Stereochemistry of Asymmetric Silicon. X. Solvent and Reagent Effects on Stereochemistry Crossover in Alkoxy–Alkoxy Exchange Reactions at Silicon Centers[1,2]

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Abstract: Alkoxy–alkoxy exchange reactions of optically active R_3Si^*OR' with alkali metal alkoxides $R''OM$ (M = Li, Na, K) are reported. These stereochemical results show that stereochemical variation (per cent retention *vs.* per cent inversion) and stereochemical crossover (from retention to inversion and *vice versa*) are a sensitive function of the alcoholic content of the solvent and the nature of the cation. The relationships that are revealed are consistent with our earlier conclusions and strongly support the reality of a quasicyclic SNi–Si mechanism for retention reactions of asymmetric silicon in R_3Si^*X compounds.

Previous papers in this series on the stereochemistry of substitution at optically active silicon centers[1,3–10] reported initial results for compounds containing the α-naphthylphenylmethylsilyl group, α-NpPhMeSi*–, designated R_3Si^*– below, and having the following leaving groups: alkoxy and siloxy;[4,7] carboxylate and tosylate;[5] halogen (F, Cl, and Br).[1,3–7,9,10] Comparison of these results with those obtained for RPhMeSi*X in which R = neopentyl, benzhydryl, or ethyl showed that the stereochemical results obtained with the original system, α-NpPhMeSi*X, are generally applicable.[8]

For good leaving groups, X, whose conjugate acids, HX, have pK_a less than *ca.* 6, the *SN2-Si stereochemistry rule of inversion of configuration for good leaving groups, regardless of the nature of the reagent, was found to apply.*[6,11]

For poor leaving groups, X, whose conjugate acids, HX, have pK_a greater than *ca.* 10 the stereochemical path, inversion or retention of configuration, was found to depend upon the nature of the reagent. Poor leaving groups whose stereochemistry of displacement is reagent dependent include –OR,[4,7] –SR,[1] $-NR_2$,[10] and –F.[9,12]

In previous papers[1,4,7–10] and elsewhere[13] it was proposed that an observed retention stereochemistry for a poor leaving group usually reflects operation of mechanism SNi–Si.

In the present paper we report a series of new and systematic studies on the reactions of optically active alkoxysilanes, R_3Si^*OR'. These reveal that stereochemistry crossover (from retention to inversion, or *vice versa*) and stereochemistry variation (for example, decreased retention) are a sensitive function of the polarity of the solvent and the nature of the reagent. We believe that the present data strongly support our original mechanistic proposals.

In previous work it was found that the coupling reactions of organolithium reagents with R_3Si^*F and R_3Si^*OMe gave inversion of configuration when charge-delocalized reagents such as benzyllithium were used, whereas simple alkyllithium reagents gave retention of configuration with the same compounds.[7,9] These facts plus the finding by Eaborn, *et al.*, that optically active $R_3Si^*OCT_3$ reacts with methanol, in methanol solvent, to give $R_3Si^*OCH_3$ with pure inversion of configuration,[14] led us to the expectation, based on mechanistic reasoning concerning operation of SNi–Si,[13] that variation in solvent polarity would lead to stereochemical crossover in alkoxy–alkoxy exchange reactions of R_3Si^*OR'.

Syntheses and Stereochemical Correlations of Configuration. Three new optically active alkoxysilanes were used in the present studies: R_3Si^*OR', R′ = ethyl, *n*-butyl, and isopropyl.

Optically active ethoxysilane was prepared by two methods.

$$\underset{[\alpha]_D\ -34.4^\circ}{(-)\text{-}R_3Si^*H} \xrightarrow[(a)]{EtOH,\ Pd\text{-}C} \underset{[\alpha]_D\ +9.77^\circ}{(+)\text{-}R_3Si^*OEt} \xrightarrow[(b)]{LiAlH_4} \underset{[\alpha]_D\ +33.8^\circ}{(+)\text{-}R_3Si^*H} \quad (1)$$

$$\underset{[\alpha]_D\ -34.6^\circ}{(-)\text{-}R_3Si^*H} \xrightarrow[(a)]{Cl_2} (+)\text{-}R_3Si^*Cl \xrightarrow[(b)]{EtOH,\ Et_2NH} \underset{[\alpha]_D\ +7.65^\circ}{(+)\text{-}R_3Si^*OEt} \quad (2)$$

Assignment of inversion of configuration to (la) and retention of configuration to (1b) is in accord with previous studies of the stereochemistry of both classes of reactions.[4,15] These assignments are in harmony

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[1] For the preceding paper in this series, see: L. H. Sommer and J. McLick, *J. Amer. Chem. Soc.*, **89**, 5806 (1967).

[2] We are grateful to the National Science Foundation, Grant GP-5662, for support of this work.

[3] L. H. Sommer, C. L. Frye, G. A. Parker, and K. W. Michael, *J. Amer. Chem. Soc.*, **86**, 3271 (1964).

[4] L. H. Sommer, C. L. Frye, and G. A. Parker, *ibid.*, **86**, 3276 (1964).

