Silicon-induced diastereoselectivity of the catalyzed phosphorylation of 1-(perfluoroalkyl)-ω-(trialkylsilyl)alkan-1-ols

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The stereochemistry of catalytic phosphorylation of 1-(perfluoroalkyl)-ω-(trialkylsilyl)alkan-1-ols with pentavalent phosphorus acid monochlorides (phosphonochloridates, methyl(phenyl)phosphinic chloride, and phosphorochloridates) was studied. The effects of the structures of alcohols and phosphorylating agents on the degree of the reaction diastereoselectivity were investigated. Methylphosphonochloridates were found to react most stereoselectively; the diastereoselectivity of the phosphorylation is independent of the donor or acceptor character of substituents at the phosphorus atom, being determined by their volumes. In the series of silylalkanols, the diastereoselectivity of the reaction the higher the closer the Si atom to the reactive site of the molecule, the larger the volume of the perfluoroalkyl substituent, and the more pronounced the electron-withdrawing properties of the substituents at the Si atom. A reaction mechanism is proposed that rationalizes the stereoselectivity of the reaction.

Key words: polyfluorinated silylalkanols, phosphorus acid monochlorides, catalytic phosphorylation, diastereoselectivity.

In many cases, introduction of a silicon atom into a certain position of an organic substrate molecule changes the directions of various reactions and their rates or selectivities. This is explained by the ability of silicon to stabilize free radicals and positive and negative charges and to interact with both *n*- and π-donors.[1]

The effect of the silicon atom on stereochemistry of reactions of organophosphorus compounds has been reported only for a limited number of examples. For instance, the high stereoselectivity of the phosphorylation of α-silyloxy aldehydes[2,3] and their *N*-trimethylsilylimides[4] with diethyl trimethylsilyl phosphite is explained by the formation of a cyclic or bicyclic transition state as a result of intra- and intermolecular coordination of the silicon atom with the O or N atom, respectively. In addition, stereospecific addition of silyl phosphites to oxo- and iminofuranoses has been described[5]. However, the latter reactions are stereospecific only because of steric factors.

Previously,[6] we showed that the phosphorylation of 1-perfluorobutyl-2-trimethylsilylethanol (**1a**) with aryl methylphosphonochloridates in the presence of catalytic amounts of metallic Mg proceeded fairly diastereoselectively.

The goal of the present work was to scrutinize the stereochemistry of the catalytic phosphorylation of racemic 1-(perfluoroalkyl)-ω-(trialkylsilyl)alkan-1-ols $R^1R^2_2Si(CH_2)_nCH(R^F)OH$ (**1—3**) with racemic phosphorus acid monochlorides $R^3R^4P(O)Cl$ (**4a—i**, **5**, **6a,b**) (Scheme 1) and to elucidate the effect of the structure of the phosphorylating agent on the ratio of the resulting diastereomers. The role of such factors as the distance between the silicon atom and the reactive site, the volume of the perfluorinated substituent R^F, and the donating or withdrawing character of substituents at the Si atom in the alcohol to be phosphorylated was also studied.

Equimolar mixtures of alcohols **1—3** and acid chlorides **4—6** were heated at 140—160 °C in the presence of 2.5 mol. % Mg until evolution of HCl ceased. The reaction products were isolated by chromatography on Al_2O_3 and analyzed by ^{31}P NMR spectroscopy (Tables 1, 2) and GLC-MS (Table 3). In some cases, analytically pure compounds were isolated by distillation *in vacuo*.

The ^{31}P NMR spectra of all products (**7—25**) show two signals for diastereomers **A*** and **B** of the resulting phosphorus acid esters. The presence of two diastereomers in the mixture is evident from GLC-MS data for these compounds. The mass spectra of a pair of diastereomers for each phosphorus acid ester studied** contain

* The diastereomer with the lower-field signal in the ^{13}P NMR spectrum was arbitrarily called diastereomer **A**.

** GLC-MS analysis of phosphorus acid esters **15—17**, **19**, and **25** was not performed because of their high molecular masses and low volatilities.

Published in Russian in *Izvestiya Akademii Nauk. Seriya Khimicheskaya,* No. 9, pp. 1930—1936, September, 2004.

