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CHEMISTRY OF TRIALKYLSILYL PERFLUOROALKANE SULFONATES PART I

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PART I.

TRIALKYLSILYL PERFLUOROALKANE SULFONATES AS SILYLATING AGENTS

1. INTRODUCTION

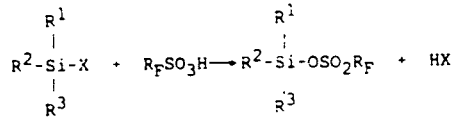
Within the past two decades, the chemistry of trifluoromethane sulfonic acid and its derivatives has displayed an enormous growth.[1a,b] In trialkylsilylation of organic compounds, formerly used for analytical purposes, a rapid expansion began in the same period so modification of the trialkylsilyl group was used as the impetus for a growing applications in organic synthesis[2–5] and in the selective protection[5,6] of functional groups. Important parts in these developments have been the synthesis and application of allylsilanes,[2–4] vinylsilanes,[2–4] arylsilanes,[7] alkynylsilanes,[2–4] silyl enolethers,[2–4,8a,b] and silylketene acetals[2–4,8a,b].

Synthesis and application of extremely reactive silylating agents like iodotrimethylsilane[4,6] and trialkylsilyl perfluoroalkane sulfonates[1b,9–11] contribute in an essential manner to this development. Since the last reviews on trialkylsilyl triflates numerous new applications as reagents and Lewis acid catalysts were published.

2. PREPARATION OF TRIALKYLSILYL PERFLUOROALKANE SULFONATES

2.1. From Silanes and Perfluoroalkane Sulfonic Acids or their Salts

The most important synthesis for silylperfluoroalkane sulfonates **1** is the solvolysis of Si–X bonds in silanes by perfluoroalkane sulfonic acids (Table I).

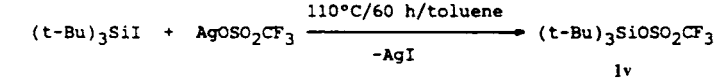


1

R^1, R^2, R^3 = H, alkyl, aryl
X = Cl, H, allyl, aryl, alkyl, 1,3-oxazolidine-2-on-1-yl
R_F = CF_3, C_4F_9, C_8F_{17}, $[(CF_2–CF_2)_m–CF(–O–CF_2CF(–CF_3)–O–CF_2CF_2–)–CF_2]_n–$

Under the usual conditions, chlorosilanes are directly reacted with equivalent quantities of the acid at 20–70°C.[9–20] Neither side reactions as solvolysis of Si–C-bonds (for R^1, R^2, R^3 = alkyl) are to be expected, nor removing of hydrogen chloride causes any problems. Under very mild conditions (0–20°C) and within short reaction times trimethylsilyltriflate (**1a**) is obtained by protodesilylation of phenyltrimethylsilane,[21] allyltrimethylsilane[22,23] and tetramethylsilane[22,24,25] or from 2-trimethylsilyl-1,3-oxazolidin-2-one[26,27] with trifluoromethane sulfonic acid. The latter ones also may serve for *in situ* synthesis of **1a**[22–24,26] as well as trimethylsilyl nonafluoro butanesulfonate (**1r**) obtained in solution from potassium nonafluorobutanesulfonate and chlorotrimethylsilane.[28,29] The cleavage of the Si–X bond in R_3SiX by trifluoromethane sulfonic acid decreases in the following manner:[17] X = α-naphthyl > phenyl > chloro > hydrogen >> methyl, ethyl, butyl. According to this scale, *trialkyl*silyltriflates are readily available by the direct reaction with the sulfonic acid whereas aryldialkylsilyl triflates cannot be obtained in high yields and purity by this method.

The preparation of esters 1 from silver perfluoralkane sulfonates and halosilanes[30,31] is only employed for the synthesis of triflates with extraordinary bulky groups such as **1v,w**:[32–35]



1v

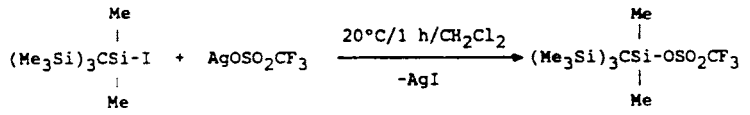
Table I. Silylperfluoroalkane Sulfonates and Dialkylsilylbistriflates from Silanes and Perfluoroalkane Sulfonic Acids[a]

Perfluoroalkanesulfonate (No.)	*Educt -silane*	*Reaction conditions [°C/h]*	*Yield [%]*	*bp [°C/torr]*	*Reference*
Trimethylsilyl triflate (**1a**)	Chlorotrimethyl-	80/6	92	32/12	9,10
	Phenyltrimethyl-	0-20/0.5	92		21
	Allyltrimethyl-	20/1	85		22,23
	Tetramethyl-	20/1	99		24,25
	Trichloromethyltrimethyl	120/1	88		38
	3-Trimethylsilyl-1,3-oxazolidine-2-on	0-40/0.25	98		26,27
t-Butyldimethylsilyltriflate (**1b**)	*t*-Butyldimethylchloro-	80/2	90	63/10	9
		60/10	80		14
		100/20 (in heptane)	89		13
	t-Butyldimethyl-	0-40/0.25	90		38
Triethylsilyltriflate (**1c**)	Chlorotriethyl-	80/6	81	72/10	9
		20/15	90		19
Triisopropylsilyl triflate (**1d**)	Chlorotriisopropyl-	22/16	97	83–87/1.7	14,19
Thexyldimethylsilyltriflate	Chlorodimethylthexyl-	60/5	80	40–42/0.15	20
Di-*t*-butylmethylsilyl triflate (**1f**)	Di-*t*-butylmethyl-	4-20/16	95	63–65/15	39
Dimethylisopropylsilyl triflate (**1g**)	Chlorodimethylisopropyl-	—	—	—	19
Dimethyloctadecylsilyl triflate (**1h**)	Chlorodimethyloctadecyl-	70/0.5	—	—	14
Tri-*n*-butylsilyl triflate (**1i**)	Tri-*n*-butylchloro-	20/18	—	—	19
Diphenylmethylsilyl triflate (**1k**)	Chlorodiphenylmethyl-	—	—	—	19
t-Butyldiphenylsilyl triflate (**1l**)	*t*-Butyltriphenyl-	70/0.5	73	115/0.02	17
Dimethylsilyl triflate (**1m**)	Chlorodimethyl-	20/5 min	95		
				123/760	17
	Dimethylphenyl-	20/5 min	86		
Methylphenylsilyl triflate (**1n**)	Diphenylmethyl-	20/5 min	93	67/0.8	17
Silyl triflate (**1o**)	Phenyl-	—	—	decomp.	17

Table I. (Continued)

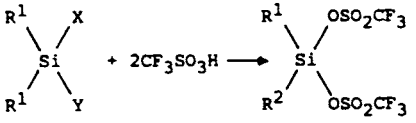
Perfluoroalkanesulfonate (No.)	*Educt -silane*	*Reaction conditions [°C/h]*	*Yield [%]*	*bp [°C/torr]*	*Reference*
t-Butylchlorophenylsilyl triflate (**1p**)	*t*-Butylchlorophenyl-	20/0.5	92	70/0.01	17
Trichlorosilyl triflate (**1q**)	Phenyltrichloro-	60/3	85	35/25	17
Trimethylsilylnonafluorobutanesulfonate (**1r**)	Chlorotrimethyl-	80/7	90	68–69/11	9,16
	Phenyltrimethyl-	0-20/0.5	89		21
t-Butyldimethylsilylnonafluorobutanesulfonate (**1s**)	*t*-Butylchlorodimethyl	60-70/12	85	94–96/16	18
Trimethylsilylheptadecafluorooctanesulfonate (**1t**)	Phenyltrimethyl-	0-20/0.5	77	42/0.001	21
Trimethylsilylnafion (**1u**)	Chlorotrimethyl-	80/5	0.8 mmol $SiMe_3$/g resin		15
	Bis-trimethylsilyltrifluoroacetamide	20/12	—	—	40
Dimethylsilyl ditriflate (**1x**)	Dichlorodimethyl-	20/5 120/12	63	94/11	37
Diisopropylsilyl ditriflate (**1y**	Chlorodiisopropyl-	Reflux/2	77	61–63/0.3	36
Di-*t*-butylsilyl ditriflate (**1z**)	Chloro-di-*t*-butyl	Reflux/2	71	73–74/0.35	36

[a]Because of greater importance triflates **1a-f** were placed ahead in the table.