[5] L. H. Sommer, G. A. Parker, and C. L. Frye, *ibid.*, **86**, 3280 (1964).

[6] L. H. Sommer, G. A. Parker, N. C. Lloyd, C. L. Frye, and K. W. Michael, *ibid.*, **89**, 857 (1967).

[7] L. H. Sommer, W. D. Korte, and P. G. Rodewald, *ibid.*, **89**, 862 (1967).

[8] L. H. Sommer, K. W. Michael, and W. D. Korte, *ibid.*, **89**, 868 (1967).

[9] L. H. Sommer and W. D. Korte, *ibid.*, **89**, 5802 (1967).

[10] L. H. Sommer and J. D. Citron, *ibid.*, **89**, 5797 (1967).

[11] L. H. Sommer, "Stereochemistry, Mechanism and Silicon," McGraw-Hill Book Co., Inc., New York, N. Y., 1965, pp 184–186.

[12] Despite the fact that the pK_a of HF places F in the category of good leaving groups, the high bond energy of Si–F (∼150 kcal/mol), the small size of F, and the capacity of F for coordination frequently cause F to behave like a poor leaving group.

[13] Reference 11, pp 56–66.

[14] R. Baker, R. W. Bott, C. Eaborn, and P. W. Jones, *J. Organometal. Chem.* (Amsterdam), **1**, 37 (1963).

with the known retention stereochemistry for (2a) and with an inversion course for (2b) based on the SN2-Si stereochemistry rule. Thus, reaction sequences 1 and 2 both lead to the conclusion that (+)-R_3Si^*H and (+)-R_3Si^*OEt have the same configuration.

Preparation and stereochemical correlations of configuration for the *n*-butoxy- and isopropoxysilanes were carried out in similar fashion. Based on reaction sequences 3-6 it is clear that (+)-R_3Si^*O-*n*-Bu and

$$\underset{[\alpha]\text{D}\ -34.4^\circ}{(-)\text{-}R_3Si^*H} \xrightarrow[\text{Pd-C}]{n\text{-BuOH}} \underset{[\alpha]\text{D}\ +8.43^\circ}{(+)\text{-}R_3Si^*O\text{-}n\text{-}Bu} \xrightarrow{\text{LiAlH}_4} \underset{[\alpha]\text{D}\ +33.6^\circ}{(+)\text{-}R_3Si^*H} \tag{3}$$

$$\underset{[\alpha]\text{D}\ -34.6^\circ}{(-)\text{-}R_3Si^*H} \xrightarrow{\text{Cl}_2} (+)\text{-}R_3Si^*Cl \xrightarrow[\text{Et}_2\text{NH}]{n\text{-BuOH}} \underset{[\alpha]\text{D}\ +8.12^\circ}{(+)\text{-}R_3Si^*O\text{-}n\text{-}Bu} \tag{4}$$

$$\underset{[\alpha]\text{D}\ -34.4^\circ}{(-)\text{-}R_3Si^*H} \xrightarrow[\text{Pd-C}]{i\text{-PrOH}} \underset{[\alpha]\text{D}\ -5.06^\circ}{(-)\text{-}R_3Si^*O\text{-}i\text{-}Pr} \xrightarrow{\text{LiAlH}_4} \underset{[\alpha]\text{D}\ +30.1^\circ}{(+)\text{-}R_3Si^*H} \tag{5}$$

$$\underset{[\alpha]\text{D}\ -34.6^\circ}{(-)\text{-}R_3Si^*H} \xrightarrow{\text{Cl}_2} (+)\text{-}R_3Si^*Cl \xrightarrow{i\text{-PrOLi}} \underset{[\alpha]\text{D}\ -3.65^\circ}{(-)\text{-}R_3Si^*O\text{-}i\text{-}Pr} \tag{6}$$

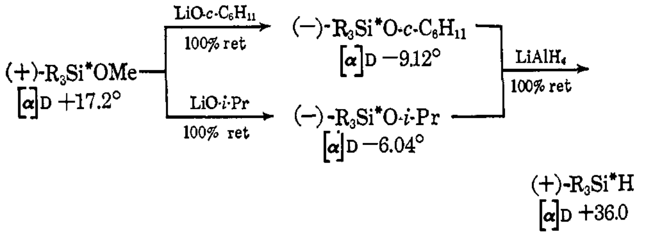
(−)-R_3Si^*O-*i*-Pr have the same configuration as (+)-R_3Si^*H.