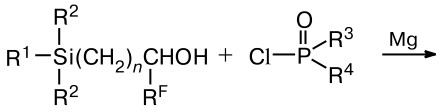
1066-5285/04/5309-2013

Table 1. Catalytic phosphorylation of alcohols $R^1R^2_2SiCH_2CH(C_4F_9)OH$ **1a,b** with phosphorus acid monochlorides $ClP(O)R^3R^4$ **4a—i**, **5**, and **6a,b**

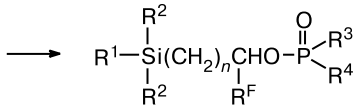
Entry	Starting alcohol	Acid chloride	*T*/°C	Reaction product				^{31}P NMR			**A** : **B**	Yield (%)*
				Compound	$R^1R^2_2Si$	R^3	R^4	δ (s) Diastereomer		Solvent		
								A	**B**			
1	**1a**	**4a**	140	**7**	Me_3Si	Me	CF_3CH_2O	34.13	32.60	$CDCl_3$	28 : 72	56
2	**1a**	**4b**	140	**8**	Me_3Si	Me	PhO	28.83	26.46	—	31 : 69	51
3	**1a**	**4c**	140	**9**	Me_3Si	Me	4-$Bu^tC_6H_4O$	28.78	26.47	C_6D_6	27 : 73	86
4	**1a**	**4d**	140	**10**	Me_3Si	Me	4-ClC_6H_4O	29.26	26.93	C_6D_6	32 : 68	68
5	**1a**	**4e**	140	**11**	Me_3Si	Me	2,4-$Cl_2C_6H_3O$	29.93	27.49	—	29 : 71	85
6	**1a**	**4f**	140	**12**	Me_3Si	Me	4-$MeOC_6H_4O$	29.20	26.85	C_6D_6	35 : 65	82
7	**1a**	**4g**	140	**13**	Me_3Si	Me	3,5-$Me_2C_6H_3O$	28.56	26.28	C_6D_6	26 : 74	79
8	**1a**	**4h**	140	**14**	Me_3Si	Me	2,6-$Me_2C_6H_3O$	29.23	26.68	—	16 : 84	82
9	**1a**	**4i**	160	**15**	Me_3Si	Ph	PhO	17.03	15.16	$CDCl_3$	50 : 50	91
10	**1b**	**4h**	140	**16**	Pr_3Si	Me	2,6-$Me_2C_6H_3O$	28.67	25.89	—	22 : 78	67
11	**1b**	**5**	160	**17**	Pr_3Si	Me	Ph	44.78	44.46	C_6D_6	38 : 62	59
12	**1a**	**6a**	140	**18**	Me_3Si	PhO	CF_3CH_2O	−7.49	−8.39	–	45 : 55	95
13	**1a**	**6b**	140	**19**	Me_3Si	2-FC_6H_4O	4-$Pr^iC_6H_4O$	−12.88	−13.00	$CDCl_3$	53 : 47	94
*14***	**1a**	**4b**	20	**8**	Me_3Si	Me	PhO	28.71	26.34	Pentane	31 : 69	85

* The content of the product in the final reaction mixture (^{31}P NMR data).
** In CH_2Cl_2 in the presence of Et_3N.

Scheme 1



1a—e, **2**, **3** **4a—i**, **6a,b**



7—25

Compound	R^1	R^2	R^F	*n*
1a, **7—15**, **18**, **19**	Me	Me	C_4F_9	1
1b, **16**, **17**	Pr	Pr	C_4F_9	1
1c, **20**	Me	Me	CF_3	1
1d, **23**, **24**	$CF_3CH_2CH_2$	Me	C_4F_9	1
1e, **25**	$CF_3CH_2CH_2$	$CF_3CH_2CH_2$	C_4F_9	1
2, **21**	Me	Me	C_3F_7	2
3, **22**	Me	Me	CF_3	3

Compound	R^3	R^4
4a, **7**	Me	CF_3CH_2O
4b, **8**, **20—23**	Me	PhO
4c, **9**	Me	4-$Bu^tC_6H_4O$
4d, **10**	Me	4-ClC_6H_4O
4e, **11**	Me	2,4-$Cl_2 \cdot C_6H_3O$
4f, **12**	Me	4-$MeOC_6H_4O$
4g, **13**	Me	3,5-$Me_2C_6H_3O$
4h, **14**, **16**, **24**, **25**	Me	2,6-$Me_2C_6H_3O$
4i, **15**	Ph	PhO
5, **17**	Me	Ph
6a, **18**	PhO	CF_3CH_2O
6b, **19**	2-FC_6H_4O	4-$Pr^iC_6H_4O$

the same fragmentation ions differing only in peak intensities. As with many organosilicon compounds, the mass spectra of these esters contain a peak of the $[M - Me]^+$ or $[M - R^1]^+$ ion rather than a molecular ion peak. The most characteristic ions are $[R^1Me_2SiOP(O)R^3R^4 + 1]^+$, $[R^1Me_2SiOP(O)R^3R^4 - R^1]^+$, and $[R^1Me_2SiOP(O)R^3R^4 - Me - R^1 - 1]^+$. Apparently, the formation of such ions involves migration of the phosphoryloxy group from the carbon atom to silicon upon electron impact with accompanying elimination of, probably, an alkene or cycloalkane from both the starting compound and its primary fragmentation ions (Scheme 2).

As a rule,* the ratios of the stereoisomers of phosphorus acid esters determined from GLC-MS and ^{31}P NMR data agree well. In most cases, the ratios are not statistical, noticeably depending on the structures of the reagents.

