Conformational analysis of the *cis*- and *trans*-1,2-bis(trimethylsilyl)-cyclohexanes (BTMSC): molecular mechanics calculations and nuclear magnetic resonance spectroscopy. A preferred diaxial conformation for the *trans*-isomer

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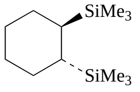
Molecular mechanics calculations (MM3-92) suggest that a slightly distorted diaxial chair conformation of *trans*-1,2-bis(trimethylsilyl)cyclohexane is at least 1.26 kcal mol^{-1} (1 cal = 4.184 J) lower in steric energy than the diequatorial form, and this is supported by NOED spectra, magnitudes of *vic*-^{1}H–^{1}H spin coupling constants, and low temperature (190 K) ^{13}C NMR spectroscopic measurements, which place the free energy difference between 1.5 and 1.7 kcal mol^{-1}.

Empirical forcefield calculations have been applied to certain organosilanes[1] and reproduce with good precision such fundamental quantities as the conformational *A* values of SiH_3[2] and $SiMe_3$[3] in cyclohexyl derivatives ($A = -\Delta G^\circ = RT \ln K$ for the axial $\rightleftharpoons$ equatorial equilibrium). Cartledge has reported[1b] calculations (MM2-82) on a variety of silylcyclohexanes, and the consequences of placing two 'bulky' Me_3Si groups [$A(SiMe_3) = 2.5 \pm 0.1$ kcal mol^{-1}][3] on adjacent carbons in cyclohexane were explored. These computations indicated that the diequatorial conformer **1e** of *trans*-1,2-bis(trimethylsilyl)cyclohexane (*trans*-BTMSC) **1** was of higher steric energy by 1.70 kcal mol^{-1} than the diaxial form **1a** with *cis*-1,2-bis(trimethylsilyl)cyclohexane **2** slightly higher still.



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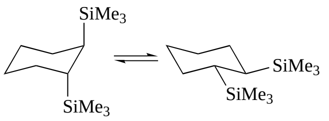
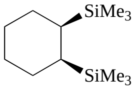


1a **1e**



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In view of our joint interest[1b,4] in these matters, we report the MM3(92) calculations for **1** and **2** and NMR investigations that confirm the predominance of **1a** in the **1a** $\rightleftharpoons$ **1e** equilibrium. Disilyl isomers **1** and **2** were originally described by Eaborn[5] who very reasonably assigned *cis* stereochemistry to the isomer with a temperature-dependent ^{1}H NMR spectrum, and conformation **1e** to the *trans* isomer, with a temperature-invariant spectrum. Isomers **1** and **2** have been re-synthesised by reduction of 1,2-bis(trimethylsilyl)benzene with lithium in ethylamine or propylamine, followed by gas-chromatographic separation[5] of the isomers.

