APPLICATION OF ^{29}Si-NMR TO ANALYSIS OF SILYLATED COMPOUNDS. NMR SPECTRA OF $(CH_3)_3Si—O—C$ DERIVATIVES

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^{29}Si and ^{13}C-NMR spectra of a series of compounds containing $(CH_3)_3Si—O—C$ fragment are presented. It is shown that the ^{29}Si chemical shift varies more in this type of compounds than in compounds with $(CH_3)_3SiC$ (sp^3) fragment. The substituent effect of chlorine atom in $(CH_3)_3SiOCH_2Cl$ is diamagnetic.

The large sensitivity of $(CH_3)_3SiO$ silicon chemical shift to substitution can be analytically utilized when a compound is isolated or prepared as a silylated derivative. ^{29}Si-NMR would be especially helpfull in analysis of polyfunctional compounds such as polyols, hydroxy acids *etc.* Examples of ^{29}Si-NMR spectra of a silylated sugar and steroids illustrate this possibility.

The first few measurements[1,2] of silicon-29 NMR chemical shifts in compounds containing fragment $X—Si—O—(CH_2)_n—Y$ lead to the observation that effects of substituents on the silicon shielding are of the same sign as those on the shielding of carbon (C*) or nitrogen in fragments in which these atoms are multiple bonded *e.g.* in fragments.

$$C^*H_2 = CH—(CH_2)_n—Y \quad \text{and} \quad N—C—(CH_2)_n—Y \quad \text{or}$$

$$X—CH_2—C^*H = CH_2 \quad \text{and} \quad X—CH_2—NO_2 .$$

If this qualitative similarity of NMR behaviour has its origin in a similarity in the bonding situations it could be anticipated that silicon would be more susceptible to substituent effect in $(CH_3)_3Si—O—(CH_2)_n—Y$ compounds than it is in $(CH_3)_3Si—(CH_2)_{n+1}—Y$ compounds. The existing theories of silicon shielding[3,4] which were not, however, aimed at predicting effects of remote substituents, would predict approximately the same sensitivity in both types of compounds.

Therefore, it is desirable to provide more data that would permit a quantitative comparison of the substituent effects on silicon shielding in these groups and also get the first data on $(CH_3)_{3-n}Cl_nSiO(CH_2)_mY$ compounds.

For practical reasons the results of this study are published in two separate communications. Since the present results demonstrate considerable sensitivity of silicon shielding to the nature of substituent Y in $Si—O—(CH_2)_m—Y$ grouping, we are

concerned, in this paper, with the practical utilization of this sensitivity in structure determination of silylated compounds. In the subsequent paper[5] the other aspects of the results will be discussed.

EXPERIMENTAL

Compounds

With the exception of chloromethoxytrimethylsilane, which was kindly donated to us by Prof. Mironov, all the compounds of the type $(CH_3)_3SiO(CH_2)_mY$ were prepared as described elsewhere[6], preparation of other studied compounds will be published later. 1,6-anhydro-2,3,4-tri--O-trimethylsilyl-β-D-glucopyranose (b.p. 162°C/10 Torr) was prepared from 1,6-anhydro-β-D--glucopyranose by the standard silylation technique[7,8]. ^{1}H-NMR proved[9] that this compound adopts a conformation very close to the boat form. The steroids and polyols were silylated similarly, silylated *d*-sorbitol and dulcitol distilled at 220°C/3 Torr and 220°C/3 Torr, resp.

NMR *Measurements*

The spectra were measured in the FT mode on a JEOL-PFT-100 spectrometer interfaced to a Nicolet 1085 data system. ^{29}Si-NMR spectra were recorded at 19·87 MHz in neat compounds using 8k memory for FID and 2000 Hz sweep width. The spectrometer was locked to ^{19}F-NMR signal of C_6F_6 in a capillary. The spectra were referenced to tetramethylsilane (TMS) in a separate sample. The values given in the Tables were obtained with proton decoupling, which might lower, due to the negative Overhauser enhancement, signal to noise ratio in the studied compounds. The data for the silylated steroids were obtained using the gated noise decoupling technique. (According to another study[10], in $(CH_3)_3SiOR$ compounds the gain in intensity due to a collapse of multiplet structure overweights the decrease caused by the negative NOE.) ^{13}C-NMR spectra were recorded at 25·15 MHz using 8k memory for FID and 3500 Hz sweep width. The spectra were measured in neat compounds to which 10% of deuteriochloroform was added in order to provide a lock signal. Additional 2—5% of hexamethyldisiloxane (HMDS) served as an internal reference compound.