Methylphosphonochloridates **4a—h** react most stereoselectively (see Table 1) and the reaction diastereoselectivity does not depend significantly on the electron-withdrawing properties of the substituent at the phosphorus atom. For instance, the ratios of the diastereomers in phosphonates **7** and **8** obtained upon the phosphorylation of alcohol **1a** with 2,2,2-trifluoroethyl methylphosphonochloridate (**4a**) and phenyl methylphosphonochloridate (**4b**), respectively, were approximately the same (see

* Some pairs of diastereomers could not be efficiently separated by GLC, which makes GLC-based quantitative estimates of the ratio between the diastereomers in the reaction mixture less accurate; for this reason, ^{31}P NMR spectroscopy is the main method for determination of this ratio (accuracy ±2%).

Table 2. Catalytic phosphorylation of alcohols $R^1R^2_2Si(CH_2)_nCH(R^F)OH$ **1a—e**, **2**, **3**, and **28** with phosphonochloridates $ClP(O)MeR^4$ **4b,h** at 140 °C

Entry	Starting alcohol	Acid chloride	Reaction product					^{31}P NMR (δ (s)) Diastereomer		Solvent	**A** : **B**	Yield (%)*
			Compound	$R^1R^2_2Si$	*n*	R^F	R^4	**A**	**B**			
1	**1c**	**4b**	**20**	Me_3Si	1	CF_3	PhO	29.00	26.49	Hexane	36 : 64	11**
2	**1a**	**4b**	**8**	Me_3Si	1	C_4F_9	PhO	28.83	26.46	—	31 : 69	51
3	**2**	**4b**	**21**	Me_3Si	2	C_3F_7	PhO	28.25	25.68	C_6H_6	38 : 62	84
4	**3**	**4b**	**22**	Me_3Si	3	CF_3	PhO	29.11	27.66	—	50 : 50	87
5	**1a**	**4h**	**14**	Me_3Si	1	C_4F_9	2,6-$Me_2C_6H_4O$	29.23	26.68	—	16 : 84	82
6	**1b**	**4h**	**16**	Pr_3Si	1	C_4F_9	2,6-$Me_2C_6H_4O$	28.67	25.89	—	22 : 78	67
7	**1d**	**4b**	**23**	$(CF_3CH_2CH_2)Me_2Si$	1	C_4F_9	PhO	29.73	26.80	C_6H_6	23 : 77	82
8	**1d**	**4h**	**24**	$(CF_3CH_2CH_2)Me_2Si$	1	C_4F_9	2,6-$Me_2C_6H_4O$	29.85	26.29	C_6H_6	10 : 90	86
9	**1e**	**4h**	**25**	$(CF_3CH_2CH_2)_3Si$	1	C_4F_9	2,6-$Me_2C_6H_4O$	29.74	26.76	C_6H_6	9 : 91	62
*10****	**28**	**4b**	**29**	$MeEt_2Si$	1	Pr	PhO	26.44	25.77	Hexane	49 : 51	64

* The content of the product in the final reaction mixture (^{31}P NMR data).
** The low yield of the target phosphonate **20** is due to its partial decomposition during catalytic phosphorylation.[7]
*** In CH_2Cl_2 in the presence of Et_3N at 20 °C.

Scheme 2

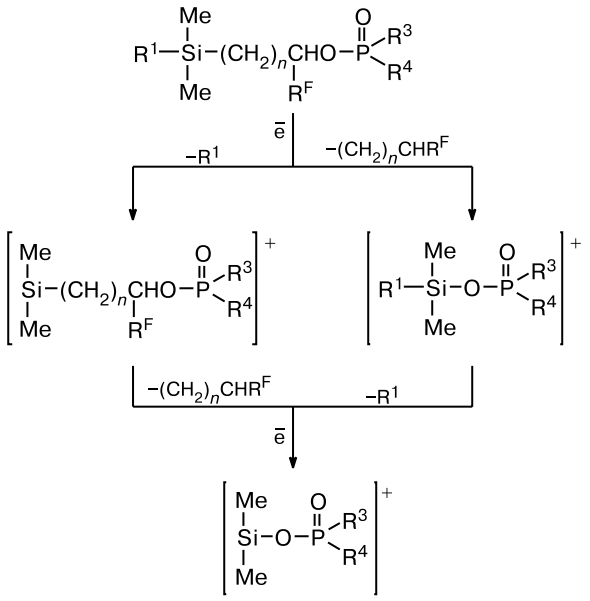


Table 1, entries *1*, *2*). No direct correlation was also found between the electron-withdrawing properties of the radicals in the aromatic ring of the aryl methylphosphonochloridates **4b—g** and the reaction stereoselectivity (see Table 1, entries *3—7*).