Computations

We have re-examined this system using the more recent MM3(92) program. MM3-calculated geometries and relative energies for some model alkylsilanes were compared with experimental values and values from *ab initio* calculations[6] (using 6-31G* geometries and MP3//6-31G* energies). These indicated that some modification of the MM3 silicon parameters was necessary. The standard MM3 parameters set provided a geometry for the *anti* conformation of 1,2-disilylethane in excellent agreement with the *ab initio* geometry, but the MM3-calculated C–C–Si bond angles for the *gauche* and eclipsed conformers of this compound were significantly smaller than the corresponding *ab initio* values, and their conformational energies (relative to the *anti* conformer) were much too small (in comparison with the MP3//6-31G* energy differences). These discrepancies could not be attributed to the C–C–Si bending term, because MM3 provided excellent geometries for a wide range of structures containing a single silicon, especially where the C–C–C–Si framework was in an *anti* arrangement; it appeared that the repulsive interactions between proximate silyl groups were significantly underestimated by MM3. By making small increases in both the van der Waals radius and the hardness parameter (ε) for silicon, we were able to obtain a much better match between the MM3 and *ab initio* geometries and relative energies for all three conformations of 1,2-disilylethane. The torsional parameters for the Si–C–C–Si system (type 19–1–1–19) were adjusted to reproduce the *ab initio* value (70°) for the Si–C–C–Si torsional angle in the *gauche* conformer. In addition, a slightly modified V3 torsional parameter for C–C–C–Si was employed so that the conformational energy for the eclipsed form of propylsilane was in better agreement with the *ab initio* value, without upsetting the excellent fit between calculation and experiment for the *gauche* conformational energy (0.6–0.65 kcal mol^{-1}).[7] Finally, a small negative V2 torsional term was included for the C–Si–C–C system to match the experimental conformational profile for ethylmethylsilane.[8] This new value provided a calculated conformational energy for 1-methylsilacyclohexane of −0.28 kcal mol^{-1}, in reasonable agreement with the experimental value of −0.34 kcal mol^{-1}.[9] The modified parameters are shown in Table 1. MM3 calculations with the modified parameter set show diaxial *trans*-1,2-bis(trimethylsilyl)cyclohexane **1a** (steric energy 12.49 kcal mol^{-1}) has a lower enthalpy than the diequatorial conformer **1e** (steric energy 13.75 kcal mol^{-1}) by 1.26 kcal mol^{-1}. In both conformations, the trimethylsilyl groups are twisted away from perfectly staggered arrangements, and examination of the steric energy changes for rotation of one of the trimethylsilyl (TMS) groups (using the driver option of MM3) shows that the diaxial trimethylsilyl groups lie in a very shallow potential well, while the corresponding energy curve for the diequatorial form is quite sharply defined (Fig. 1). Consequently, the diaxial form **1a** has a wider range of accessible TMS rotamers (*i.e.* lower entropy) than the diequatorial form **1e**; Boltzmann distribution calculations based on the potential

Table 1 Modified MM3 parameters

van der Waals Type	ε	r_0	
19	0.18(1)	2.35	
Torsional Atom types	V1	V2	V3
1–1–1–19	0	0	0.45
1–1–19–1	0	−0.2	0.167
19–1–1–19	0.34	0.18	0.67

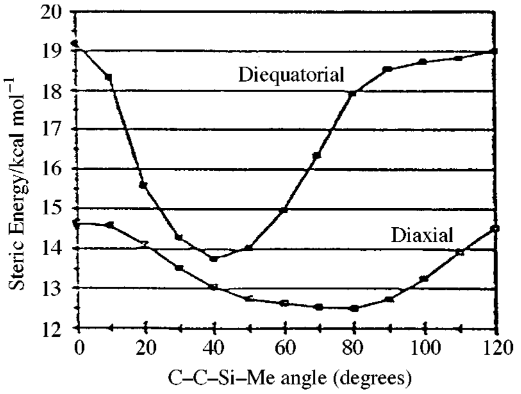


Fig. 1 Rotation potentials and modified MM3 parameters for **1a** and **1e**

energy curves shown in Fig. 1 indicate that **1a** comprises approximately 95% of the conformational equilibrium at 300 K, corresponding to an overall free energy difference of *ca.* 1.7 kcal mol^{-1}. This value is coincidentally the same as the steric energy difference found in the earlier MM2 study[1b] in which no entropic factors were considered.

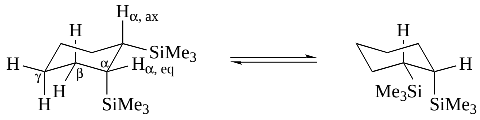
The *cis* isomer **2** (steric energy 13.89 kcal mol^{-1}) is calculated to be slightly higher in energy than the *trans*-diequatorial conformer **1e**, but the *trans*-twist-boat form is significantly higher (14.96 kcal mol^{-1}). Even though the C–Si bond is considerably longer (1.9 Å) than a C–C bond (1.54 Å), there are still significant steric interactions between the axial TMS groups and the ring in the distorted chair conformation of the *trans*-isomer. This causes the C–Si bonds to bend away (Si–C–C–Si torsional angle 144°), with consequent flattening of the corresponding portion of the ring. The diequatorial chair conformation calculated to have the next lowest energy (+1.26 kcal mol^{-1}) incorporates major steric interaction between the TMS groups, which twist away from each other (Si–C–C–Si torsional angle of 63°) again causing flattening of the nearby section of the ring. Analysis of the calculated van der Waals interactions for these two conformations **1a** and **1e** shows that the most significant difference reflects interactions between the TMS groups; in the diequatorial case, there is a substantial destabilising interaction (*ca.* 0.7 kcal mol^{-1}), while in the diaxial case, the interaction is stabilising (*ca.* 1.1 kcal mol^{-1}), because there are now a large number of interactions which fall into the attractive region of the van der Waals effect (at relatively large interatomic distances). This stabilising interaction is only partly offset by the effect of placing the bulky TMS groups in axial positions.

