substantial steric interactions between the *ortho* hydrogens of the phenyl ring and the trimethylsilyl group. Therefore, one would not expect to see any substantial upfield shifts in the proton spectrum, since only when the $SiMe_3$ group is *gauche* to phenyl can the methyls on silicon be in the face of the aromatic ring.

The arguments given above are similar to those used to explain the stability of axial-phenyl 1-phenyl-1-methylcyclohexane relative to the equatorial-phenyl isomer.[10]

These arguments are further supported by the results obtained for the cyclic compounds **1**, **2** and **3**. The conformations deduced (primarily from lanthanide-induced shift studies) as being important for these three compounds[11] are shown in Fig. 2.

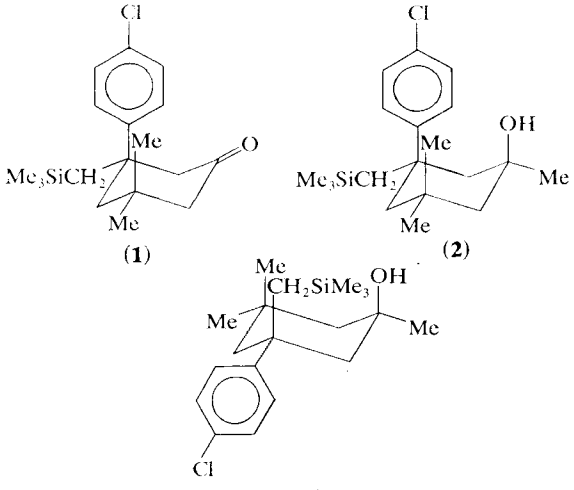


Fig. 2

The chemical shifts observed for the CH_2SiMe_3 fragments in these compounds show two major differences from the chemical shifts of the acyclic model systems. First, the $SiMe_3$ groups have chemical shifts which are even further upfield than is the case for compounds **5**, **6** and **7**, and second, the chemical shift difference of the methylene protons adjacent to silicon is much greater in compounds **1**, **2** and **3** than it is in compound **6**.

The methylene protons adjacent to silicon in compounds **1**, **2**, **3** and **6** are, of course, diastereotopic since they are adjacent to a chiral center. However, the rather large chemical shift differences (0·25 to 0·47 ppm) for these protons could indicate a high degree of rotational biasing in **1**, **2** and **3**. If there is rotational biasing as suggested with the $SiMe_3$ group *gauche* to the phenyl ring, then, one of the methylene protons adjacent to silicon will also be *gauche* to the aromatic ring while the other will be *anti*. This is identical to the situation which obtains for the methylene protons at C-2 and C-4 of the cyclohexane ring. For these methylene pairs the equatorial protons have chemical shifts considerably downfield (0·5 to 1·0 ppm) of their axial partners owing to a significant deshielding from the 'edge effect' of the aromatic ring.[1] (It should be mentioned that the considerable downfield shifts observed (δ = 1·77, 1·30) for the CH_2—Si protons in *trans*-alcohol (**3**) are the result of a deshielding by the *syn*-axial hydroxyl group.) This is by no means a conclusive argument since the 'intrinsic non-equivalence' of these protons can only be approximated by a consideration of the chemical shift difference in **6**.

This is supported, however, by the observed chemical shifts for the trimethylsilyl group. The substantial upfield shifts observed for these protons in **1**, **2** and **3** imply a marked degree of non-equivalence of the amounts of rotational isomers. It is of interest to speculate upon why the observed chemical shifts of the $SiMe_3$ groups are further upfield in the cyclohexane derivatives than in the acyclic model compounds.

At the present time it is felt that the increased upfield shifts in the cyclohexyl compounds are the result of two different types of rotational biasing forced upon these heavily substituted carbocycles. A consideration of the conformations of these molecules, as shown in Fig. 2 suggests that the increased upfield shifts

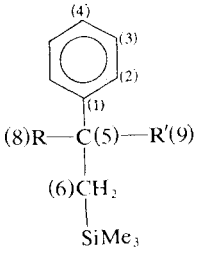
could be due to a greater biasing of the aromatic ring rotational populations toward the conformation where the *p*-chlorophenyl group occupies an axial position. The presence of the *syn*-axial methyl group at C-5 of the cyclohexane ring might well greatly hinder free rotation of the aromatic ring.

A second effect, which is important for the *trans*-alcohol (**3**), is that one of the two conformations which this compound adopts in solution is one in which the trimethylsilylmethyl group occupies an axial position, as deduced from lanthanide-induced shift studies. In this case, the $SiMe_3$ group would be expected to be almost entirely in a position *gauche* to the equatorial *p*-chlorophenyl group, owing to the steric hindrance of the *syn*-axial methyl group at C-5 and hydroxyl group at C-1.