1w

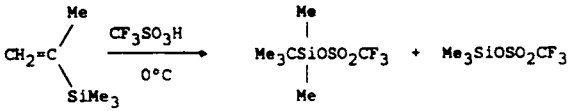
Dialkylsilyl-bis-triflates **1x–z** are accessible by the reaction of dialkyldihalosilanes or dialkylhalosilanes with trifluoromethane sulfonic acid. For quantitative conversion longer reaction periods than those needed for monotriflates are required.[36,37]



1x-z

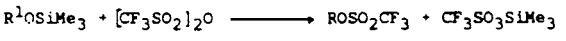
2.2. By Other Methods

1b can be obtained by reaction of 2-trimethylsilylpropene with trifluoromethane sulfonic acid with simultaneous rearrangement. The by-product is **1a**, which can be separated by distillation.[41]



1b (66%) **1a** (~ 15%)

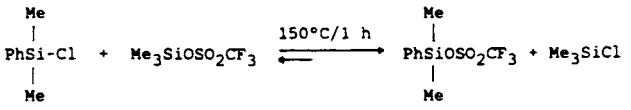
Siloxanes,[42,43] silyl ethers,[44] and silyl phosphonates[45] are cleaved by trifluoromethane sulfonic acid anhydride to yield silyl triflates **1**, e.g.,



1a (88%)

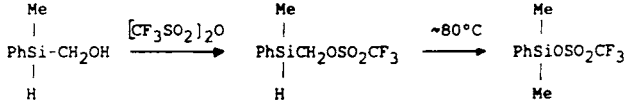
$R^1 = SiMe_3$

For the preparation of aryl substituted silyl triflates, transesterification of arylchlorosilanes by **1a** in the presence of 4-dimethylaminopyridine may be of interest.[46]



1k' (60%)

The triflate **1k'** also results from thermally induced rearrangement of methyl phenylsilylmethyl triflate:[47]



The electrophilic dehalogenation of silanes by perfluoroalkane sulfonic acid hypohalogenites is only of importance for the preparation of special silyl triflates:

$$C_4F_9SO_2OX + BrSiF_3 \longrightarrow C_4F_9SO_2OSiF_3 + BrX^{48}$$

$$CF_3SO_2OX + SiCl_4 \longrightarrow CF_3SO_2OSiCl_3 + ClX^{49}$$

X = Cl, Br

3. PROPERTIES OF TRIALKYLSILYL PERFLUOROALKANE SULFONATES

The esters **1** generally are liquids,distillable without decomposition, very soluble in solvents of low polarity, stable in dry atmosphere but strongly fuming in moist air due to rapid hydrolysis. Among all silylating agents—except the perchlorates—they exhibit the highest Lewis acidity as is shown by low field ^{29}Si NMR absorption in Table II.[12,17,19,50] Although silicenium ions do not exist in equilibrium,[50] esters **1** can be considered as "bulky protons".[51] With heterofunctional groups onium ions are formed in equilibrium reactions (see Chapter 2). With boron trihalides they give donor–acceptor complexes, but no dissociation into silicenium ions takes place.[19]

4. REACTIVITY OF TRIMETHYLSILYLATING AGENTS

By measuring the reaction rates in silylation of cyclopentanone and diisopropyl ketone with silylating agents, Me_3SiX, in the presence of triethylamine the following relative rate constants, k_{rel}^{23} in 1,2-dichloroethane as solvent are observed.[53]

X	Cl	$MeSO_3$	4-$MeC_6H_4SO_3$	$PhSO_3$	Me_3SiOSO_3	4-$BrC_6H_4SO_3$
k_{rel}^{23}	1	40	100	160	270	570
X	Br	$F_3CCH_2SO_3$	F_3CSO_3 (**1a**)	I		
k_{rel}^{23}	10^4	$1.4 \cdot 10^4$	$6.7 \cdot 10^8$	$\sim 7 \cdot 10^9$		

Accordingly, the silylation potential of chlorotrimethylsilane is surpassed with **1a** by a factor of nearly 10^9. A similar reactivity scale could be derived from determination of equilibrium constants in the exchange reaction of 1,3-bis(tri-

Table II. Spectroscopic Data of Some Trialkylsilyl Perfluoroalkanesulfonates[a]

Perfluoroalkane sulfonates	^{29}Si *NMR*[19]	^{1}H *NMR (CDCl$_3$)*
1a	43.54	0.48 (s)[17]
1b	43.50	0.48 (s), 1.0 (s)[14,17]
1c	44.46	1.02 (m)[9]
1d	41.15	1.05-1.6 (m)[14]
1r	—	0.52 (s)[21]
1f	—	0.50 (s), 1.12 (s)[39]
1x	—	0.87 (s)[37]
1y	—	1.24 (d), 1.59 (sept)[36]
1z	—	1.25 (s)[36]
Trimethylsilyltrifluoroacetate[50]	34.2	
Bis(trimethylsilyl) sulfate[12]	33.7	

[a] ν_{SO_2} in silyl triflates[52] and silyl nonafluorobutane sulfonates[18,21] is observed at 1390 cm^{-1}.

methylsilyl)imidazolium salts with silylating agents where the order of reactivity[54,55] is Me_3SiClO_4[16] > $Me_3SiOCO_2CF_3$ (**1a**) > Me_3SiI > Me_3SiBr > Me_3SiCl.

5. GENERAL ASPECTS OF SILYLATION WITH TRIALKYLSILYL PERFLUOROALKANESULFONATES

Because of the extreme reactivity of the esters **1** towards nucleophiles moisture must be excluded in all reactions. Silylations with these reagents generally proceed at 0–20°C and are finished within a few minutes or hours. Yields are ordinarily high. Suitable solvents are hydrocarbons (benzene, toluene), ethers (ethyl ether, 1,2-dimethoxyethane, 1,4-dioxane), chlorocarbons (dichloromethane, 1,2-dichloroethane, trichloroethylene, carbontetrachloride), triethylamine or 1 : 1 triethylamine/1,2-dichloroethane mixtures.

The silylation of ketones take place 100 times faster in 1,2-dichloroethane compared with the nonpolar tetrachloromethane as solvents. Tetrahydrofuran is slowly cleaved by **1a** and acetonitrile is silylated in the presence of a base (Chapter 6.4.3). These latter two solvents, therefore, are only recommended for very quick reactions of **1** with the substrates. N,N-dialkylcarboxylic acid amides and **1** form iminium salts of lower reactivity in exothermic reactions (Chapter 6.2.6.10). As for auxiliary bases—as far as adducts are formed with **1** (Chapter 6.4.1)—triethylamine is suitable in most cases. The reactivity of esters **1** is much less decreased, owing to strong reversible adduct formation with triethylamine than by trimethylamine or N-methylpyrrolidine which form complexes of considerable

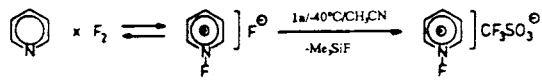
trimethylamine or N-methylpyrrolidine which form complexes of considerable thermodynamic stability with **1a**. Also N-substituted imidazoles are not to be recommended for the same reason. A further advantage of triethylamine is to be found in the separation of triethylammonium triflate as a liquid. Because of the ability to detect triethylammonium triflate, the progress of the reactions consequently are followed in a facile manner.

In order to get high yields in the silylation, a low solubility of trialkylammonium salts is often crucial due to the reversibility of the silylation processes (protodesilylation). Hünig-bases and 2,6-lutidine (silylations with **1b,d**) are also successfully employed. Chapter 6.5.2 deals with the regioselectivity in silylations with **1a** in presence of different bases.

6. REACTIONS OF TRIALKYLSILYL PERFLUOROALKANE SULFONATES

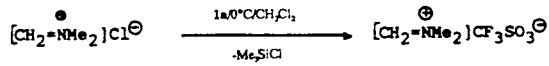
6.1. With Halogen Nucleophiles

Because of extraordinary leaving group ability of the triflate anion, **1a** rapidly reacts with halide anions to yield halogenosilanes. In the reaction with fluoride ion, the equilibrium is quantitatively shifted to the fluorotrimethylsilane side because of the high Si–F bond energy. This exchange is of importance for the synthesis of the stable fluorination agent **2**:[56–58]



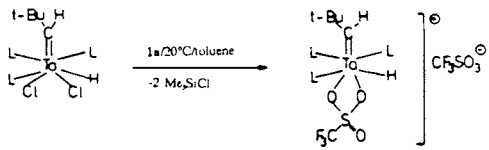
2 (78%)

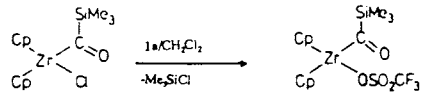
Fluorotrimethylsilane can be prepared from potassium fluoride and **1a**.[59] The replacement of chloride anion is achieved in aprotic media and may be used for the preparation of Mannich reagents **3**:[60]



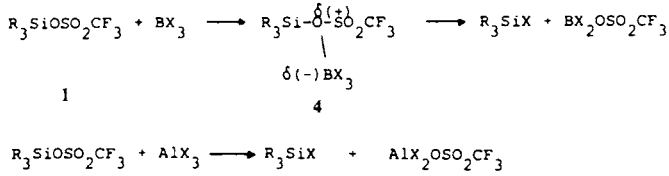
3 (~100%)

In numerous metal complexes the exchange of chlorine ligands by **1a** succeeds under mild conditions in a quantitative manner.[61–65]

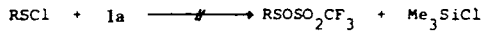




Olah et al.,[19] who tried to generate silicenium ions from the donor–acceptor complexes of triflates **1** with halides of the third main group elements **4**, found ligand exchange to be a competing process. Its rate increases by increasing the ionic character of the element–halogen bond.