In the case of the analogous *trans*-1,2-di-*tert*-butylcyclohexane, the twist-boat form is calculated to be only slightly higher in energy than the diaxial form (*ca.* 0.5 kcal mol^{-1}), and is detectable in solution by NMR methods.[10] The diequatorial conformer is much higher in energy (*ca.* 6.2 kcal mol^{-1} higher than the diaxial), and is not observable. The calculated van der Waals interactions indicate that the repulsive interaction between diequatorial *tert*-butyl groups is larger than for TMS groups (because the shorter C–C bonds place the *tert*-butyl groups closer together), and the interaction between diaxial *tert*-butyl groups is less stabilising (because fewer pairs of atoms fall into the attractive van der Waals region).

NMR spectroscopy

cis-1,2-Bis(trimethylsilyl)cyclohexane: *cis*-BTMSC 2

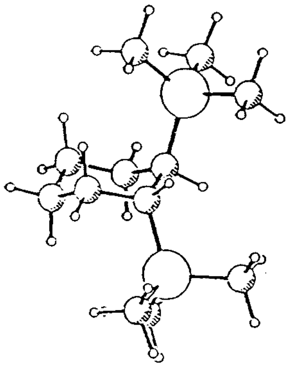
The ^1H and ^{13}C NMR data[11] for ambient probe temperature (295 K) (at which temperature **2** is presumably rapidly executing chair–chair reversal) and at lower temperature (220 K) are summarised below. These assignments are based on ^1H–^1H and ^{13}C–^1H COSY spectra and homo-decoupling experiments. (The symbols α, β, γ indicate proximity to a Me_3Si group.) *J* values are in Hz.



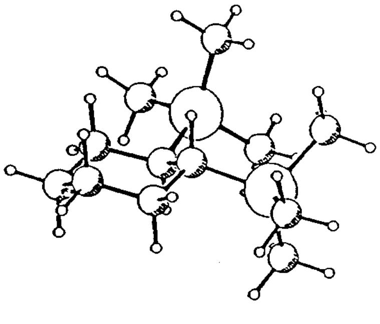
295 K. δ_H +0.06 (Me_3Si); 1.09 (2H, *J* 2.9, 5.5, H_α); 1.45 (2H, H_γ); 1.53 (2H, H_β); 1.59 (2H, H_γ); 1.70 (2H, H_β). δ_C 0.3 (Me_3Si); 27.55 (C_γ); 29.66 (br, C_α and C_β).

223 K. δ_H −0.13, −0.03 (2 × Me_3Si); 0.82 ($H_{\alpha,ax}$, *J* 12.36), 1.03 ($H_{\alpha,eq}$, br s); 1.13–1.25 (4 axial H), 1.45 (overlapping doublets, 2 equatorial H), 1.64 (d, *J* 11.3, 1 equatorial H), 1.82 (d, *J* 12.2, 1 equatorial H). (The smaller equatorial–equatorial and axial–equatorial couplings were not well-resolved in the 223 K spectrum). δ_C −2.59, 1.31 (Me_3Si); 24.1, 24.5, 24.6, 28.4, 31.0, 32.6. (Above data for both temperatures for CD_2Cl_2 solution at 500 MHz. Referenced to solvent resonances at δ_C 54.2 and δ_H 5.32.)