RESULTS AND DISCUSSION

Silicon-29 NMR chemical shifts of the studied compounds are summarized in Tables I and II. For the purpose of comparison, included are also literature values for some model compounds which were obtained under similar conditions though by different measuring technique[5,11]. Carbon-13 chemical shifts which were not of our primary interest were included for the sake of completeness and future use. The observed trends in ^{13}C chemical shifts in the studied series of compounds are in agreement with the trends expected on the basis of known substituent effects.

The data of Table I demonstrate the effects of successive chlorine substitution ($R = CH_2CH_3$, CH_2CH_2Cl, CH_2CHCl_2, CH_2CCl_3), of chain length ($R = CH_2$. .CH_2OCH_3, $CH_2CH_2CH_2OCH_3$) and branching ($R = CH_3$, CH_2CH_3, $CH(CH_3)_2$). These and other trends can be generally described by the noted dependence of silicon

shielding on Taft polar substituent constant[6] in compounds of this type. Such dependence is in agreement with the two mentioned theories[3,4] as well as with the assumption of a multiple bonding between silicon and oxygen. In chloromethoxytrimethylsilane the silicon nucleus is shielded more than it is in methoxytrimethylsilane. Such substituent effect of chlorine is not well understood and is not in accord with the mentioned theoretical approaches. Its origin is discussed in detail elsewhere[5,6].

Above all, the data of Table I convincingly show that the silicon shielding is much more sensitive to substituent effects in $(CH_3)_3Si—O—R$ than it is in $(CH_3)_3Si—R$ (not to mention $(CH_3)_3Si—CH_2—R$) compounds. (Naturally we consider here only substituents R which have sp^3 carbon as the first atom and not those which differ in the nature or hybridization of their β atoms as would be the case of comparing tetramethylsilane with trimethylvinyl- or phenylsilane.) The range of chemical shifts of silicon-29 in $(CH_3)_3SiO$ derivatives studied here covers some 10 p.p.m. (or 15 p.p.m. if $(CH_3)_3SiOCH_2Cl$ is included into consideration). This is quite remarkable variation considering the substituents involved. Data of Table II suggest that this sensitivity is reduced if the methyl groups on the silicon atom are replaced by chlorine atoms.

Since trimethylsiloxy (TMSO) groups are easily introduced to and removed

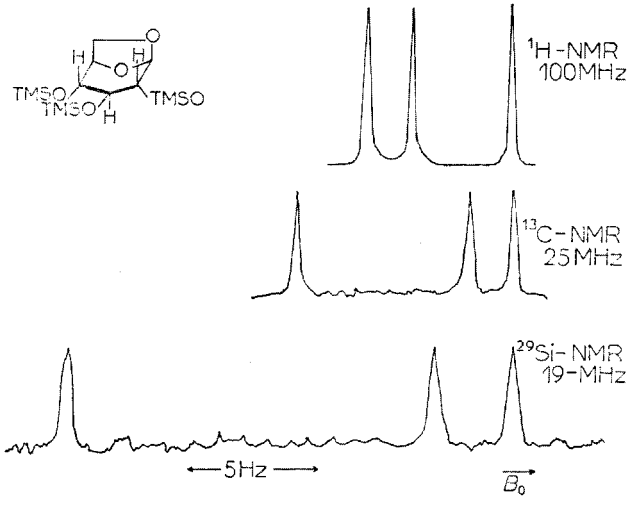


FIG. 1

NMR Spectra of 1,6-Anhydro-2,3,4-tri-O-trimethylsilyl-β-D-glucopyranose in the Field of 2·35 T

	Chemical shifts in δ scale		
^{1}H-NMR	0·38	0·37	0·33
^{13}C-NMR	0·13	−0·13	−0·20
^{29}Si-NMR	18·31	17·60	17·45

TABLE I

^{13}C-NMR Chemical Shifts in Compounds of the Type $(CH_3)_3SiOR$ and ^{29}Si-NMR Chemical Shifts in Compounds of the Types $(CH_3)_3SiOR$, $(CH_3)_3SiCH_2R$, and $(CH_3)_3SiR$[a]