Reaction sequences 1 and 3 show that both steps in each sequence are very stereospecific. In order to calculate the optical purity of the alkoxysilanes it is assumed that lithium aluminum hydride reduction is usually 100% stereospecific. Thus, on the basis of the rotation of optically pure R_3Si^*H, 36.0°, the values for the rotations of optically pure alkoxysilanes can be calculated. However, $LiAlH_4$ reduction of R_3Si^*OMe does not seem to be 100% stereospecific. The rotation of optically pure R_3Si^*OMe from the following reaction[4] is 19.1°.

$$\underset{[\alpha]\text{D}\ -15.7^\circ}{(-)\text{-}R_3Si^*OMe} \xrightarrow{\text{LiAlH}_4} \underset{[\alpha]\text{D}\ -30.0^\circ}{(-)\text{-}R_3Si^*H}$$

This seems to be too high in view of the fact that the highest rotation ever obtained for crystalline, presumably optically pure methoxysilane, was 17.2°. The stereospecificity of the reduction of methoxysilane with $LiAlH_4$ appears to be lower than 100%, which may reflect a lack of stereospecificity or a greater tendency to undergo racemization relative to the other alkoxysilanes.

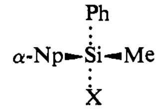
That the $LiAlH_4$ reduction of other alkoxysilanes is nearly 100% stereospecific and that optically pure methoxysilane has a specific rotation of around 17.2° are demonstrated by the following scheme.



The above scheme indicates that the stereospecificities of both the exchange reactions and the $LiAlH_4$ reductions are close to 100% and that optically pure methoxysilane has a rotation close to [α]D 17.2°.

The absolute configurations and specific rotations of optically pure alkoxysilanes dealt with in the present paper are presented in Table I.

Table I. α-NpPhMeSi*X Compounds Having the Configuration



Si*X	[α]D, deg, solvent	Si*X	[α]D, deg, solvent
(+)-Si*H	+36.0, pentane	(+)-Si*O-*n*-Bu	+9.0, pentane
(+)-Si*OMe	+17.2, pentane	(−)-Si*O-*i*-Pr	−6.0, pentane
(+)-Si*OEt	+10.3, pentane	(−)-SiO-cyclo-C_6H_{11}	−9.1, pentane

Stereochemical Studies of Alkoxy–Alkoxy Exchange. In our studies the entering alkoxide group differed in structure from the leaving group. It is clear from Table I that certain combinations of R_3Si^*OR' and alkoxide reagent permit a simple and direct determination of stereochemical path. The first studies concern reaction of R_3Si^*OMe with *n*-butoxide in benzene solvent and results are presented in Table II. In detail, the reactions studied are

$$R_3Si^*OMe + n\text{-BuOH} \xrightarrow{n\text{-BuOM (M = Li, Na, K)}} R_3Si^*O\text{-}n\text{-}Bu \tag{I}$$

For runs in which the solvents contained small amounts of 1-butanol, the solution was refluxed to increase reaction rates and to evaporate off methanol as an azeotrope (runs I-1, I-5, and I-9). Larger amounts of 1-butanol in the solvents naturally favor formation of R_3Si^*O-*n*-Bu and make heating and removal of methanol unnecessary because of rate and equilibrium factors (runs I-2, I-3, I-4, I-6, I-7, and I-8). Also, in the latter runs, the reaction was not heated because *n*-butoxysilane tends to be racemized at elevated temperature in polar media. When the solvent is largely 1-butanol, *n*-butoxysilane becomes optically unstable and is racemized during the reaction even at room temperature (runs I-4 and I-8). In all runs products examined by ir showed no trace of methoxysilane remaining.

From Table II it is exceedingly interesting to note that very excellent retention stereochemistry in 2.3% butanol–97.7% benzene changes to lower retention in 16.7% butanol and that stereochemistry crossover to net inversion of configuration is realized at 51.2% butanol and is maintained in 100% butanol. Cation effects on stereochemistry are also of interest. The change from lithium to sodium while maintaining the solvent composition at 16.7% butanol changes the stereochemistry from predominant retention to predominant inversion of configuration. These solvent and cation effects are extremely instructive from a mechanistic standpoint.

A second series of stereochemical studies similar to I was carried out using *n*-hexane as a solvent.

$$R_3Si^*OMe + n\text{-BuOH} \xrightarrow{n\text{-BuOM (M = Li, Na, K)}} R_3Si^*O\text{-}n\text{-}Bu \tag{II}$$

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(15) L. H. Sommer and J. E. Lyons, *J. Amer. Chem. Soc.*, **89**, 1521 (1967).

Table II. Stereochemical Studies of Reactions I

Run[a]	Reaction time, hr	Metal alkoxide (mol × 10^4)	n-BuOH (mol)/ n-BuOM (mol)	n-BuOH (mol)/ R_3Si^*OMe (mol)	n-BuOH (vol % in solvent)	Stereospecificity,[b,c] %
I-1	12	n-BuOLi (3.8)	10	2.6	2.3	100 ret
I-2	3.8	n-BuOLi (22)	10	15	16.7	89 ret
I-3	3.5	n-BuOLi (9.5)	72	47	51.2	65 inv
I-4	0.14	n-BuOLi (5.5)	210	79	100	>81 inv[d]
I-5	6.5	n-BuONa (2.6)	15	2.6	2.3	95 ret
I-6	1.0	n-BuONa (7.8)	28	15	16.7	76 inv
I-7	2.5	n-BuONa (3.9)	180	49	52.0	82 inv
I-8	0.25	n-BuONa (2.7)	450	83	100	>77 inv[d]
I-9	3.8	n-BuOK (8.2)	4.7	2.6	2.3	Racemic

[a] Runs I-1, I-5, and I-9 were at refluxing temperature; others at room temperature. [b] A stereospecificity of, say, 90% means that the product was 80% optically pure (20% racemic), if an optically pure reactant was used. [c] Stereospecificity is based on optically pure (+)-R_3Si^*OMe, $[\alpha]_D$ +17.2°, and (+)-R_3Si^*O-n-Bu, $[\alpha]_D$ +9.0° in pentane. [d] n-Butoxysilane was partially racemized during the reaction and the exact stereospecificity could not be estimated.