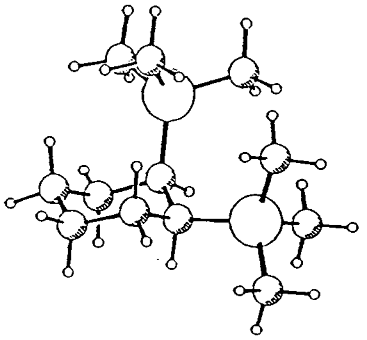
The data at 223 K confirm the equilibrium is being observed under slow-exchange conditions, with all of the expected eight ^{13}C signals being resolved. The *vic*-coupling constants for H_α (to H_β) (calculated from the MM3-minimised structures) are *J* 3.35 and 7.7 for the 295 K spectrum (rapid chair reversal) and *J* 13.4,



1a



1e



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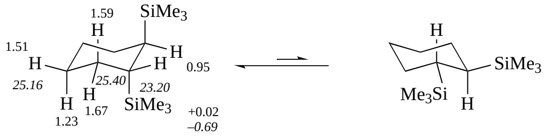
2.1 for $H_{\alpha,ax}$ and J 4.6, 2.0 for $H_{\alpha,eq}$ for the 223 K spectrum (slow chair reversal). The experimental values capable of measurement are in reasonable agreement. The Me_3Si signals coalesce at 236 K, and using $k_c = \pi(\nu_1 - \nu_2)/\sqrt{2}$, a value of $\Delta G^{\ddagger} = 12.0$ kcal mol^{-1} can be calculated for the ring reversal, somewhat higher than that for cyclohexane (10.3 kcal mol^{-1}).[12] This could reflect the proximity of the Me_3Si groups during chair reversal, as $\Delta G^{\ddagger} = 16.3 \pm 0.3$ kcal mol^{-1} has been determined for *cis*-1,2-di-*tert*-butylcyclohexane.[13]

trans-1,2-Bis(trimethylsilyl)cyclohexane: *trans*-BTMSC 1

The ^1H and ^{13}C NMR spectra exhibited only slight changes over the range 295 to 220 K, indicating a very predominant conformer in the equilibrium. The MM3 computed difference in steric energy between **1a** and **1e** (1.26 kcal mol^{-1}) would mean a 90 : 10 ratio at 295 K, but an even more lopsided ratio at lower temperatures (*ca.* 95 : 5 at 223 K).

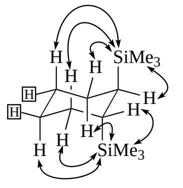


1a **1e**

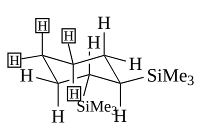
300 K. δ_H 0.02 (Me_3Si) and five multiplets centred at 0.95; 1.23; 1.51; 1.59; 1.67. δ_C −0.69 (Me_3Si); 23.20 (C_α); 25.16 and 25.40 (C_β, C_γ) (DEPT). [500 MHz; $CDCl_3$ solvent. Referenced to δ_C 77.00 ($CDCl_3$) and δ_H 7.24, for residual $CHCl_3$.]