R	$\delta(^{13}C^*)$			$\delta(^{29}Si)$		
	$^*CH_3Si$	O—C*	OC—C*	$(CH_3)_3SiOR$	$(CH_3)_3SiCH_2R$[b]	$(CH_3)_3SiR$[b]
CH_2CH_3[c]	−1·8	56·5	17·3	13·5	0·7	1·6
CH_2CH_2Cl	−0·51	63·16	44·89	18·36	1·5	−0·4
CH_2CHCl_2	−0·48	69·25	72·05	20·65		
CH_2CCl_3	−0·36	76·12	98·84	21·75		
CH_2CH_2Br	−0·45	62·96	32·76	18·29	2·0[d]	
$CH_2CH_2OCH_3$	−0·39	62·14	74·28[e]	16·25	0·4	−0·1
$CH_2CH_2CH_2OCH_3$	−0·57	69·22	33·05[f]	15·53		0·4
CH_3[g]	−1·9	48·9	—	17·2	1·6	0·00
$CH(CH_3)_2$	0·15	64·69	25·91	12·12		
$C(CH_3)_3$	2·58	71·91	32·11	[h]		
CH_2Cl	1·91	76·29	—	6·81	−0·4	1·7[i]
$CH_2CH{=}CH_2$	−0·41	63·55	137·57[j]	16·59	1·0	−0·4
$CH_2C_6H_5$	−0·46	64·42	140·92[k]	17·40	1·1	0·4
C_6H_5	0·16	155·06[l]	129·37[l]	19·62	0·4	−5·1
$CH{=}CH_2$						−7·6
$CH_2CH_2CH_2C(CH_3)_3$	−0·48	63·37	28·14[m]	14·69		
$CH_2CH_2C(CH_3)_3$				15·60[n]		

[a] All the chemical shifts are in δ scale (*i.e.* in p.p.m. relative to TMS, paramagnetic shifts are positive). Approximate error ±0·10 p.p.m.; [b] data of ref[11].; [c] data of ref.[5]; [d] data of ref.[12]; [e] $\delta(O^*CH_3) = 58{\cdot}66$; [f] $\delta(O^*CH_3) = 58{\cdot}31$, $\delta(CH_3O^*C) = 59{\cdot}28$; [g] data of ref.[13]; [h] value apparently in error; [i] data of ref.[14]; [j] $\delta(^*CH_3{=}C) = 113{\cdot}88$; [k] other aromatic carbons; δ(C *ortho*) = 128·10, δ(C *meta*) = 126·31, and δ(C *para*) = 126·94; [l] other aromatic carbons: δ(C *meta*) = 120·05 and δ(C *para*) = 121·41; [m] $\delta(OCC^*CH_2) = 40{\cdot}12$, $\delta(C^*C(C)_3) = 30{\cdot}01$, and $\delta(^*CH_3C) = +9{\cdot}42$; [n] 30% (v/v) solution in CCl_4.

from a molecule and lend sometimes favourable properties to the compounds, silylation is frequently used in analysis of organic materials (foodstuffs, pharmaceuticals, *etc.*), in separation of natural products, and through organic syntheses[7]. Compounds containing this group are therefore often reported[15]. Though there are problems with their identification by means of ^{1}H-NMR (due to a small variation in H_3CSi proton chemical shifts) ^{29}Si-NMR has not yet been used for such a purpose.

The above demonstrated sensitivity of silicon-29 shift to the nature of substituent R in the compounds of $(CH_3)_3SiOR$ type suggests that measuring ^{29}Si-NMR spectra might be fruitful for identification or analysis of the silylated compounds, especially in the case of polyfunctional compounds which yield polysilylated products in silylation reactions. According to the above results a number of different silicon nuclei should be seen in ^{29}Si-NMR spectrum of such a polysilylated product. Depending on the silylation procedure used, the number of different ^{29}Si signals would indicate directly the number of different functional groups or the number of different positions in which these groups occur in the molecule.

The feasibility of such an approach is illustrated on Fig. 1 where the NMR spectra of $(CH_3)_3SiO$ region of 1,6-anhydro-2,3,4-tri-O-trimethylsilyl-β-D-glucopyranose are shown. Though, in this particular case in which all three trimethylsiloxy groups assume practically equatorial positions, ^{1}H- and ^{13}C-NMR spectra also indicate the presence of three different trimethylsiloxy groups in the molecule, the three groups are differentiated best in ^{29}Si-NMR spectrum. This is not only the trivial consequence of the fact that ^{29}Si nuclei are much nearer the site of differentiation than ^{1}H or ^{13}C nuclei of the trimethylsiloxy group. Silicon atom attached directly to the site of differentiation (carbon atom) would be very little sensitive to the sub-

TABLE II

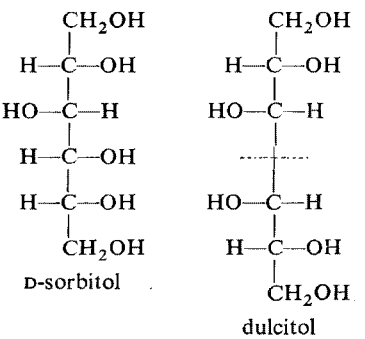
^{13}C and ^{29}Si-NMR Chemical Shifts in Compounds of the Type $(CH_3)_{3-n}Cl_nSiOR$, where $R = CH_2CH_3$ and CH_2CCl_3[a]