Table III. Stereochemical Studies of Reactions II

Run[a]	Reaction time, hr	Metal alkoxide (mol × 10^4)	n-BuOH (mol)/ n-BuOM (mol)	n-BuOH (mol)/ R_3Si^*OMe (mol)	n-BuOH (vol % in solvent)	Stereospecificity, %
II-1	4.5	n-BuOLi (3.8)	10	2.6	2.3	98 ret
II-2	3.8	n-BuOLi (22)	10	15	16.7	72 ret
II-3	1.0	n-BuOLi (9.3)	73	47	51.2	70 inv
II-4	0.14	n-BuOLi (5.5)	210	79	100	>81 inv
II-5	4.5	n-BuONa (2.6)	13	2.2	2.0	65 ret
II-6	1.0	n-BuONa (22)	10	15	16.7	78 inv
II-7	1.0	n-BuONa (4.4)	160	49	52.0	>77 inv
II-8	0.25	n-BuONa (2.7)	450	83	100	>77 inv
II-9	3.8	n-BuOK (8.2)	4.7	2.6	2.3	Racemic

[a] Runs II-1, II-5, and II-9 were run at refluxing temperature. The rest of the runs were at room temperature.

Table IV. Stereochemical Studies of Reactions III

Run[a]	Reaction time, hr	Metal alkoxide (mol × 10^4)	$C_6H_{11}OH$ (mol)/ $C_6H_{11}OM$ (mol)	$C_6H_{11}OH$ (mol)/ R_3Si^*OMe (mol)	$C_6H_{11}OH$ (vol % in solvent)	Stereospecificity,[b] %
III-1	2.5	$C_6H_{11}OLi$ (15)	9.6	6.7	9.1	100 ret
III-2	3.5	$C_6H_{11}ONa$ (4.4)	33	6.7	9.1	98 ret
III-3	2.0	$C_6H_{11}OK$ (1.3)	110	6.7	9.1	63 ret
III-4	2.0	$C_6H_{11}OK$ (1.3)	37	2.2	3.2	63 ret
III-5	1.3	$C_6H_{11}OK$ (1.3)	370	22	29.4	55 ret
III-6	0.8	$C_6H_{11}OK$ (1.3)	740	45	66.7	Racemic

[a] All reactions were run at refluxing temperature. [b] Based on optically pure (+)-R_3Si^*O-c-C_6H_{11}, $[\alpha]_D$ +9.1°.

Results of series II are given in Table III and are similar to those given in Table II, except that, relative to reactions I, corresponding studies in series II show an increased tendency in the direction of invertive stereochemistry.

Our next studies comprised change of the alkoxide reagent to cyclohexoxide and isopropoxide while keeping the reactant the same. The following reaction series were carried out in refluxing toluene in order to obtain practical reaction rates. At room temperature reaction was too slow.

$$R_3Si^*OMe + c\text{-}C_6H_{11}OH \xrightarrow{c\text{-}C_6H_{11}OM\ (M\ =\ Li,\ Na,\ K)} R_3Si^*O\text{-}c\text{-}C_6H_{11} \quad \text{(III)}$$

$$R_3Si^*OMe + i\text{-}PrOH \xrightarrow{i\text{-}PrOM\ (M\ =\ Li,\ Na,\ K)} R_3Si^*O\text{-}i\text{-}Pr \quad \text{(IV)}$$

Results are given in Tables IV and V. Again, dramatic cation effects are seen which are consistent with the stereochemical cation relationships revealed in Tables II and III. Also, in harmony with the data for methoxy–butoxy exchange, the more alcoholic solvents lead to decreased retention stereochemistry. However, in Tables IV and V stereochemistry crossover from retention to predominant inversion is not observed and this is discussed below.