However, phosphorylation with methylphosphonochloridate **4h** containing the bulky 2,6-dimethylphenoxy radical at the P atom is more diastereoselective (see Table 1, entries *7*, *8*). Obviously, the steric hindrance due to two *ortho*-methyl groups prevents the formation of minor diastereomer **A** to a larger extent than the formation of diastereomer **B**. For the sterically even more hindered phenyl phenylphosphonochloridate **4i**, in which the methyl group at the phosphorus atom is replaced by the phenyl group, higher reaction temperature is required and the reaction is not stereoselective at all (see Table 1, entries *2*, *9*).

At the same time, a pronounced but not very high diastereoselectivity was attained in the reaction of methyl(phenyl)phosphinic chloride **5** with 1-perfluorobutyl-2-tripropylsilylethanol (**1b**) (see Table 1, entries *10*, *11*). As in the preceding case, the reaction occurs only at 160 °C, although phosphinic chloride **5** is a reactive phosphorylating agent.

In the phosphorylation of alcohol **1a** with phosphochloridates **6a,b** (see Table 1, entries *12*, *13*), the ratio of the resulting diastereomers only slightly deviates from the statistical distribution.

Room-temperature phosphorylation of polyfluorinated silylalkanols with methylphosphonochloridates in the presence of triethylamine (as the hydrogen chloride scavenger) in an inert solvent is also diastereoselective. Under these conditions, the phosphorylation of alcohol **1a** with compound **4b** afforded phosphonate **8** with the same diastereomer ratio (31 : 69) as in the Mg-catalyzed reaction (see Table 1, entries *2*, *14*). This suggests that the reaction diastereoselectivity in both cases is determined by the same factors.

The stereoselectivity of phosphorylation substantially depends on the structure of an alcohol. The reactions with aryl methylphosphonochloridates **4b,h** are stereoselective only for alcohols **1** and **2**, in which the Si atom is separated from the reactive site by one or two methylene units (see Table 2). When the alkylene chain is lengthened from $n = 1$ to $n = 2$ and the sizes of the radicals R^F

Table 3. GLC-MS data for phosphorus acid esters **7**—**14**, **18**, and **20**—**24**