	$R = CH_2CH_3$				$R = CH_2CCl_3$			
	$\delta(^{13}C)$			$\delta(^{29}Si)$	$\delta(^{13}C)$			$\delta(^{29}Si)$
n	CH_3Si	CH_2	CH_3C		CH_3Si	CH_2	CCl_3	
0[b]	−1·8	56·5	17·3	13·5	−0·36	76·12	98·84	21·75
1	1·85	58·84	17·84	12·18	2·11	75·53	97·58	17·22
2	4·31	60·36	17·49	−10·71	4·20	75·40	96·38	−7·22
3	—	62·52	17·26	−38·34[c]	—	76·42	95·50	−36·43[c]

[a] All the chemical shifts are in δ scale. Approximate error ±0·10 p.p.m.; [b] data of Table I; [c] 30% (v/v) solution in CCl_4.

stituent effects. Apparently, if a further effort can be invested in the structure determination of a given compound it can be converted to other derivative or/and it can be more conveniently analysed by NMR of some other nucleus (*e.g.* a sugar can be converted into a permethylated compound in which ^{13}C chemical shift of H_3CO would vary over several p.p.m.[16]). But in cases when a compound is prepared or isolated as a trimethylsiloxy derivative it will be informative and worthwhile to measure its ^{29}Si-NMR spectrum. The information obtained from such spectra (number and intensity of the signals) would be worth the extra effort even if the spectra are left unassigned.

An example to demonstrate this point is provided by ^{29}Si-NMR spectra of hexakis--O-trimethylsilyl-D-sorbitol and hexakis-O-trimethylsilyl dulcitol. The spectrum of the former compound (signals at δ = 16·68, 16·14, 16·14, 15·91, and 15·62 have unit intensity, signal at δ = 16·34 has double intensity) is indicative of the presence of five types of different silicon atoms of which one has double population than the others. In accord with the symmetrical structure of dulcitol

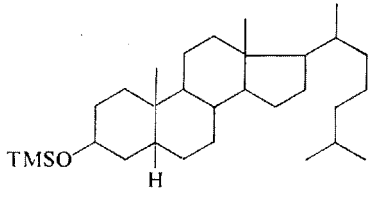


the spectrum of its hexakis(trimethylsilyl) derivative shows only three lines (at δ = = 16·67, 15·90, and 15·20).

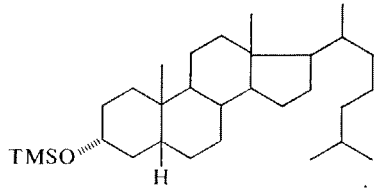
The estimate of the potential of ^{29}Si-NMR for such analytical purposes as provided by the above examples is rather conservative. All the trimethylsiloxy groups present in the molecules (except for the end groups) are bonded to secondary carbon atoms which all bear oxygen and carbon atoms. They all differ only stereochemically and in substitution several bonds away from the silicon. With the compounds in which silylation occurs on atoms of different nature and/or with different substituents the difference in silicon chemical shifts will be larger.

In order to test further the limits of the proposed method the silicon chemical shifts were measured in trimethylsiloxy derivatives of four steroids. Whether the difference in the chemical shifts can be utilized to stereochemical determinations is not yet clear, but since of the four compounds three differ only stereochemically

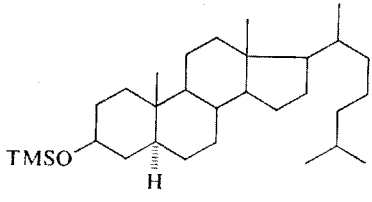
and still exhibit quite different chemical shifts, the functional groups differing only in their stereochemical positions would lead to different ^{29}Si-NMR signals.



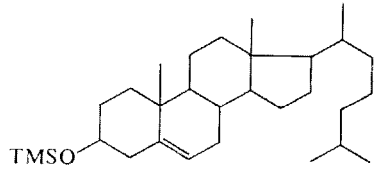
3β 5β
δ(Si) = 13.89



3α 5β
δ(Si) = 16.18



3β 5α
δ(Si) = 15.85



δ(Si) = 13.32

TMS = trimethylsilyl

The high field shift observed in the 3β 5β compound, in which the trimethylsiloxy groups is in axial position and A and B rings are in *cis* arrangement, can be caused by a steric interaction of the trimethylsiloxy groups with the steroid skeleton. Such interaction is much weaker in 3α 5β and 3β 5α steroids possessing equatorial trimethylsiloxy groups. Similar steric effects were found[17] in ^{13}C-NMR spectra of other related steroids.

These examples prove that measuring ^{29}Si-NMR spectra of silylated products could bring useful information about the structure of the compound. Measuring of such spectra is especially advisable when the compound is prepared as a silylated derivative and in sufficient quantity.

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