The last two stereochemical series in this paper deal with the reactions of c-$C_6H_{11}OM$ with R_3Si^*OEt and R_3Si^*O-i-Pr in refluxing toluene.

$$R_3Si^*OEt + c\text{-}C_6H_{11}OH \xrightarrow{c\text{-}C_6H_{11}OM(\ M\ =\ Li,\ Na,\ K)} R_3Si^*O\text{-}c\text{-}C_6H_{11} \quad \text{(V)}$$

$$R_3Si^*O\text{-}i\text{-}Pr + c\text{-}C_6H_{11}OH \xrightarrow{c\text{-}C_6H_{11}OM\ (M\ =\ Li,\ Na,\ K)} R_3Si^*O\text{-}c\text{-}C_6H_{11} \quad \text{(VI)}$$

Results of the above studies are presented in Tables VI and VII. Relative to series III, the change from the methoxy leaving group to ethoxy and isopropoxy does not alter the essential stereochemical pattern found for the corresponding studies in Table IV. Thus,

Table V. Stereochemical Studies of Reactions IV

Run	Reaction time, hr	Metal alkoxide (mol × 10^4)	*i*-PrOH (mol)/ *i*-PrOM (mol)	*i*-PrOH (mol)/ R_3Si^*OM (mol)	*i*-PrOH (vol % in solvent)	Stereospecificity,[a] %
IV-1	2.5	*i*-PrOLi (15)	13	9.2	9.1	100 ret
IV-2	2.5	*i*-PrONa (7.0)	28	9.2	9.1	73 ret
IV-3	1.5	*i*-PrOK (1.3)	150	9.2	9.1	60 ret
IV-4	2.5	*i*-PrONa (4.4)	18	3.7	3.8	89 ret
IV-5	2.5	*i*-PrOLi (12)	55	31	31.2	89 ret
IV-6	1.3	*i*-PrOLi (11)	120	61	100	77 ret

[a] Based on optically pure (+)-R_3Si^*O-*i*-Pr, $[\alpha]_D$ +6.0°.

Table VI. Stereochemical Studies of Reactions V

Run[a]	Reaction time, hr	Metal alkoxide (mol × 10^4)	$C_6H_{11}OH$ (mol)/ $C_6H_{11}OM$ (mol)	$C_6H_{11}OH$ (mol)/ R_3Si^*OEt (mol)	$C_6H_{11}OH$ (vol % in solvent)	Stereospecificity,[b] %
V-1	7.0	$C_6H_{11}OLi$ (20)	7.2	6.4	9.1	96 ret
V-2	4.5	$C_6H_{11}ONa$ (6.1)	13	6.4	9.1	93 ret
V-3	3.0	$C_6H_{11}OK$ (2.6)	55	6.4	9.1	73 ret

[a] Runs carried out in refluxing toluene. [b] Based on optically pure (+)-R_3Si^*OEt, $[\alpha]_D$ +10.3° in pentane.

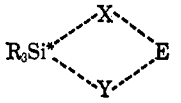
Table VII. Stereochemical Studies of Reactions VI

Run[a]	Reaction time, hr	Metal alkoxide (mol × 10^4)	$C_6H_{11}OH$ (mol)/ $C_6H_{11}OM$ (mol)	$C_6H_{11}OH$ (mol)/ R_3Si^*O-*i*-Pr	$C_6H_{11}OH$ (vol % in solvent)	Stereospecificity, %
VI-1	7.5	$C_6H_{11}OLi$ (20)	7.2	6.1	9.1	93 ret
VI-2	7.5	$C_6H_{11}ONa$ (5.2)	28	6.1	9.1	92 ret
VI-3	8	$C_6H_{11}OK$ (2.6)	55	6.1	9.1	69 ret

[a] Runs carried out in refluxing toluene.

cation effects on stereochemistry are very similar. Reaction rates in series V and VI are, for corresponding solvents, much slower than for series IV, and this fact plus the complication of decreased spacing between displacement and product racemization rates imposed severe limitations on the range of studies that could be carried out in series V and VI. Nevertheless, the results are quite significant and are discussed below.

General Mechanism Considerations. In this section, it is proposed to examine the general mechanistic significance of the above stereochemical study, with particular regard for their bearing on previous proposals concerning mechanism models for retention reactions of R_3Si^*X. The latter have comprised four-center (or three-center) quasicyclic transition states in which the "bonds" to silicon from the entering group Y and the leaving group X are relatively long and weak compared to the nonreacting Si–R bonds. In the following rough approximation E is the electrophilic part of an attacking reagent EY in a four-center mechanism, and this class of polar mechanisms of R_3Si^*X has been termed SNi–Si.[4,13]



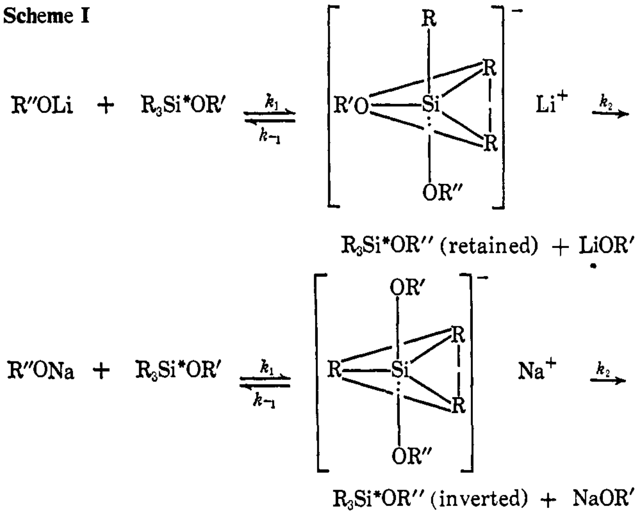
SNi–Si retention

SNi–Si transition states can have over-all tetragonal-pyramid or trigonal-bipyramid geometries with both formulations having a near pyramidal arrangement of R groups and Si.[4,13] For retention reactions of R_3Si^*X the most common mechanism path has been proposed *not to involve a full-fledged pentacovalent-silicon intermediate containing five full bonds to silicon.*