Compound	Ratio of the diastereomers **A** : **B**	MS m/z ($I_{rel,\,A}/I_{rel,\,B}$ (%))*
7	**	482 $[M - Me + 1]^+$ (24/12), 477 $[M - F]^+$ (16/0), 251 $[Me_3SiOP(O)(OCH_2CF_3)Me + 1]^+$ (16/13), 235 $[Me_3SiOP(O)(OCH_2CF_3)Me - Me]^+$ (32/29), 73 $[Me_3Si]^+$ (100/71)
8	37 : 63	475 $[M - Me]^+$ (86/95), 471 $[M - F]^+$ (49/30), 271 $[M - C_4F_9]^+$ (31/34), 245 $[Me_3SiOP(O)(OPh)Me + 1]^+$ (22/23), 229 $[Me_2SiOP(O)(OPh)Me]^+$ (71/70), 213 $[Me_2SiOP(O)(OPh)Me - Me - 1]^+$ (61/56), 73 $[Me_3Si]^+$ (100/100)
9	27 : 73	546 $[M]^+$ (12/35), 530 $[M - Me - 1]^+$ (91/100), 526 $[M - HF]^+$ (38/15), 373 $[Me_3SiOP(O)(OC_6H_4CMe_3)Me + Me_3Si]^+$ (53/60), 301 $[Me_3SiOP(O)(OC_6H_4CMe_3)Me + 1]^+$ (37/39), 285 $[Me_3SiOP(O)(O\,C_6H_4CMe_3)Me - Me]^+$ (100/99), 269 $[Me_3SiOP(O)(OC_6H_4CMe_3)Me - 2Me - 1]^+$ (23/28), 73 $[Me_3Si]^+$ (41/60)
10	31 : 69	509 $[M - Me]^+$(39/47), 278 $[Me_3SiOP(O)(OC_6H_4Cl)Me]^+$ (21/25), 263 $[Me_3SiOP(O)(OC_6H_4Cl)Me - Me]^+$ (100/100), 73 $[Me_3Si]^+$ (60/71)
11	33 : 67	542 $[M - Me - 1]^+$ (62/73), 538 $[M - HF]^+$ (26/34), 385 $[Me_3SiOP(O)(OC_6H_3Cl_2)Me + Me_3Si]^+$ (11/46), 313 $[Me_3SiOP(O)(OC_6H_3Cl_2)Me + 1]^+$ (9/13), 297 $[Me_3SiOP(O)(OC_6H_4CMe_3)Me - Me]^+$ (89/44), 281 $[Me_3SiOP(O)(OC_6H_4CMe_3)Me - 2\,Me - 1]^+$ (47/28), 73 $[Me_3Si]^+$ (100/100)
12	33 : 67	520 $[M]^+$ (59/100), 505 $[M - Me]^+$ (39/35), 501 $[M - F]^+$ (59/16), 274 $[Me_3SiOP(O)(OC_6H_4OMe)Me]^+$ (38/38), 259 $[Me_3SiOP(O)(OC_6H_4OMe)Me - Me]^+$ (93/56), 73 $[Me_3Si]^+$ (60/71)
13	29 : 71	502 $[M - Me - 1]^+$ (58/52), 499 $[M - F]^+$ (51/16), 272 $[Me_3SiOP(O)(OC_6H_3Me_2)Me]^+$ (10/13), 213 $[Me_3SiOP(O)(OC_6H_3Me_2)Me - Me]^+$ (100/100), 73 $[Me_3Si]^+$ (68/69)
14	19 : 81	502 $[M - CH_4]^+$ (37/42), 499 $[M - F]^+$ (16/12), 498 $[M - HF]^+$ (47/34), 272 $[Me_3SiOP(O)(OC_6H_3Me_2 - 2,6)Me]^+$ (63/73), 257 $[Me_2SiOP(O)(OC_6H_3Me_2\text{-}2,6)Me]^+$ (73/84), 241 $[Me_2SiOP(O)(OC_6H_3Me_2\text{-}2,6)Me - Me - 1]^+$ (59/21), 73 $[Me_3Si]^+$ (100/100)
18	41 : 59	558 $[M - Me - 1]^+$ (84/67), 401 $[Me_3SiOP(O)(OCH_2CF_3)(OPh) + Me_3Si]^+$ (64/78), 329 $[Me_2SiOP(O)(OCH_2CF_3)(OPh) + 1]^+$ (33/42),), 313 $[Me_3SiOP(O)(OCH_2CF_3)(OPh) - Me]^+$ (47/69), 73 $[Me_3Si]^+$ (84/80)
20	34 : 66	325 $[M - Me]^+$ (48/48), 321 $[M - F]^+$ (49/30), 245 $[Me_3SiOP(O)(OPh)Me + 1]^+$ (13/15), 229 $[Me_2SiOP(O)(OPh)Me]^+$ (45/70), 213 $[Me_2SiOP(O)(OPh)Me - Me - 1]^+$ (45/40), 73 $[Me_3Si]^+$ (73/81)
21	42 : 58	438 $[M - CH_4]^+$ (58/52), 229 $[Me_2SiOP(O)(OPh)Me]^+$ (17/34), 213 $[Me_2SiOP(O)(OPh)Me - Me - 1]^+$ (65/58), 73 $[Me_3Si]^+$ (100/100)
22	48 : 52	353 $[M - Me]^+$ (100/91), 229 $[Me_2SiOP(O)(OPh)Me]^+$ (28/30),), 73 $[Me_3Si]^+$ (21/33)
23	24 : 76	475 $[M - CH_2CH_2CF_3]^+$ (61/42), 327 $[Me_2(CF_3CH_2CH_2)SiOP(O)(OPh)Me + 1]^+$ (30/10), 229 $[Me_2SiOP(O)(OPh)Me]^+$ (46/44), 213 $[Me_2SiOP(O)(OPh)Me - Me - 1]^+$ (18/35), 59 $[Me_2Si]^+$ (100/100)
24	**	585 $[M - Me]^+$ (12/27), 503 $[M - CH_2CH_2CF_3]^+$ (45/56), 355 $[Me_2(CF_3CH_2CH_2)SiOP(O)(OC_6H_3Me_2\text{-}2,6)Me + 1]^+$ (100/95), 335 $[Me_2(CF_3CH_2CH_2)SiOP(O)(OC_6H_3Me_2\text{-}2,6)Me - F]^+$ (45/45), 257 $[Me_2SiOP(O)(OC_6H_3Me_2\text{-}2,6)Me]^+$ (68/100), 59 $[Me_2Si]^+$ (75/73)

* $I_{rel,\,A}$ and $I_{rel,\,B}$ are the relative intensities of the ion peaks in the mass spectra of diastereomers **A** and **B**, respectively.
** Poorly separated.

are similar, the reaction diastereoselectivity is reduced (see Table 2, entries *2*, *3*). The phosphorylation of alcohol **3** ($n = 3$) gave phosphonate **22**, the ratio of the diastereomers being almost statistical (see Table 2, entry *4*).

The stereochemistry of phosphorylation also depends on the electron-withdrawing character of substituents at the Si atom. For instance, replacement of the methyl group at silicon ($\sigma_I = -0.020$ [8])* by a stronger electron-donating propyl group ($\sigma_I = -0.060$ [8]) somewhat reduces the reaction diastereoselectivity, all other factors being equal (see Table 2, entries *5*, *6*). In contrast, attachment of an electron-withdrawing trifluoropropyl substituent ($\sigma_I = 0.047$)[8] to the Si atom significantly enhances the diastereoselectivity of the phosphorylation (see Table 2, entries *2*, *5*, *7*—*9*).

The reaction diastereoselectivity is also enhanced as the radical R^F becomes bulkier (see Table 2, entries *1*, *2*).