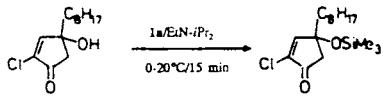
Attempts to convert sulfenylchlorides into sulfenyl triflates failed presumable because of their thermal lability.[66]



6.2. With Oxygen Nucleophiles

6.2.1. With Alcohols and Phenols—Synthesis of Trialkyl Silyl Ethers

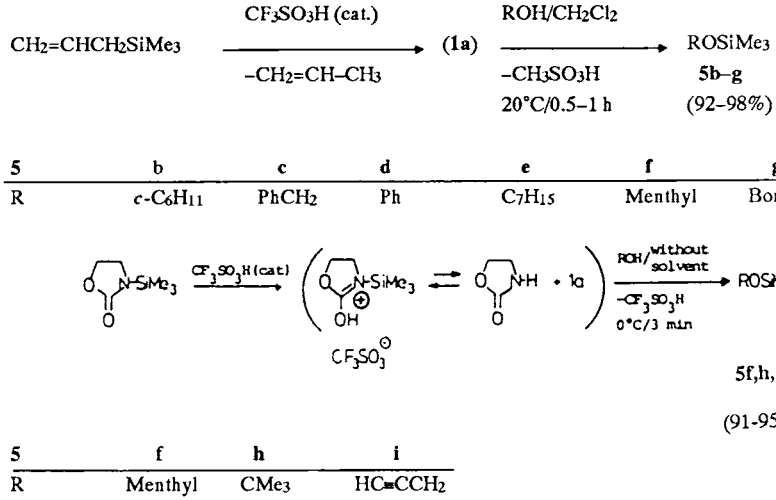
The trialkylsilylation of primary and secondary alcohols by use of equivalent quantities of **1a**[67] or Nafion-TMS (**1u**)[15] is of little importance. For this conversion more economic procedures with less reactive silylating agents are available.[2–5] However, as a mild method it is to be recommended for the effective silylation of tertiary alcohols.[68]



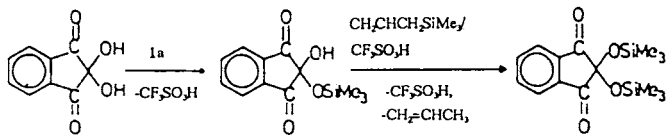
5a

Of more interest are processes in which **1a** is generated with catalytic amounts of trifluoromethane sulfonic acid from allyltrimethylsilane[22,23] or 3-trimethylsilyl-1,3-oxazolidine-2-one[27] in the presence of alcohols or phenols. Under these conditions, formation of trimethylsilyl ethers occurs almost immediately. Although

only propene or the scarcely soluble 1,3-oxazolidin-2-on result as by-products working up is very simple.

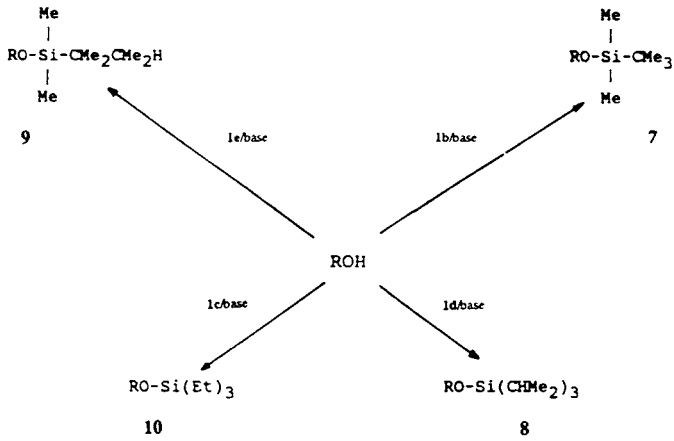


This acid catalyzed silylation proceeds without any problems, so protodesilylation is insignificant for alkylsilyl ethers **5**. Acetal **6** is obtained from ninhydrin and allyltrimethylsilane with catalysis of **1a**:[69]



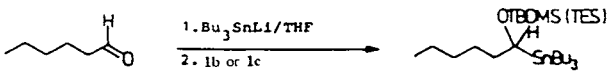
Of considerably more interest is the introduction of bulky silyl groups as protective groups, especially during natural product synthesis.[6] So often problems occur in silyl-protection of tertiary and sterically hindered secondary alcohols in reaction with the usual silylating agents.[13,14,70] Corey et al.[14] introduced *tert*-butyldimethylsilyl (TBDMS) triflate (**1b**) and triisopropylsilyl (TIPS) triflate (**1d**) to circumvent these problems. Recently, instead of **1b** the less expensive thexyldimethylsilyl (TDS) triflate (**1e**) has also been applied.[20]

The conversions proceed at 0–25°C within 5 min–1 h in the case of **1b**, 2–5 h in the case of **1d**. Dichloromethane or chloroform are commonly used as solvents.[13,14,20,67,68,70–83] 2,6-Lutidine (Method A) or triethylamine (Method B) serve well as auxiliary bases. The ratio of the reactants generally is alcohol : silyl triflate : base = 1 : 1.5 : 2–2.5. Under such conditions primary and secondary alcoholic functions are protected by the TBDMS, TIPS, and TDS groups. Tertiary alcohols still react with **1b** and **1e**, but not with **1d**.



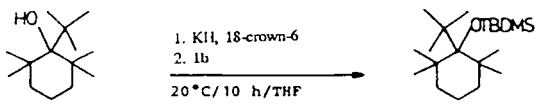
Base = 2,6-lutidine or triethylamine

Triethylsilyl triflate (**1c**) is used only seldom.[67] Sensitive functional groups and centers of chirality are not affected and side reactions do not occur under the mild, almost neutral reaction conditions. As expected lithium alkanolates produced *in situ* are rapidly silylated by **1b,c**.[84]



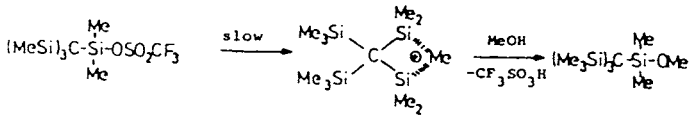
7t or 10b

Application of "naked" alkanolates should only be necessary in cases of extreme steric hinderance.[85]



7u (54%)

According to the extraordinary shielding of silicon in triflate **1w** methanolysis proceeds in a S_N1-mechanism via a bridged silicenium ion:[33,34]



1w 11

Method A

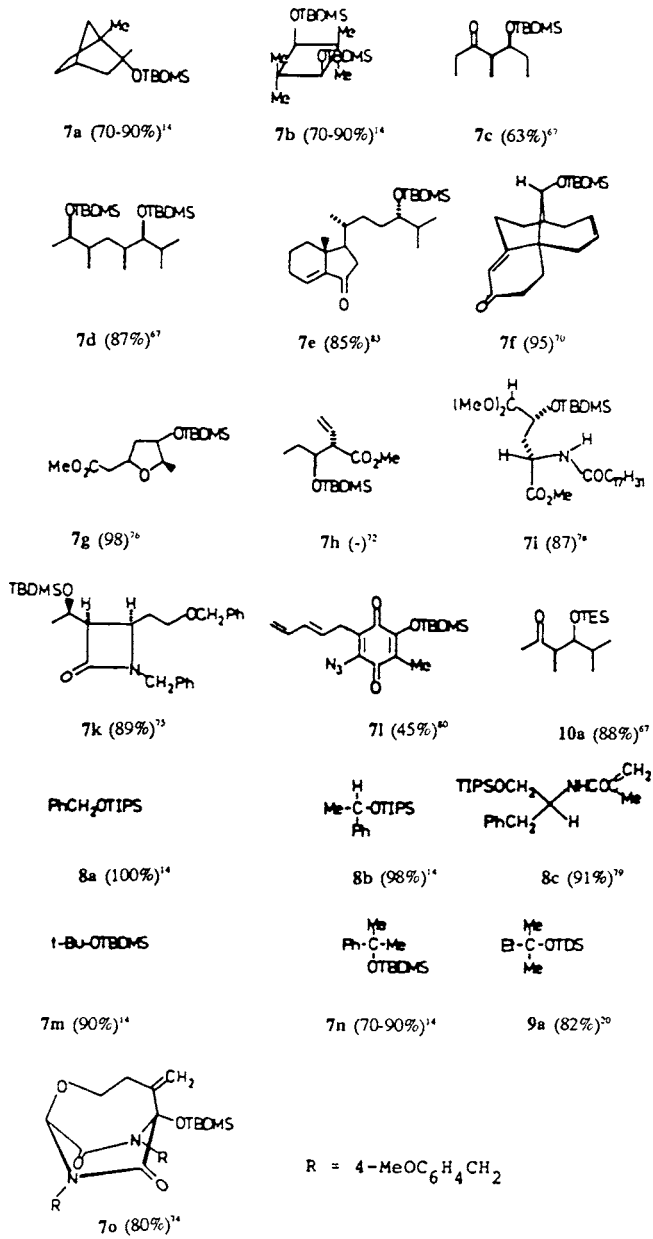
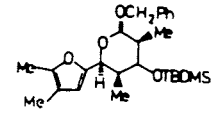
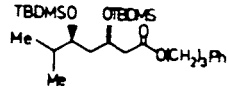


Figure 1. Some silyl ethers **7–10** prepared by silylation of secondary and tertiary alcohols with **1b,d,e,c** in presence of 2,6-lutidine (Method A) or triethylamine (Method B).