In the present paper, stereochemistry crossover engendered by the change from *n*-BuOLi to *n*-BuONa (Tables II and III and 16.7 vol % butanol) and other cation effects on stereochemistry make it exceedingly improbable that the alkoxy–alkoxy exchanges of R_3Si^*OR' involve preliminary full addition of alkoxide anion to silicon followed by expulsion of OR′ in a subsequent step.

For example, it would be very difficult to explain how the change from lithium cation to sodium cation

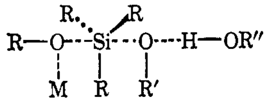
Scheme I



could change the over-all geometry of Si-5 intermediates in the way outlined in Scheme I.

Thus, mechanisms SN2*-Si ($k_{-1} >> k_2$, $k_{-1} >> k_1$) and SN2**-Si ($k_2 >> k_{-1}$, $k_{-1} >> k_1$)[16] would seem to be ruled out by the observed cation stereochemistry effects. On the other hand, mechanism model SNi-Si intimately involves the cationic part of the reagent, *E*, in the rate- and stereochemistry-controlling steps and predicts (correctly) that the relatively covalent reagent, *n*-BuOLi (tighter O–M bond), should favor operation of a retention mechanism, whereas the more ionic reagent, *n*-BuONa (looser O–M bond), whose component parts can function more independently should be more favorable toward operation of mechanism SN2–Si in which $R''O^-$ attacks at the back face of the silicon tetrahedron while electrophilic assistance by solvated Na^+ and by hydrogen bonding from $R''OH$ at the front side aid removal of the poor leaving group $R'O^-$ with inversion of configuration.

Mechanistic conclusions which are the same as those just reached result from consideration of solvent effect on stereochemistry crossover and stereochemistry variation. Consideration of the data in Tables II–V shows that more alcoholic solvents favor inversion of configuration, most likely by providing sufficient electrophilic assistance for removal of $R'O^-$ *via* hydrogen bonding, thus favoring operation of mechanism SN2–Si.[6]



SN2–Si inversion

Decreased hydrogen-bonding capacity of cyclohexanol and 2-propanol relative to 1-butanol (due to steric and/or electronic factors) may be responsible for lack of stereochemistry crossover in reaction series III and IV.

An additional factor favoring SN2–Si in the more alcoholic solvents is simply the circumstance that mechanism SNi–Si involves minimization of charge separation in the transition state, and the increased polarity of the more alcoholic solvents would tend to make such minimization of charge separation less necessary and would permit increased operation of the most common polar mechanism for R_3Si^*X reactions, the SN2–Si mechanism.

Experimental Section[17]

Chromatography of the Products. Alkoxysilanes were often accompanied by small amounts of silanol. Since the desired products were not totally stable during the chromatography used to remove silanol, proper procedure was important. The following conditions were used for 2–3 mmol of product: ethoxy- and *n*-butoxysilane, 5 × 1.3 cm silica gel column with elution by 80 ml of 75% pentane–25% benzene (by volume); isopropoxysilane, 17 × 1.3 cm silica gel column with elution by 100 ml of 50% pentane–50% benzene; cyclohexoxysilane, 20 × 1.3 cm silica gel column with elution by 100 ml of 60% pentane–40% benzene.

Preparation of (+)-α-Naphthylphenylmethylethoxysilane. a. To 1.50 g of (−)-R_3Si^*H (6 mmol), $[\alpha]_D$ −34.4° (*c* 2.1, pentane), and 0.13 g of 5% palladium on charcoal in a 25-ml erlenmeyer flask was added 12 ml of pentane and 0.8 ml of ethanol (13.7 mmol). Vigorous bubbling started immediately and ceased in 1 hr. The flask equipped with a $CaCl_2$ drying tube was left for another hour. The solution was filtered and solvent was removed by distillation. The product (1.7 g) had a small amount of silanol, and 0.85 g of product was chromatographed. The recovered material (0.63 g) free of silanol had $[\alpha]_D$ +9.77° (*c* 3.8, pentane). An infrared spectrum in CCl_4 showed the expected R_3Si^*– system peaks plus new bands at 3.37 (s), 3.42 (w), 3.49 (w), 7.20 (m), 8.62 (m), 9.05 (s), and 9.31 μ (s) apparently related to the Si-OEt moiety. The substance had n^{23}_D 1.6012.

Anal. Calcd for $C_{19}H_{20}OSi$: C, 78.00; H, 6.89. Found: C, 78.18; H, 7.03.