At the same time, steric hindrance in an alcohol to be phosphorylated, which is due to a bulky perfluorinated

* σ_1 is the inductive constant of the corresponding substituent R at the silicon atom.

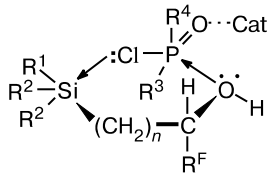
radical as well, is not a sufficient condition for high reaction stereoselectivity. For instance, the catalytic phosphorylation of the sterically hindered secondary alcohol $Me_3CCH(CF_3)OH$ (**26**) containing no silicon atom with phosphonochloridate **4b** led to a nearly statistical ratio of the diastereomers of the resulting phosphonate $Me_3CCH(CF_3)OP(O)Me(OPh)$ (**27**) (52 : 48).

Apparently, the presence of a β-Si atom in secondary alcohols is also insufficient, by itself, for stereoselective phosphorylation. For instance, the phosphorylation of the alcohol $MeEt_2SiCH_2CH(Pr)OH$ (**28**) containing a propyl radical (approximately equal in volume to a fluorinated group) in the α-position with phosphonochloridate **4b** is virtually non-diastereoselective, yielding nearly equal amounts of diastereomers of the phosphonate $MeEt_2SiCH_2CH(Pr)OP(O)Me(OPh)$ (**29**) (see Table 2, entry *10*).

Thus, noticeable diastereoselectivity cannot be achieved without (1) a Si atom in a certain position of an alcohol to be phosphorylated, (2) a methyl group at phosphorus, and (3) an α-polyfluoroalkyl group in the alcohol. The diastereoselectivity can be enhanced by (1) an increase in the electron-withdrawing properties of substituents at silicon, (2) the use of a phosphorylating agent with a bulkier aryl group in the Ar—O—P fragment, (3) and a reduction in the number of methylene units in the alcohol to $n = 1$.

The ratio of the diastereomers of the resulting phosphonates remained unchanged upon further heating; thus, these compounds are configurationally stable under the reaction conditions and the reaction stereochemistry is kinetically controlled.

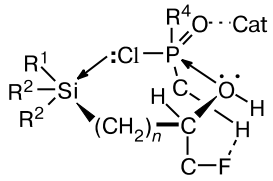
Obviously, the formation of unequal amounts of diastereomers suggests the reaction to involve diastereomeric transition states with different energies, which results in different reaction rates of the *R*- and *S*-alcohol with the *R*- and *S*-isomers of an acid chloride. In turn, the above differences are due to a particular mutual arrangement of substituents in these transition states. The decisive role of the silicon atom in the reaction diastereoselectivity can be associated with its ability to reduce the conformation flexibility of a reactant molecule and stabilize the transition state in a certain conformation. Apparently, the conformation is stabilized due to the formation of a cyclic transition state as a result of coordination of the Cl atom to the Si atom.



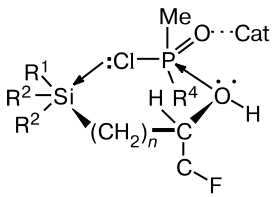
In addition to a decrease in the configurational flexibility of the P atom in the transition state, such a coordination somewhat facilitates, through the electrophilic assistance by Si, the nucleophilic substitution of the Cl atom at phosphorus. The formation of a six-membered ring in the case of alcohols with $n = 1$ is optimum from the viewpoint of the transition state stability. The possibility of Cl→Si coordination bonding is essential for the reaction to proceed diastereoselectively. For instance, introduction of electron-withdrawing substituents to the Si atom strengthens the Cl→Si coordination bond and enhances diastereoselectivity. Apparently, the cyclic transition states become less flexible when the Cl and Si atoms approach closer to each other and the energy difference between the diastereomeric transition states differing in the mutual arrangement of substituents R^F and H at the carbon atom and substituents R^3 and R^4 at the phosphorus atom is increased. A system in which steric repulsion is minimum will have the lowest energy. It would be natural to expect that the diastereoselectivity will be enhanced with an increase in the volume of R^F in the alcohol and in the difference between the volumes of R^3 and R^4 at the phosphorus atom, which was observed experimentally.

An analysis of Tables 1 and 2 shows that the reaction diastereoselectivity depends on yet another substantial factor, namely, the presence of the methyl group at the phosphorus atom. For instance, the phosphorylation of polyfluorinated alkanols with acid chlorides **4i** and **6a,b** containing no methyl group is only slightly diastereoselective or even not at all.

Apparently, the key role of the methyl group at the phosphorus atom is due to a possible weak intramolecular hydrogen bonding, in the transition state, between the H atoms of the methyl group and the F atoms[9] of the polyfluoroalkyl fragment of the alcohol.



Along with the putative formation of a six-membered ring through Cl→Si coordination, closure of such a seven-membered ring as the result of hydrogen bonding favors additional stabilization and mutual orientation of the reactants in this bicyclic transition state, thus lowering its energy. In contrast, a monocyclic transition state in which hydrogen bonding is impossible due to the unfavorable



mutual arrangement of the P—Me and C—R^F fragments has a higher energy.