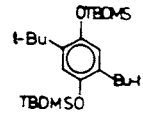
Method B



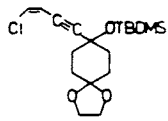
7p (96%)[73]



7q (80%)[82]



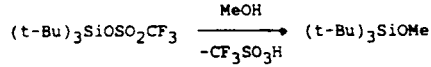
7r (83%)[13,71]



7s (82%)[81]

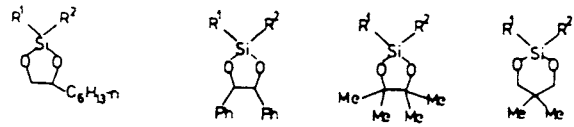
Figure 1. (Continued)

The similar reaction rate in methanolysis of triflate **1v** may be interpreted by a S_N2 mechanism.[32]

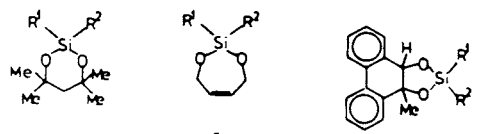


1v **12**

For the protection of alkanediols Corey et al.[36] introduced the very effective triflates **1y,z**. Reactions with 1,2-, 1,3-, and 1,4-diols in the presence of 2,6-lutidine proceed at 0–25°C in chloroform to give rise to ethers **13**, **14** in nearly quantitative yields.



13,14 a b c d



e f g

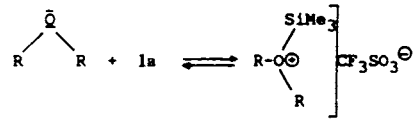
13: R^1,R^2 = *i*-Pr (~100%)

14: R^1,R^2 = *t*-Bu (70-96%)

Figure 2. Dialkylsilyl ethers **13**, **14** from diols and dialkylsilyl bistriflates **1y,z** in the presence of 2,6-lutidine.[36,86]

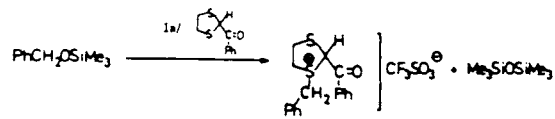
6.2.2. With Ethers

In the course of equilibrium reactions with ethers **15** triflates **1** form oxonium triflates **16**:

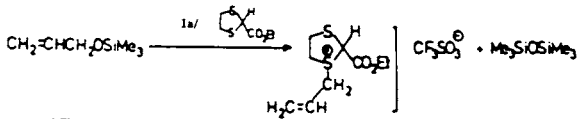


15 **16**

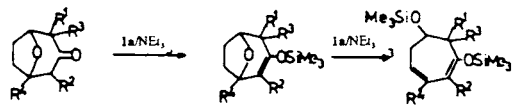
Because of the low nucleophilic properties of the triflate anion dialkylethers are not whereas tetrahydrofuran is cleaved in a slow reaction rate.[87] Concerning the cleavage of acetals and orthoesters in bond formations catalyzed by **1a** see Chapter 3, Part II, Section 4.1. In the presence of soft S-nucleophiles heterolysis of C–O bonds in allyl and benzyl ethers occurs.[88] For cleavage of benzyl ethers in peptide synthesis see Chapter I, 6.2.3. The reason for rapid cleavage of the ether bridge in ketones **18**, **19** to yield silyldienol ethers **20** or tropones **21** is probably due to an allylic stabilization of intermediate carbocations.[89]



15a **17a**

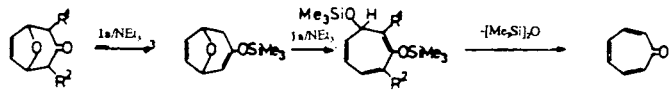


15b **17b**



18 **20**

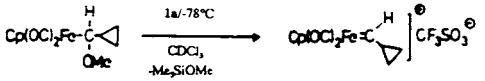
R^1, R^2, R^3, R^4 = H, Me



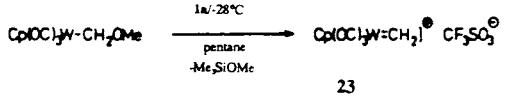
19 **21**

R^1, R^2 = H, Et

Preparation of metal-carbene-complexes **22** and **23** proceeds by cleavage of the ether bonds with **1a** in nonpolar solvents.[90–93]



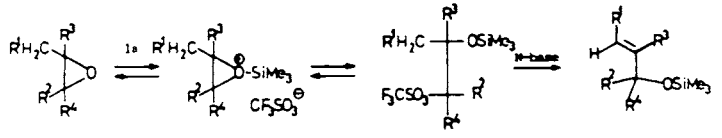
22



23

Investigated in a detailed manner and used for preparative purposes is the cleavage of oxiranes **24** to allyltrialkylsilyl ethers **25** by means of **1a**[9,10,94] or **1b**.[95]

According to Noyori et al.,[10,94] the transformation is to be interpreted as trans addition of **1a** to the 2,2-di-,tri-, tetra-, and 2,3-cycloalkylidene substituted oxirane ring followed by nitrogen base promoted anti elimination of trifluoromethane sulfonic acid. Primary intermediates are again oxonium ions **16**.



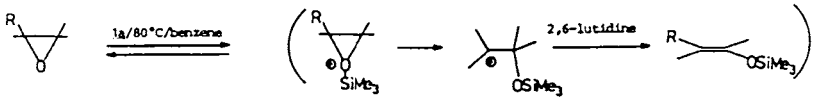
24 **16** **25** (60-87%)

24/25	R^1	R^2	R^3	R^4
a	$-(CH_2)_2-$		H	H
b	$-(CH_2)_3-$		H	H
c	$-(CH_2)_4-$		H	H
d	$-(CH_2)_5-$		H	H
e	H	Me	Me	Me
f	H	$-(CH_2)_4-$		H
g	$R^1,R^3 = -(CH_2)_4-$,	R^2 = H		H
h	H	H	Me	$Me-C(O)-CH_2CHMe(CH_2)_2-$
i	H	H	Me	$Me_3SiO(CH_2)_2CHMe(CH_2)_2-$
k	H	H	Me	$MeO_2CCH_2CHMe(CH_2)_2-$
l (*cis* and *trans*)	$Me_2C=CHCH_2-$	H	Me	Me_3SiOCH_2-
m	H	H	$Me_2C=CH(CH_2)_2-$	Me_3SiOCH_2-

Although ketonic and ester substrates are susceptible to silylation (Chapter 6.2.6.2 and 6.2.6.5) by **1a** in the presence of nitrogen bases, the oxirane ring is cleaved much faster leaving these functions intact.[94] The production of the allylsilylethers **25**—not a silyl enol ether—is a consequence of anti elimination of trifluoromethane sulfonic acid. Participation of olefinic bonds in ring cleavage followed by transannular cyclization is observed in humulene epoxides.[96,96a] The conversions usually are accomplished in one step at room temperature in benzene or toluene with 1,8-diazabicyclo[5.4.0]undec-7-en (DBU) as base or in two steps with 2,6-lutidine

(trans addition at –78°C followed by DBU promoted elimination at 20°C). The somewhat faster ring cleavage by lutidine/**1a** compared with DBU/**1a** is due to the different reactivities of the amine-**1a** complexes (see chapter 6.5.2).