Chromatographed material (0.3 g) was reduced with 0.3 g of $LiAlH_4$ in 25 ml of ether. The mixture was refluxed for 3.5 hr; the excess $LiAlH_4$ was decomposed by slow addition of acetone and the mixture worked up with a combination of ice, 50 ml of pentane, and 5 ml of concentrated HCl in a separatory funnel. After washing the organic layer to neutrality, drying over sodium sulfate, and stripping of solvent, white crystalline material identified as R_3Si^*H showed $[\alpha]_D$ +33.8° (*c* 2.36, pentane).

b. (+)-Chlorosilane was prepared by chlorination[3] of 0.5 g of (−)-R_3Si^*H (2 mmol), $[\alpha]_D$ −34.6°. Into a 50-ml pentane solution of 0.6 ml of EtOH (0.01 mol) and 0.83 ml of Et_2NH (0.008 mol) in a separatory funnel, the (+)-R_3Si^*Cl dissolved in 30 ml of pentane was added. The funnel was swirled and the contents washed with water five times. After drying over sodium sulfate, stripping of solvent gave 0.50 g of crude product. Chromatography gave 0.35 g of R_3Si^*OEt, $[\alpha]_D$ +7.65° (*c* 3.3, pentane), whose ir coincided with the above authentic sample.

Preparation of (+)-α-Naphthylphenylmethyl-*n*-butoxysilane. a. By a procedure similar to method a for ethoxysilane, *n*-butoxysilane was prepared using 1 g of (−)-R_3Si^*H, $[\alpha]_D$ −34.4° (*c* 2.1, pentane). Chromatographed product had $[\alpha]_D$ +8.43° (*c* 4.7, pentane). An infrared spectrum in CCl_4 showed the expected R_3Si^*– system peaks, plus new bands at 3.38 (s), 3.42 (s), 3.49 (s), 6.84 (m), 7.20 (m), 9.25 (vs), and 9.61 μ (m) apparently related to the SiO–*n*-Bu moiety. The substance had n^{23}_D 1.5878.

Anal. Calcd for $C_{21}H_{24}OSi$: C, 78.71; H, 7.54. Found: C, 78.94; H, 7.32.

Reduction of 0.3 g of the product was performed with 0.3 g of $LiAlH_4$ by refluxing in ethyl ether for 5 hr. After working up as mentioned above, the crude product was chromatographed over a 35 × 1.3 cm silica gel column, eluted first with 70 ml of pentane and then 100 ml of 80% pentane–20% benzene, yielding 0.17 g of white crystalline (+)-R_3Si^*H, $[\alpha]_D$ +33.6° (*c* 1.6, pentane).

b. (+)-Chlorosilane was prepared from 0.5 g of (−)-R_3Si^*H, $[\alpha]_D$ −34.6°. Stirring magnetically a solution of 35 ml of pentane, 0.92 ml of 1-butanol (0.01 mol), and 0.82 ml of Et_2NH (0.008 mol), (+)-R_3Si^*Cl dissolved in 25 ml of pentane was added. After 0.5 hr, the solution was washed with water and dried over sodium sulfate. Chromatography of 0.53 g of the crude product gave 0.42 g of (+)-R_3Si^*O-*n*-Bu, $[\alpha]_D$ +8.12° (*c* 3.7, pentane), whose ir spectrum coincided with an authentic sample.

Preparation of (−)-α-Naphthylphenylmethylisopropoxysilane. a. By a procedure similar to method a for ethoxysilane, isopropoxysilane was prepared using 1.5 g of (−)-R_3Si^*H, $[\alpha]_D$ −34.4° (*c* 2.1, pentane). The chromatographed product had $[\alpha]_D$ −5.06° (*c* 5.26, pentane). An infrared spectrum (neat) was identical with that of an authentic sample.[18] Reduction of 0.35 g of the product was performed with 0.5 g of $LiAlH_4$ by refluxing in 30 ml of *n*-butyl ether and 20 ml of ethyl ether for 5 hr at 83°. After working up in the usual manner, the crude product was chromatographed, yielding 0.21 g of (+)-R_3Si^*H, $[\alpha]_D$ +30.1°.

b. Lithium isopropoxide was prepared by adding 1.5 ml of *n*-butyllithium in hexane (1.6 *M*, 2.4 mmol) to a solution of 1 ml of *i*-PrOH and 12 ml of benzene. To this solution, 0.6 g of (+)-R_3Si^*Cl, $[\alpha]_D$ +5.02°, was added in 3 ml of benzene solvent. After 0.5 hr the solution was taken up by 60 ml of pentane, washed with water, and dried over sodium sulfate. Chromatography of 0.56 g of crude product gave 0.44 g of (−)-R_3Si^*O-*i*-Pr, $[\alpha]_D$ −3.7° (*c* 3.9, pentane), identified by ir.

Exchange Reactions

A. Runs I-1, I-5, I-9, II-1, II-5, and II-9. A three-necked, 50-ml microflask was equipped with a thermometer, a still head, and an addition funnel. The

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(16) Reference 11, pp 179–182.