The phosphorylation of a Si-containing alcohol free of fluorine is not diastereoselective because the CF...HCP-type hydrogen bonding is impossible.

The possibility of such an intramolecular hydrogen bonding is as important as the presence of a silicon atom. However, hydrogen bonding alone is insufficient for appreciable diastereoselectivity: the reaction of silicon-free polyfluoroalkanol **28** is not stereoselective.

Thus, the diastereoselective synthesis of esters is only possible where all the three aforementioned structural elements, namely, a silicon atom and a polyfluoroalkyl group in the alcohol and a methyl group at the P atom of the phosphorylating agent are present. The highest diastereoselectivity was achieved with reagents that ensure the formation of a bicyclic transition state (for one of the diastereomers) with electron-withdrawing substituents at silicon and bulky aryl radicals in the Ar—O—P fragment.

Experimental

NMR spectra were recorded on a Bruker WP-200SY instrument in $CDCl_3$ with signals for the residual protons of the deuterated solvent as the internal standard (^1H) and H_3PO_4 (^{31}P) and Me_4Si (^{29}Si) as the external standards. GLC-MS analysis was carried out on a Varian-3400 chromatograph with a DB-1 capillary column (30 m × 0.32 mm; the layer thickness was 0.25 μm); the temperature was programmed from 60 to 250 °C at a rate of 6 deg min^{-1}. A Finnigan-MAT 800 AT ion trap served as a detector (EI, 70 eV).

Silylalkanols **1**—**3** were prepared as described earlier.[10] Acid chloride **5** (Acros) was used without additional purification. The procedures for the syntheses of phosphorus acid chlorides **4** and **6** will be published elsewhere.

Catalytic phosphorylation of polyfluoroalkanols 1—3 and 26 with phosphorus acid monochlorides 4—6 (general procedure). Equimolar amounts of alcohol **1**—**3** or **26** and acid chloride **4**—**6** were heated in the presence of 2.5 mol. % Mg at 140—160 °C until the evolution of HCl ceased (1.5—8 h). The reaction product was isolated by chromatography on Al_2O_3 in ether and the solvent was removed *in vacuo*. The resulting esters **7**—**25** and **27** were analyzed by ^{31}P NMR spectroscopy and GLC-MS.

1,1,1,2,2,3,3,4,4-Nonafluoro-6-trimethylsilylhexan-5-yl phenyl methylphosphonate (8). Yield 37%, b.p. 103—105 °C (1 Torr), n_D^{20} 1.4213. Found (%): C, 39.16; H, 4.25; F, 34.65; P, 6.16. $C_{16}H_{20}F_9O_3PSi$. Calculated (%): C, 39.18; H, 4.11; F, 34.89; P, 6.32. ^1H NMR ($CDCl_3$), δ: 0.00, 0.11 (both s, 9 H, MeSi); 1.31 (d, 2 H, $C\underline{H}_2CH$, J = 6.8 Hz); 1.62, 1.63 (both d, MeP, $J_{H,P}$ = 18.0 and 17.6 Hz, respectively); 5.12—5.23 (m, 1 H, CH); 7.14—7.37 (m, 5 H, C_6H_5). ^{29}Si NMR, δ: 0.47 s, 0.23 s.

Phenyl 1,1,1-trifluoro-5-trimethylsilylpentan-2-yl methylphosphonate (22). Yield 67%, b.p. 121—124 °C (1 Torr). Found (%): C, 49.42; H, 6.67; F, 15.45; P, 8.40; Si, 7.35. $C_{15}H_{24}F_3O_3PSi$. Calculated (%): C, 48.90; H, 6.57; F, 15.48; P, 8.41; Si, 7.60. ^1H NMR ($CDCl_3$), δ: −0.12, −0.02 (both s, 9 H, MeSi); 0.27—0.65 (m, 2 H, $SiCH_2C$); 1.27—1.54 (m, 2 H, $SiCH_2C\underline{H}_2$); 1.62—1.88 (m, 2 H, $C\underline{H}_2CH$); 1.67, 1.68 (both d, 3 H, MeP, $J_{H,P}$ = 17.6 and 18.0 Hz, respectively); 4.75—4.90 (m, 1 H, CH); 7.15—7.34 (m, 5 H, C_6H_5). ^{29}Si NMR, δ: 0.94 s, 0.72 s. ^{31}P NMR ($CDCl_3$), δ: 29.64 s, 28.02 s.