Mono- and 2,3-dialkylsubstituted oxiranes are isomerized to silyl enol ethers and converted to their respective compounds after aqueous workup:[10,94]



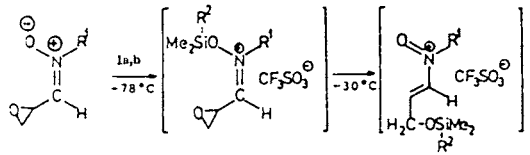
24n

R = n-C_8H_{17}

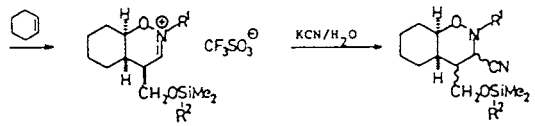
25n

From glycidylmethacrylates and **1a** mixtures of isomeric methacrylates are obtained.[97]

The *in situ* synthesis of heterodienes **28** is achieved by ring cleavage of epoxy nitrones **26** with **1a,b**. The dienes **28** are quenched by means of an inverse Diels-Alder-reaction.[31,98]

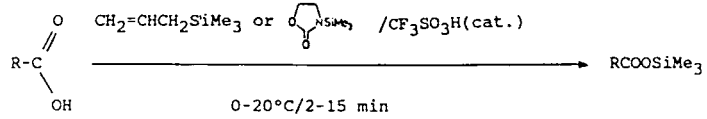


26 27 28

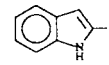


6.2.3. With Carboxylic Acids and Carboxylic Acid Esters—Synthesis of Trialkylsilyl Carboxylates (Ester Cleavage)

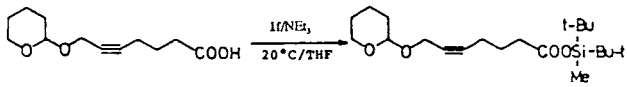
Sufficient methods exist[2–5] for the synthesis of trimethylsilyl carboxylates from carboxylic acids. Preparation of silyl esters **29** by means of **1a** catalytically generated from allyltrimethylsilane or 3-trimethylsilyl-1,3-oxazolidin-2-on is of some interests.[22,23,27] Carboxylic acids are quantitatively converted into the esters **29** within a few minutes at 0–20°C. Thus, the presence of bases for the silylation is not necessary and carboxylic acids which decarboxylate easily are transformed into silylcarboxylates without any problems under these conditions.[27]



29 (91-97%)

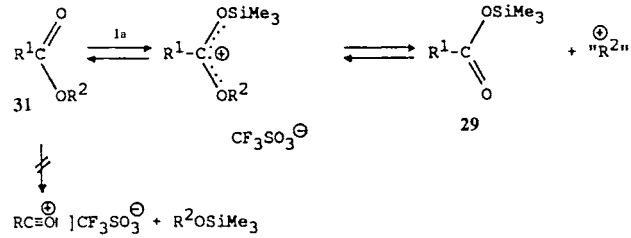
29	a	b	c	d	e	f	g	h	i	k
R	H	Me	*t*-Bu	CCl_3	Et	Ph	MeCH=CH	PhCH=CH		PhCHCOOH

Only one report on the silylation of carboxylic acids by trimethylsilyl-nafion (**1u**) has appeared.[15] Di-tert-butylsilylcarboxylates **30** are not only resistant against hydrolysis, but also convertible in numerous reactions without affecting the carboxyl groups are obtained in high yields from carboxylic acids and **1f**/NEt_3:[39]

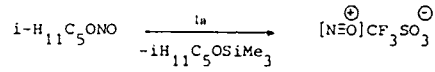


30a (92%)

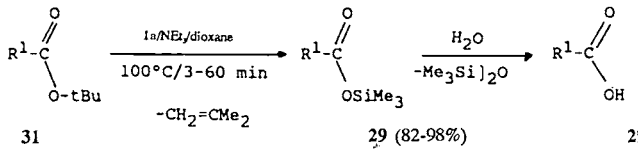
Esters **31** containing groups R^2 which are able to form stabilized carbocations are silylatively cleaved by **1**.[9,99–101]



An acylium ion till now was only observed in reaction of **1a** with isoamyl nitrite:[102]



Thus, under mild and nonacidic conditions *tert*-butylcarboxylates **31** are selectively transformed into silylcarboxylates **29** by means of **1a**/NEt_3. Other ester groups are not affected.[9,99–101]

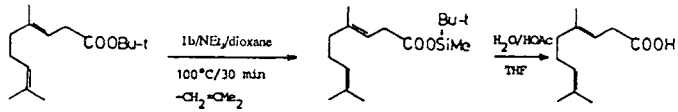


31 29 (82-98%) 29'

31, 29, 29'	b	e	f	l	m	n
R^1	Me	Et	Ph	n-C_5H_{11}	$MeOCOCH_2$	$PhCH_2OCO(CH_2)_2$

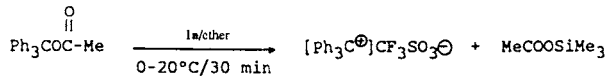
31, 29, 29'	o	p
R^1	$PhOCONHCH_2$–	$PhCH_2CH$(NHCOOCH$_2$Ph)–

The superiority of this method compared with the cleavage by iodotrimethylsilane was demonstrated in synthesis of the acid **29'r**:[103]



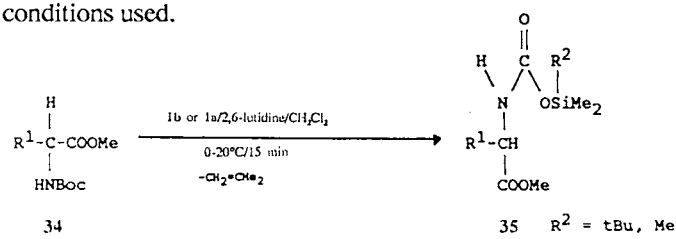
31r 29r 29'r

An analogous cleavage of tritylacetate (**32**) in the absence of bases is useful for the synthesis of trityltriflate **33**.[100]

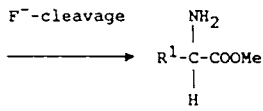


32 33 29b

These ester cleavage reactions have proved especially useful in the selective removal of the N-Boc protecting group in amino acids and peptides[105–108] as it was prior found by Vorbrüggen et al.[16,104] N–Z protective groups are not affected under the mild conditions used.

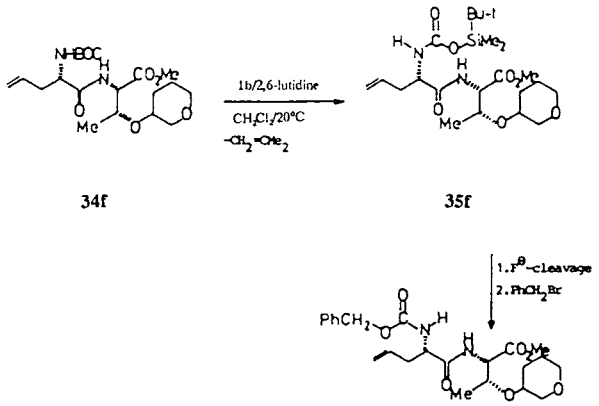


34 35



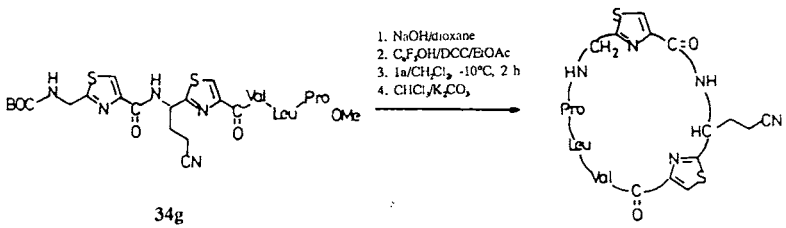
36

34,35,36	a	b	c	d	e
R^1	$ZNH(CH_2)_4$	CH_2=$CHCH_2$	Me_2CH	$MeS(CH_2)_2$	$PhCH_2$



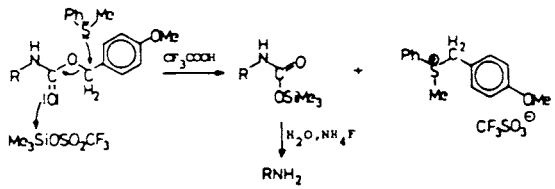
34f 35f

Schmidt et al.[109–111] applied this extremely mild and selective method to remove N-Boc groups from **34g** with **1a** (CH_2Cl_2 at $-40 \rightarrow 20°C$) in the last step before ring closure to yield the cyclopeptide **36.** Removal of the Boc group and cyclization also can be combined in a "one-pot" procedure.[109]



34g 36

Benzyl-type protective groups in esters, ethers, and thioethers can be removed by **1a** in trifluoroacetic acid as polar protic solvent and especially well in the presence of cation scavengers such as thioanisole. The cleavage processes with **1a** proceed much faster (15–30 min, 0°C) than those with trifluoromethane sulfonic acid/thio anisole[112–114] (Table III).



With the **1a**/trifluoroacetic acid/thioanisole mixture the removal of peptides from the Merrifield resin is achieved.[115]

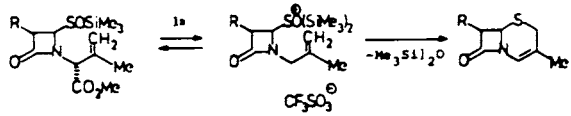
Table III. Removal of Different Protective Groups by 1 M **1a**/Trifluoroacetic Acid at 0°C/30 min.