(17) Analyses by the Analytical Laboratory, University of California, Berkeley, Calif.

(18) Racemic isopropoxysilane was originally prepared by C. L. Frye, Ph.D. Thesis, The Pennsylvania State University, 1958, pp 84.

flask also had a magnetic bar for stirring. The whole system was flushed with nitrogen before carrying out the reactions. Metal alkoxides were prepared in 1-butanol prior to the reaction. As a typical example, the procedure for I-1 is described. Benzene (12 ml) was deaerated by nitrogen in the three-necked, 50-ml flask, and 0.35 ml of 1-butanol containing 0.38 mmol of lithium *n*-butoxide was added. After flushing the whole system with nitrogen, the temperature of the solution was raised to reflux. A solution of 0.51 g of (−)-R_3Si^*OMe (1.86 mmol), $[\alpha]_D$ −16.1° (*c* 2.2, pentane), in 3 ml of benzene was added to the refluxing solution. As the reaction proceeded, methanol evaporated off as an azeotrope with benzene. However, the azeotrope was not taken off, since the still head temperature remained well above the azeotrope boiling point. The still head had a well of 0.2 ml, and it was likely that methanol would either stay in the well or in the refluxing column. (Maximum total volume of methanol–benzene azeotrope is *ca.* 0.15 ml.) After 12 hr, the solution was cooled to room temperature, taken up in 60 ml of pentane, washed with water, and dried over sodium sulfate. After taking off the solvent, the infrared spectrum of the crude product (0.49 g) showed no methoxysilane left (no characteristic band at 3.55 μ), no silanol formed (no OH bond), and $[\alpha]_D$ −8.50° (*c* 4.95, pentane). In other runs, using the same solvent and reagent concentrations, the reactions were incomplete after 7 and 9 hr.

B. Runs I-2, I-3, I-4, I-6, I-7, I-8, II-2, II-3, II-4, II-6, II-7, and II-8. The reactions were run using a 25 × 1.5 cm polarimeter tube. The optical rotations of the reaction mixture could be watched during the course of the reactions, with the exception of runs I-2 and II-2. After the optical rotation of the solution had reached a maximum, if the rotation started to decrease, that is, *n*-butoxysilane was being racemized (I-4, I-8, II-4, II-7, and II-8), the solution was quickly taken up in 60 ml of pentane and washed with water. On the other hand, if the rotation remained constant at the maximum, that is, *n*-butoxysilane was optically stable in the solution (I-3, I-6, I-7, II-3 and II-6), the solution was kept for 0.5 hr and taken up in 60 ml of pentane. The solutions of runs I-2 and II-2 were opaque, and the optical rotations could not be followed visually. *n*-Butoxysilane was presumed to be optically stable in these solutions, since it was optically stable in more polar solvents (I-3 and II-3). As a typical example, a procedure for I-7 is described. To the mixture of 5.5 ml of 1-butanol and 6 ml of benzene in the polarimeter tube 0.42 g of (−)-R_3Si^*OMe (1.5 mmol), $[\alpha]_D$ −16.0° (*c* 1.9, pentane), was added. The observed rotation was −2.37°. Then 0.5 ml of 1-butanol containing 0.20 mmol of *n*-BuONa was added. The observed rotation gradually changed from minus to plus. In 2 hr, the rotation reached +0.746° and stayed constant for 0.5 hr. The whole solution was taken up in 60 ml of pentane, washed with water until neutral, and dried over sodium sulfate. After taking off the solvent, an infrared spectrum of the crude product showed it to be almost exclusively *n*-butoxysilane plus a very small amount of silanol. It was chromatographed in the manner mentioned before and the recovered material, 0.20 g, had $[\alpha]_D$ +5.28° (*c* 2.1, pentane).

C. Runs III-1 to III-6, IV-1 to IV-6, V-1 to V-3, VI-1 to VI-3. The same apparatus as for A was used. As a typical example, a procedure for III-1 is described. Toluene (12 ml) in a 50-ml, three-necked flask was flushed with nitrogen, and 1.5 ml of cyclohexanol was added. After flushing the whole system with nitrogen, 10 mg of lithium wire (1.4 mg-atoms) was added, and the solution was heated to reflux. Lithium wire was dissolved in 2 hr, forming lithium cyclohexoxide. To the refluxing solution, 0.52 g of (−)-R_3Si^*OMe (1.9 mmol), $[\alpha]_D$ −16.3° (*c* 2.2, pentane), was added in 3 ml of toluene solvent. As the reaction proceeded, methanol evaporated off as an azeotrope with toluene. However, methanol was not taken out of the system for the reason mentioned under A above. After 2.5 hr the reaction mixture was cooled, taken up in 60 ml of pentane, washed with water, and dried over sodium sulfate. After taking off the solvent, an infrared spectrum of the crude product showed no methoxysilane. The crude product was chromatographed and the recovered material, 0.53 g, identified as cyclohexoxysilane, had $[\alpha]_D$ +8.70° (*c* 4.85, pentane).