On the basis of DEPT, ^1H–^1H, ^1H–^{13}C COSY and decoupling experiments (500 MHz), the ^{13}C and ^1H spectra were assigned as shown above on **1a**. These experiments provide the following specific data: (*i*) irradiation at δ 1.51 removed a small coupling from the H_α signal at δ 0.95, indicating the latter is equatorial, to complete the 'w' array as shown on **1a**. This coupling was also evident in the ^1H–^1H COSY spectrum. (*ii*) Decoupling at δ 1.67 reduced the H_α signal to a doublet (br) with $J_{\alpha\text{-}\beta ax}$ 5.65, and the same type of experiments led to estimates of $J_{\alpha\text{-}\beta eq}$ *ca.* 1.2–1.4 Hz. ECOSY spectra[14] (parameterised using 2,3-dibromopropionic acid) provided slightly smaller values, *viz.* $J_{\alpha\text{-}\beta ax}$ 4.87 and $J_{\alpha\text{-}\beta eq}$ 0.98. Values for these coupling constants calculated[15] from the MM3 structure for **1a** (with torsion angles H_α–C–C–$H_{\beta ax} = 46°$ and H_α–C–C–$H_{\beta eq} = 69°$) are J 5.6 and 1.4, in excellent agreement with the measured values. However, the calculated values for the diequatorial conformers **1e** (J 13.4 and 3.2) and the twist-boat form (J 7.5 and 4.8) are in very poor agreement. With respect to ^{13}C chemical shifts, there is a general shielding trend on going from the *cis* to the *trans* isomer, and this is explicable by a combination of the (shielding) γ-*gauche* effect from an axial $SiMe_3$ group,[2] and the proposal that *anti*-vicinal hydrogens have a deshielding effect on each of the carbon atoms in the H–C–C–H array.[16]

Although the above data appear to require that the predominant conformer of *trans*-BTMSC is the diaxial form **1a**, confirmatory evidence is provided by an NOED spectrum. Irradiation of the Me_3Si signal shows positive NOE effects to all ring hydrogens except to $H_{\gamma\text{-}eq}$ (at δ 1.51) (see Fig. 2). This is anticipated for the diaxial form **1a**, but not for **1e**, as shown below. (Boxed hydrogens are anticipated to exhibit *no* NOE effect.)



1a



1e

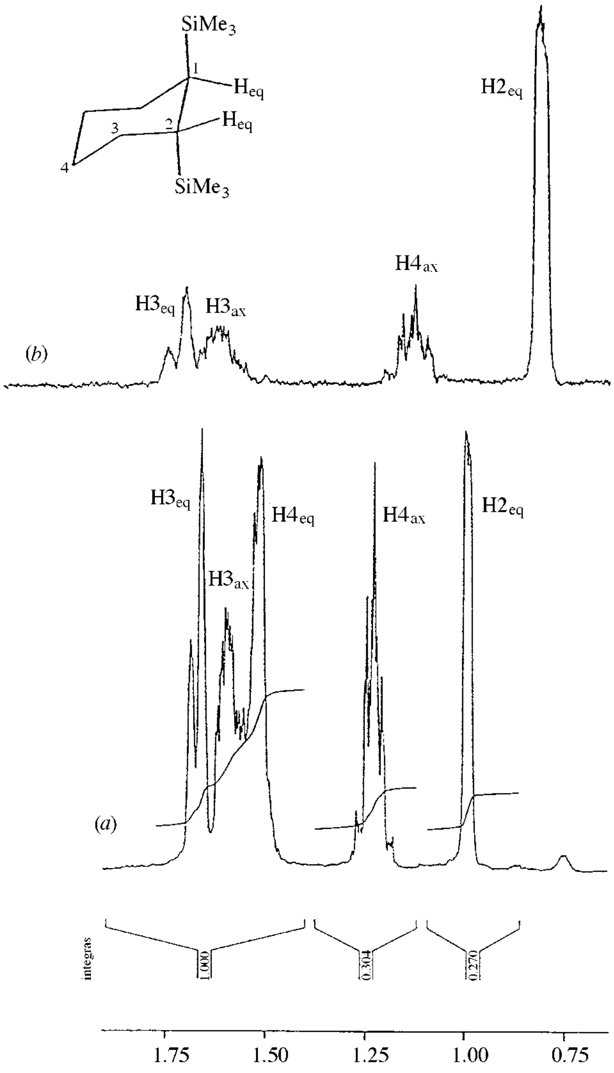
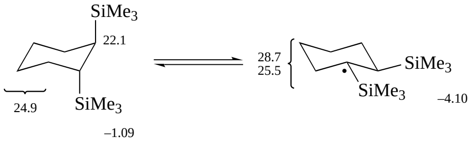


Fig. 2 (*a*) The 500 MHz ^1H NMR spectrum of *trans*-1,2-bis(trimethylsilyl)cyclohexane **1** at *ca.* 300 K. [The $(CH_3)_3Si$ resonance has been omitted.] Solvent, $CDCl_3$. (*b*) The difference NOE spectrum of **1**, with irradiation of the $(CH_3)_3Si$ signal (400 MHz, $CDCl_3$ solvent). There is a positive NOE effect to all ring hydrogens except $H4_{eq}$.