However, although there are some additional factors which affect the preferred conformations of the trimethylsilylmethyl group in the cyclohexane systems, the basic preference of the trimethylsilyl group to be *gauche* to the aromatic ring in these systems is clearly not a result of the highly substituted cyclohexyl systems.

Carbon-13 NMR

For ease in discussion the following numbering scheme will be used for the carbons of interest in compounds **1** to **3** and **5** to **7**. The ^{13}C chemical shifts for these compounds are presented in Table 2.



(7)

TABLE 2. ^{13}C CHEMICAL SHIFTS[a] (δ_C)

Carbon	(1)	(2)	(3)	(5)	(6)	(7)
(1)	145·3	145·5	149·7	145·0	147·3	151·0
(2)	128·1	127·4	127·1	127·8	126·6	125·4
(3)	128·1	128·6	127·9	128·2	128·2	127·9
(4)	131·6	130·8	131·0	125·4	125·7	125·3
(5)	44·8	40·9	40·8	30·1	36·5	37·2
(6)	38·8	42·6	34·0	18·7	27·0	34·9
(7)	0.0	0.0	0.2	−1.7	−1.0	0.3
(8)	55·5	52·4	50·8	—	26·6	32·4
(9)	54·2	51·4	50·6	—	—	32·4

[a] 0·5 to 1·0 M solutions in deuterochloroform.

As expected, the ^{13}C chemical shifts are not very informative with respect to the rotational state of the trimethylsilylmethyl group, since anisotropy effects are relatively unimportant in ^{13}C NMR because ^{13}C chemical shifts are dominated by substituent effects.[12] Thus, the chemical shifts presented in Table 2 are dominated by substituent effects.

There are, however, certain exceptions, based on steric factors. For example, note the downfield position of C-1 in compound **3** relative to compounds **1** and **2** since in **3** the aromatic ring occupies an equatorial position and consequently C-1 does not experience the 'γ-effect'[13] which is known to produce upfield shifts for axial carbons in cyclohexane systems. There are, therefore, no significant new or unusual effects resulting from the introduction of the silicon atom. Although there is not enough data available at present, it appears that it will be possible to develop substituent parameters to describe the ^{13}C chemical shifts of organosilanes in much the same manner, and with similar results, as has been done for hydrocarbons.

With only one exception, the chemical shifts presented in Table 2 can be determined to arise from either substituent effects or well-known steric factors. The one exceptional chemical shift value is that for C-5 in compound **7**. On the basis of substituent effects, it might be expected that the chemical shift for this carbon in compound **7** would be an additional 5 to 7 ppm downfield from the chemical shift of this carbon in compound **6**. However, this is not what is observed. It is not clear why the chemical shift of C-5 in **7** is much further upfield than would be expected, but it is tempting to speculate that this must be the result of the increased steric strain in this rather crowded molecule.

Acknowledgements—The authors wish to acknowledge the generous financial support for this research by The Robert A. Welch Foundation, Houston, Texas. The authors also wish to thank Professors K. E. Harding and D. H. O'Brien for helpful discussions. Support by The National Science Foundation via Grant No. GP-32912 for the purchase of the JEOL PFT-100 spectrometer is gratefully acknowledged.

REFERENCES

1. See, for example, B. L. Shapiro, M. D. Johnston, Jr and M. J. Shapiro, *Org. Magn. Resonance* **5**, 21 (1973).
2. M. J. Gattuso, PhD Dissertation, Texas A & M University, 1970.
3. J. Dyer and J. Lee, *Spectrochim. Acta (A)* **26**, 1045 (1970).
4. B. L. Shapiro, M. J. Gattuso, N. F. Hepfinger, R. L. Shone and W. L. White, *Tetrahedron Letters* 219 (1971).
5. (a) R. J. Ouellette, D. Baron, J. Stolfo, A. Rosenblum and and P. Weber, *Tetrahedron* **28**, 2163 (1972); (b) M. T. Tribble and N. L. Allinger, *Tetrahedron* **28**, 2147 (1972).
6. G. G. Woods, *J. Amer. Chem. Soc.* **69**, 2549 (1947).
7. A. W. P. Jarvie, *Organomet. Chem. Rev. A*, **6**, 153 (1970).
8. (a) L. F. Cason and H. G. Brooks, *J. Org. Chem.* **19**, 1278 (1954); (b) R. A. Benkeser and R. G. Severson, *J. Amer. Chem. Soc.* **73**, 1424 (1951).
9. J. E. Anderson and H. Pearson, *J. Chem. Soc. Perkin II* 1779 (1974).
10. N. L. Allinger and M. T. Tribble, *Tetrahedron Letters* 3259 (1971).
11. T. W. Proulx, PhD Dissertation, Texas A & M University, 1975; these results will be published at a later date.
12. J. B. Stothers, *Carbon-13 NMR Spectroscopy*, Academic Press, New York, 1972, p. 103.
13. J. B. Stothers, *Carbon-13 NMR Spectroscopy*, Academic Press, New York, 1972, p. 163.