	Yield [%] of free amino acid[a]	
Amino-acid derivative	*A*	*B*
Z(OMe)-Ser(Bzl)-OH	84	91.7
Z(OMe)-Glu(OBzl)-OH	92.2	99.3
Boc-Asp(OChp)-OH	91.4	100.0
Boc-Tyr(Bzl)-OH	63.3	100.0
Boc-His(Tos)-OH	88.5	94.5
Boc-Trp(Mts)-OH	74.7	100.0
H-Cys(MBzl)-OH	100.0	100.0
Boc-Cys(*t*-Bu)-OH	0	87.3
Z(OMe)-Cys(Ad)-OH	91.7	100.0

[a] A: in absence, B: in the presence of molar quantities of thioanisole.

6.2.4. With Sulfenic Acid Silyl Esters

Sulfenic acid silylester **37** is cyclized via an intermediate siloxonium cation in the presence of **1a** to give the cephem carboxylate **38**.[116]



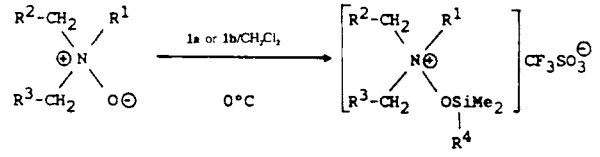
37 **38**

6.2.5. With Amine-N-oxides

Trialkylsiloxy-ammonium triflates **40** are obtained in quantitative yields from amine oxides **39** and **1a** or **1b**.[117–120] The salts **40** are obtained in solution and characterized by ^{1}H NMR.[117,120] They are intermediates in the dealkylation of tertiary amines,[117,120] in the synthesis of aminonitriles by reaction with trimethylsilylcyanide,[119] and in the Silyl-Polonovsky reaction[120].

6.2.6. With Carbonyl Systems

*6.2.6.1. Reaction Course in Silylation of Ketones **41** with **1a**.* The reaction mechanism in the formation of silyl enol ethers **42e**, **42q** from diisopropyl ketone **41e** and cyclopentanone **41q** and **1a** in the presence of triethylamine and in 1,2-dichloroethane as solvent at 23°C were studied.[9,53,121] According to these results triethylamine and **1a** form the N-silylammonium triflate **A** in the primary

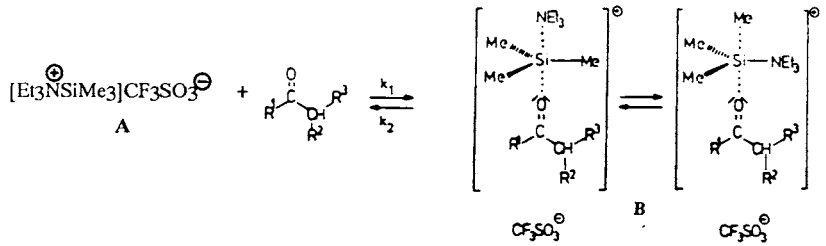


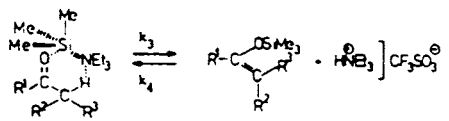
39 40

R' = Me, *t*-Bu

39,40	R^1	R^2	R^3
a	Me	$-(CH_2)_3-$	
b	Et	$-(CH_2)_3-$	
c	$PhCH_2$	$-(CH_2)_3-$	
d	Me		
e	Me	H	Ph
f	Et	Me	Me
g	$PhCH_2$	Ph	Ph

step. Because of its ionic constitution, **A** is highly electrophilic and adds to ketones **41e** or **41g** in a fast further step to give the pentacoordinated complex **B**. Most likely via a six-membered transition state **B** decomposes into silyl enol ethers **42e,g** and triethylammonium triflate. All processes are equilibria:





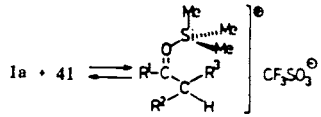
42e,g

41/42	R^1	R^2	R^3
e	*i*-Pr	Me	Me
g	$-(CH_2)_3-$		H

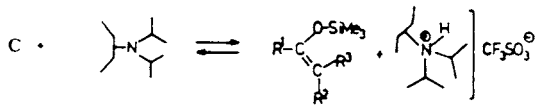
The overall reaction is first-order, indicating that the components aggregate rapidly to the complex **B**, the decomposition of which comprises the rate determining step ($k_1 >> k_3 >> k_2$).[121] In addition to the kinetic α-CH-acidity the reaction rate is mainly

influenced by the stability of the Si–N bonds, as can be proved by using different tertiary amines (see chapter I, 6.5.2). Analogous mechanisms are to be assumed for the reaction of **1a** with other carbonyl systems.

In the presence of sterically hindered amines, which cannot form ammonium salts such as **A**, oxonium ions **C** are proposed as intermediates. Deprotonation to give silyl enol ethers **42** is then the result of external attack of the base on the complex.

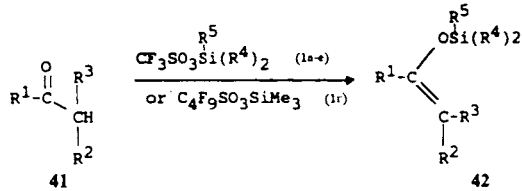


C



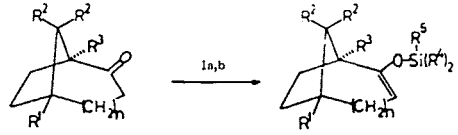
42

6.2.6.2. With Ketones and Aldehydes (Silyl Enol Ether Synthesis[2–4,8a,b]). From dialkyl ketones, cycloalkanones, aryl-alkyl ketones **41**, bicyclic ketones **43**, α-phenylthio ketones **45**, α-bromo ketones **47** or α,β-unsaturated ketones **49**, and equivalent quantities of the triflates **1a–e,r** silyl enol ethers **42**, **44**, **46**, **48**, **50** are prepared (Table IV).[8b,9,14,20,27,28,122–131] Silylations usually proceed exothermically and are finished in general quantitative (^{1}H NMR spectroscopic) after a few hours at 0–20°C even with the sterically hindered triflate **1d**.[14] Electron-withdrawing groups have little effect on reaction rates[9,122,83a,125]; in reactions with sterically hindered carbonyl compounds the rates are slower. Silylations also can be accomplished by *in situ* prepared triflates **1a**[22] or **1r**.[28] Because of very simple workup triethylamine[9,122] is usually preferred as the proton acceptor (chapter I, 5). Other tertiary nitrogen bases such as DBU,[27] 2, 6-lutidine, or Hünig's base[132,133] are seldom used. Ether, 1,2-dimethoxyethane, or dichloromethane are suitable solvents. In the less polar tetrachloromethane or hydrocarbons the silylations are slower. To shorten reaction periods, the higher boiling 1,2-dichloroethane is chosen for reactions with sterically hindered ketones.[121,122] Because the reverse reaction

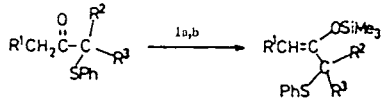


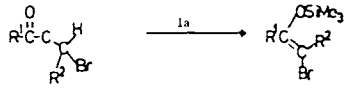
41 42

1	a	b	c	d	e
R^4	Me	Me	Et	*i*-Pr	Me
R^5	Me	*i*-Bu	Et	*i*-Pr	Me_2CHCMe_2

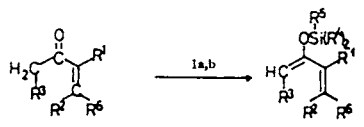


43 44





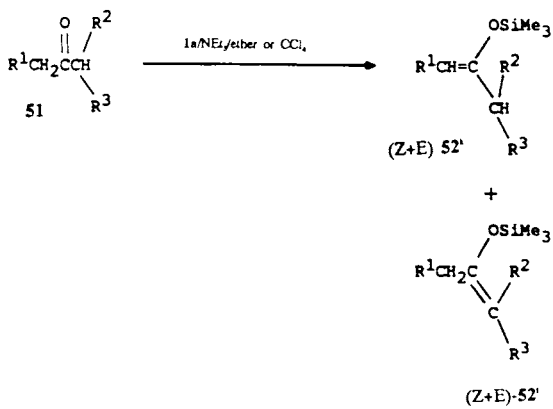
47 (E+Z)-48



49 50

(protodesilylation) is insignificant, the solubility of trialkylammonium triflates is not a concern when selecting a solvent.