Low-temperature ^1H and ^{13}C NMR spectra of *trans*-isomer **1** were obtained and in the 125.7 MHz ^{13}C spectrum at *ca.* 190 K (CD_2Cl_2 solvent), minor signals are present which are confidently assigned to diequatorial conformer **1e**. Signal changes were reversible with temperature, and the assignments are shown below. (Relative to the central signal of CD_2Cl_2 at δ 54.2.) Based on data for a series of 4-substituted cyclohexyltrimethylsilanes,[3] axial-$SiMe_3$ groups are less shielded (in the ^{13}C spectrum) than corresponding equatorial-$SiMe_3$ (*ca.* δ −0.3 *vs.* −3.60) and the low temperature data for the *cis*-isomer **2** exhibit shifts of δ −2.59 and +1.31 for the equatorial and axial groups, so that a consistent difference of *ca.* 3.60 ppm appears to apply. It is also to be noted that ring carbon shifts are more shielded in **1a** than **1e**, presumably reflecting the operation of the γ-*gauche* effect of the silicon group[2] and other contributions outlined earlier. Estimates of the relative amounts of **1a**



• Uncertain

1a **1e**

and **1e** were aided by the presence of the satellite signals associated with ^{29}Si (I $\frac{1}{2}$, 4.7% natural abundance) [J (^{29}Si–^{13}C) 49], so that comparisons between signals of similar intensities were possible, *i.e.* the δ −4.10 signal ascribable to Me_3Si in the minor **1e** and the high-field satellite about the Me_3Si signal of the heavily predominant **1a**. The **1a**/**1e** equilibrium constant was estimated to lie in the range 70–80, leading to a free-energy difference between 1.50 and 1.70 kcal mol^{-1}. This value is in very good agreement with the computed values.

Consequently, the experimental and computational approaches are harmonious in that the diaxial conformer of *trans*-BTMSC **1a** is of significantly lower steric energy than **1e**, and provides support for the parametrisation utilised for these silicon compounds, and confidence for extensions to derivatives of other Group 14 congeners. The original conclusion[4] that 3,4-bis(trimethylsilyl)cyclohexene was stereospecifically hydrogenated is probably correct, but this work requires that both isomers were *trans*, and not *cis*.

Experimental

Compounds

trans- and *cis*-1,2-Bis(trimethylsilyl)cyclohexanes **1** and **2**, respectively, were prepared as described by Eaborn[5] and separated by preparative gas chromatography. The ^{1}H and ^{13}C NMR spectra[11] are in agreement with the assigned structures.

Computations

Ab initio calculations were carried out on a DEC Station 500 computer using GAUSSIAN90. Optimised geometries were obtained at the 6-31G* level, and energies were obtained using single point calculations on these geometries at the MP3 level. Molecular mechanics calculations were performed using MM3(92), utilising the modified silicon parameters shown in Table 1. Rotational potential energy profiles for rotation of trimethylsilyl groups were obtained using the DRIVER option in MM3 for rotation of a single trimethylsilyl group about the C−Si bond in 10° steps.

NMR spectroscopy

^{1}H and ^{13}C NMR spectra were recorded on a Bruker AMX-500, a Bruker AMX-400 or a JEOL GX-400 spectrometer, with ^{1}H chemical shifts relative to residual $CHCl_3$ (δ 7.24) or residual $CHDCl_2$ (δ 5.32), and ^{13}C shifts relative to the central signal of the $^{13}CDCl_3$ triplet (δ 77.00) or CD_2Cl_2 quintet (δ 54.2). 2D NMR spectra were recorded with either a Bruker AMX-500 or a Bruker DRX-500 spectrometer, using supplied software.

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