1,1,1,2,2,3,3,4,4-Nonafluoro-6-trimethylsilylhexan-5-yl phenyl 2,2,2-trifluoroethyl phosphate (18). Yield 46%, b.p. 111—114 °C (1 Torr), n_D^{20} 1.4010. Found (%): C, 36.28; H, 3.34; F, 39.39; P, 5.45; Si, 4.71. $C_{17}H_{19}F_{12}O_4PSi$. Calculated (%): C, 35.54; H, 3.34; F, 39.71; P, 5.40; Si, 4.87. ^1H NMR (C_6D_6), δ: 0.05, 0.07 (both s, 9 H, MeSi); 1.19 (d, 1 H, $SiCH_2$, $J_{H,H}$ = 7.1 Hz); 1.34 (d, 1 H, $SiCH_2$, $J_{H,H}$ = 7.2 Hz); 3.81—4.22 (m, 2 H, CF_3CH_2); 5.27—5.45 (m, 1 H, CH); 6.86—7.36 (m, 5 H, C_6H_5). ^{29}Si NMR, δ: 0.66 br.s.

Phenyl 1,1,1-trifluoro-3,3-dimethylbutan-2-yl methylphosphonate (27). ^{31}P NMR, δ: 28.9 s, 27.5 s. MS, m/z ($I_{rel,A}$ (%)/$I_{rel,B}$ (%))*: 311 $[M + 1]^+$ (100/100), 275 $[M - Me - HF]^+$ (28/30), 174 $[M - Bu^tCHCF_3 + 1]^+$ (51/35), 77 $[Ph]^+$ (61/40).

Noncatalytic phosphorylation of silylalkanols 1a and 28 with phenyl methylphosphonochloridate 4b (general procedure). A equimolar mixture of alcohol **1a** or **28** and phosphonochloridate **4b** was stirred in the presence of a 10% excess of Et_3N in CH_2Cl_2 for 48 or 24 h, respectively. The precipitate of the salt was filtered off and the solution was concentrated *in vacuo*. The residue was chromatographed on Al_2O_3 in ether and the solvent was removed *in vacuo*. The resulting phosphonate **8** or **29** was analyzed by ^{31}P NMR spectroscopy and GLC-MS.

1,1,1-Trifluoro-3,3-dimethylbutan-2-ol (26)[11]. Ethyl trifluoroacetate (213.8 g, 3.0 mol) was added over 75 min to a water-cooled solution of the Grignard reagent prepared from metallic magnesium (76.8 g, 3.2 mol) and *tert*-butyl chloride (296.5 g, 3.2 mol) in 1.6 L of anhydrous ether. The reaction mixture was stirred for 1.5 h, left for 12 h, and then treated with a mixture of conc. HCl (290 mL) and water (350 mL). The organic layer was separated, and organic material from the aqueous layer was extracted with pentane (3×50 mL) and ether (2×50 mL). The extracts and the organic layer were combined and dried with $MgSO_4$. Distillation gave alcohol **26** (89.3 g, 38.2%), b.p. 110.5—110.8 °C, n_D^{20} 1.3675.

1-[Diethyl(methyl)silyl]pentan-2-ol (28). Butanal (5.0 g, 0.07 mol) in 30 mL of anhydrous ether was added dropwise to a solution of the Grignard reagent prepared from $MeEt_2SiCH_2Cl$ (10.4 g, 0.07 mol) and Mg (1.68 g, 0.07 mol) in 50 mL of anhydrous ether. The reaction mixture was stirred for 1 h and then refluxed for 0.5 h. On cooling, the mixture was treated with dilute H_2SO_4 (3 : 1, 50 mL). The organic layer was separated and the aqueous layer was extracted three times with ether. The combined extracts were dried with $MgSO_4$ and concentrated. The residue was dissolved in hexane and chromatographed on Al_2O_3 in hexane. The solvent was removed and the residue was distilled *in vacuo* to give alcohol **28** (8.9 g, 56.3%), b.p. 70 °C (8 Torr, slightly decomp.), n_D^{20} 1.4494. Found (%): C, 65.10; H, 12.85; Si, 13.99. $C_{10}H_{24}OSi$. Calculated (%): C, 63.76; H, 12.84; Si, 14.91. ^1H NMR ($CDCl_3$), δ: −0.03 (s, 3 H, MeSi); 0.51 (q, 4 H, $SiC\underline{H}_2Me$, $J_{H,H}$ = 8.0 Hz); 0.82, 0.83 (both d, 2 H, $SiC\underline{H}_2CH$, $J_{H,H}$ = 7.6 and 6.4 Hz, respectively); 0.85—0.93 (m, 9 H, $CCH_2C\underline{H}_3$, $SiCH_2C\underline{H}_3$); 1.29—1.40 (m, 5 H, CH_2CH_2, OH); 3.74—3.81 (m, 1 H, CH). ^{29}Si NMR (C_6D_6), δ: −4.11 s.

* $I_{rel,A}$ and $I_{rel,B}$ are the relative intensities of the ion peaks in the mass spectra of diastereomers **A** and **B**, respectively.

This work was financially supported by the Foundation of the President of the Russian Federation (Program for Support of Leading Scientific Schools of Russia, Grant NSh-1100.2003.3).

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Received April 30, 2004;
in revised form July 22, 2004