Unsymmetrical ketones **51** are converted to mixtures of regioisomeric silyl enol ethers **52**^{k} (kinetic product), and **52**^{t} (thermodynamic product) under the usual conditions (5% excess of **1a**/NEt_3/20°C/ether) with a preponderant formation of the Z isomers.[9,27,43,122,127] The amount of silyl enol ethers **52**^{k} generated under kinetic control decreases with increasing reaction time. Almost quantitative isomerization of **52**^{k} →**52**^{t} is achieved by adding a 10% excess of ketone **51** and triflate **1a** to the reaction mixture (Table V). Trimethylsilylcarboxonium triflates **53** may be responsible for this isomerization.[9,122]



(Z+E) **52**^{t}

+

(Z+E)-**52**^{t}

Table IV. Synthesis of Trialkylsilyl Enol Ethers **42, 44, 46, 48, 50** from Ketones **41, 43, 45, 47, 49** and Trialkylsilylperfluoroalkane Sulfonates **1a–e, 1r** in the Presence of Triethylamine (TEA).

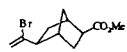
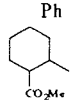
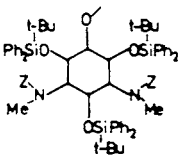
Perfluoro alkane sulfonate	*Product No.*	R^1	R^2	R^3	*Reaction time [h] /temp.[°C] /solvent*	*Yield [%]*	*Reference*
1a	**42a**	Me	H	H	1/20/ether	65	9,122
1a	**42b**	*t*-Bu	H	H	4/20/ether	95	9,122,123
1e	**42c**	*t*-Bu	H	H	/20/CH_2Cl_2	72	20
1b	**42d**	Et	H	Me	5 min/20/CH_2Cl_2	100	127
1a	**42e**	*i*-Pr	Me	Me	1/20/DCE	68	9,122
1c	**42f**	*i*-Pr	Me	Me	24/20/ether	90	9,122
1a	**42g**	$-(CH_2)_3-$		H	4/20/ether	87	9,122,123
1a	**42g**	$-(CH_2)_3-$		H	A	72	22
1a	**42g**	$-(CH_2)_3-$		H	0.3/20/CH_2Cl_2[a]	96	27
1r	**42g**	$-(CH_2)_3-$		H	B	72	28
1b	**42h**	$-(CH_2)_3-$		H	5 min/20/DCE	100	127
1d	**42i**	$-(CH_2)_3-$		H	1/23/benzene	>98	14
1a	**42k**	$-(CH_2)_4-$		H	4/20/ether	85	9,122,123
1a	**42k**	$-(CH_2)_4-$		H	0.25/20/CH_2Cl_2[a]	84	27
1a	**42k**	$-(CH_2)_4-$		H	A	81	22
1r	**42k**	$-(CH_2)_4-$		H	B	71	28
1d	**42l**	$-(CH_2)_4-$		H	1/23/benzene	>98	14
1d	**42m**	$-(CH_2)_5-$		H	1/23/benzene	>98	14
1a	**42n**		H	H	3/20/ether	79	9,122
1b	**42o**		H	H	5 min/20/CH_2Cl_2	100	134
1a	**42p**		H	H	1/20/CH_2Cl_2	99	126
1a	**42q**			H	2/20/ether	71	9,122
1a	**42r**			H	1/20/benzene	64	128
1a	**42s**	Ph	H	H	2/20/ether	82	9,122,123
1a	**42s**	Ph	H	H	0.5/20/CH_2Cl_2[a]	86	27
1a	**42s**	Ph	H	H	A	76	22
1r	**42s**	Ph	H	H	B	71	28
1a	**42t**		H	H	3/20/toluene	60	125

Table IV. (Continued)

Perfluoro alkane sulfonate	*Product No.*	R^1	R^2	R^3	*Reaction time [h] /temp.[°C] /solvent*	*Yield [%]*	*Reference*
1a	**42u**	Ph	H	Me	2/20/ether	82	9,122
1a	**42v**	Ph	Me	Me	4/20/ether	89	9,122
1b	**44a**	H	H	$H_{n=0}$	5 min/20/DCE	100	127
1a	**44b**	Me	Me	$H_{n=0}$	5/20/CCl_4	78	9,122,123
1b	**44c**	H	Me	$Me_{n=0}$	5 min/20/DCE	100	127
1a	**44d**	CO_2Me	H	$H_{n=1}$	—/—/benzene	—	124
1a	**46a**	H	Me	CH_2=$CHCH_2$	—/20/DME	91	124a
1a	**46b**	H	Me	Me_2C=$CHCH_2$	—/20/DME	88	124a
1a	**46c**	H	Me	Et	—/20/DME	90	124a
1a	**46d**	–$(CH_2)_3$–		Me	—/20/DME	87	124a
1a	**48a**	Ph	H	—	1/20/ether	83	9,122
1a	**48b**	Ph	Me	—	2/70/DCE	73	9,122
1a	**48c**	Ph	Et	—	3/80/DCE	67	9,122
1a	**48d**	Ph	Ph	—	2/20/ether	72	9,122

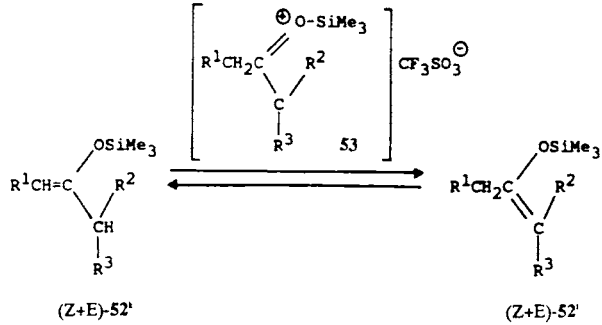
		R^1	R^2	R^3	R^6			
1a	**50a**	H	H	H	H	1/20/ether	95	9,122
1a	**50b**	H	–$(CH_2)_2$–		H	2/20/CCl_4	72	9,122
1b	**50c**	H	–$(CH_2)_2$–		H	5 min/20/CH_2Cl_2	100	134
1a	**50d**	Me	–$(CH_2)_2$–		H	4/20/ether	71	9,122
1b	**50e**	Me	–$(CH_2)_2$–		H	5 min/2O/CH_2Cl_2	100	134
1c	**50f**	Me	OMe	Me	H	0.5/0/ether	73	73
1a	**50g**	Me	O-*t*-Bu	H	H	0.5/0/ether	99	129
1a	**50h**	Me	O-(1-menthyl)	Me	H	1/0/CCl_4	82	129
1a	**50i**	OAc	O-(1-phen-menthyl)	H	H	4/0/ether	83	129
1b	**50k**	OCOMe [b]		H	H	—/—/ether	—	131
1a	**50l**			–$(CH_2)_2$–		—/—/CH_2Cl_2	—	135

[a] DBU as auxiliary base

[b] R^2 = 

A: Allyltrimethylsilane/CF_3SO_3H/CH_2Cl_2/20 min/0–20°C.

B: Potassium nonafluorobutanesulfonate/chlorotrimethylsilane/cyclohexane/1 h/110°C.



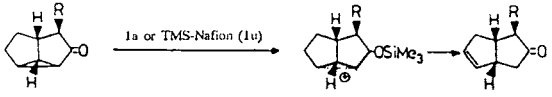
Silylations of ketones **51** with **1b** afford similar results.[127] Selective formation of kinetic regioisomers is observed in reactions with 20-oxosteroids.[127] The isomeric ratios in the synthesis of silyldienol ethers from 3-oxosteroids and **1b** in the presence of different bases were determined.[136] Compound **1b** was repeatedly used in the silylation of polycyclic ketones in the course of the synthesis of bruceantin.[137]

The silylation of ketones proceeds faster than the cleavage of ethers with the exception of oxiranes, as confirmed by the reaction of 8-oxabicyclo-[3.2.1]-octane-3-ones **18** with **1a**/NEt_3 (see chapter I, 6.2.2).[83]

Trialkylsilyloxonium triflates, e.g., **53**, are also intermediates in rearrangements of α-cyclopropylcarbonyl systems:

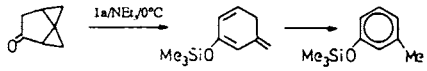
Table V. Isomerization of Kinetically to Thermodynamically Produced Silyl Enol Ethers **52**^{k} and **52**^{t} in the Reaction of Ketones with **1a** in CCl_4 at 20°C [9,122]

					Ratio of **52**^{k}:**52**^{t}		
Product	R^1	R^2	R^3	*Reaction time [h]*	*Usual conditions*	*With 10% excess* **51** + **1a**	*Yield [%]*
52a	H	H	Me	0.5	41:59	—	
				19	38:62	5:95	84
52b	H	Me	Me	0.25	80:20	—	
				95	63:37	7:93	
				191	—	0:100	78
52c	H	H	*i*-Pr	1	84:16	—	
				19	80:20	18:82	85
52d	Ph	H	H	0.25	60:40	—	
				48	20:80	—	
				72	0:100	—	74
52e	$-(CH_2)_4-$		Me	1.5	27:73		
				4	18:82	8:92	
				120	—	0:100	80



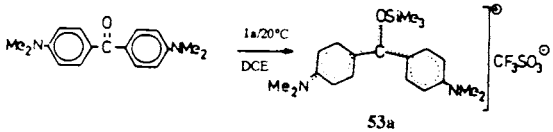
Refs. 25,40

53

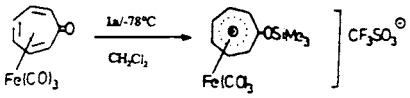


Ref. 138

In the case of sufficient stabilization trialkylsilyloxonium salts can be isolated:[9,122,139]

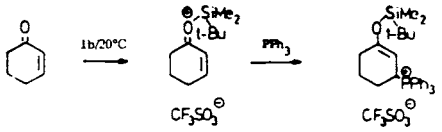


53a



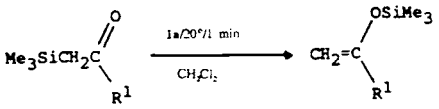
53b

Phosphoniosilylation of α,β-unsaturated carbonyl compounds **49**, a methodology which reveals new preparative aspects, proceeds via siloxonium ions as intermediates to yield phosphonium triflates **54**, e.g.,



49 54

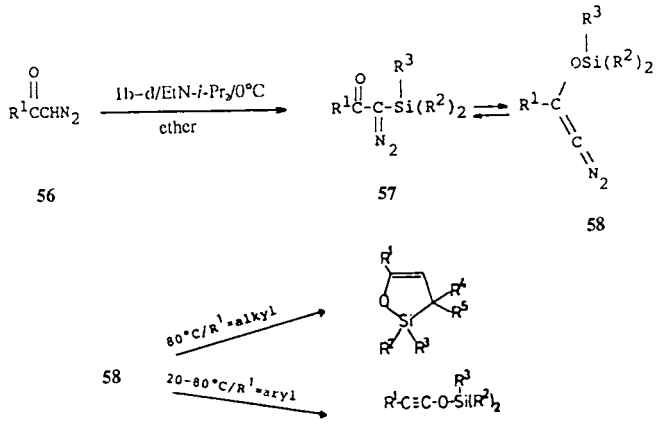
α-C-silylations of ketones never have been observed. The reason for this is found in the greater thermodynamic stability of silyl enol ethers, which can also be seen by the rapid **1a** catalyzed rearrangement of α-trimethylsilylketones to silyl enol ethers **42**:[9]



55 42

R^1 = Me, Ph

Diazoketones **56** are smoothly silylated by triflates **1b–d** to form trimethylsilyldiazoketones **57**. Dependent on the substituents rearrangement to silyl enol ethers **58** takes place at 20–80°C accompanied by immediate decomposition with loss of nitrogen:[132,133]

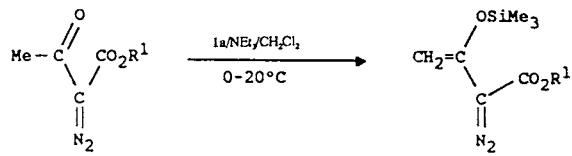


56 57 58

58

R^1 = Ph, 4-MeC_6H_4, 4-$MeOC_6H_4$, 4-ClC_6H_4, 4-BrC_6H_4, 2-thienyl, 2-furyl, Me, *t*-Bu, *n*-Bu, $Ph(CH_2)_3$
R^2 = Me, Et, *i*-Pr
R^3 = Et, *i*-Pr, *t*-Bu
R^4,R^5 = H, Me

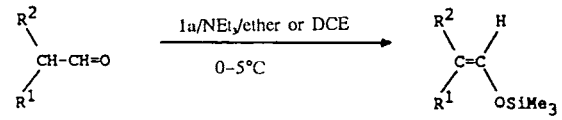
Regioisomeric silyl enol ethers **59** (R^1=Me, *n*-Bu) were not found. A compound of this kind results as a stable reaction product in the silylation of **60** with **1a**.[142]



60 59

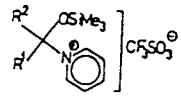
R^1 = $CH_2C_6H_4NO_2$-4

The formation of silyl enol ethers with **1a**/NEt_3 also takes place with aliphatic aldehydes **61**. Because of competing aldol reactions the yields of silyl enol ethers **62** are sometimes lower.[9,122,143,144] Adducts of type **A**, which recently could be isolated from reaction of aldehydes with **1a**/pyridine, are possible intermediates at least in the presence of sterically nonhindered bases.[145]



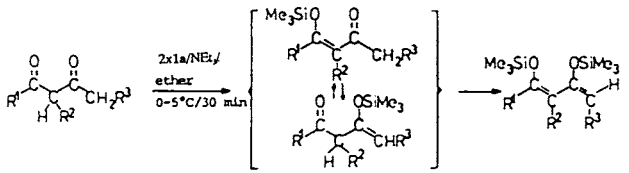
61 62 (42-74%)

61/62	a	b	c	d
R^1	Me	Me	*n*-C_6H_{11}	
R^2	H	Me	H	H



A

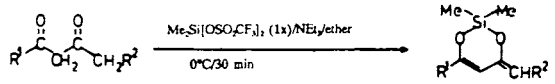
6.2.6.3. With 1,3- and 1,2-Diketones. Since the research work of Danishefsky et al.,[8b] 1,3-bis(trimethylsiloxy)-1,3-dienes **65** have moved into the center of synthetic interest. These highly useful dienes are very smoothly formed in quantitative crude yields (purity ~95%) by silylation of 1,3-dicarbonyl compounds **63** with two equivalents of **1a**/NEt3.[9,37,130,146] The intermediate 2-acyl-trimethylsilyl enol ethers **64** are also isolable.[37,147] Di-*tert*-butylsilyl enol ethers of type **64**, obtainable by silylation of β-ketoaldehydes with **1f**, are characterized by their high stability towards hydrolysis.[39]



63 64 65 (~100%)

63,65	R^1	R^2	R^3	63,65	R^1	R^2	R^3
(E+Z)-a	Me	H	H	k	–CH_2–		H
(E)-b	*t*-Bu	H	H	l	–CH_2–		Me
(E)-c	Et	H	Me	m	–$(CH_2)_2$–		H
(E+Z)-d	Ph	H	H	n	–$(CH_2)_2$–		Me
(E)-e	Ph	H	Me	(E)-o	H	H	H
(E)-f	Me	Me	H				
g	H	–$(CH_2)_3$–					
h	–$(CH_2)_4$–		H				
i	–$(CH_2)_4$–		Me				

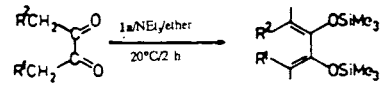
The s-trans configuration of dienes **65** could be spectroscopically confirmed by comparison of the ^{1}H NMR spectra with dienes **66**, obtained by cyclosilylation of diketones **63**:[37]



63 66 (55-75%)

63/66	R^1	R^2
a	Me	H
d	Ph	H
e	Ph	Me

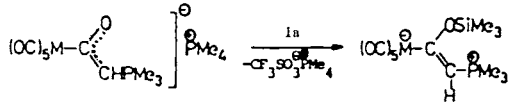
1,2-Diketones **67** are disilylated under surprisingly mild conditions to yield dienes **68**:[9,22,122,123]



67 68 (60-70%)

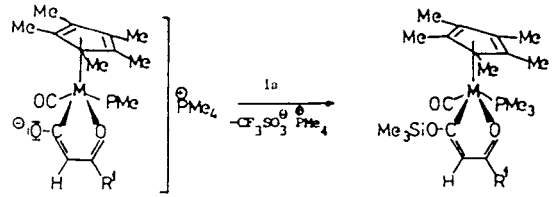
67/68	R^1	R^2
a	H	H
b	$-(CH_2)_2-$	

6.2.6.4. With Metal-Acyl-Complexes. Treatment of acyl metal-phosphorylides, e.g., **69**, with **1a** provides trimethylsiloxyvinyl complexes **70**.[148–150] From phosphonium metalates **71** and **1a** neutral complexes **72** result.[151]



69 70

M = Cr, Mo, W

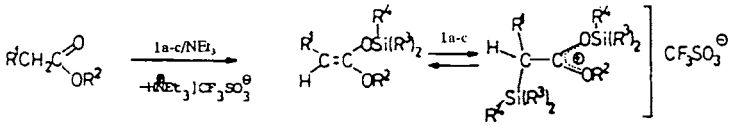


71 M=W, Mo 72

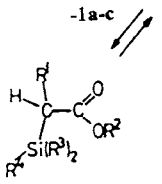
Coupling of carbyne and carbonyl ligands in tantalum and niobium complexes by means of **1d** has been described.[152]

6.2.6.5. With Carboxylic Acid Esters. Carboxylic acid esters **73**, **76**, **78**, **81** react with **1a–c**/NEt_3 in thermodynamically controlled reactions to give O-alkyl-O-trimethylsilyl ketene acetals **74**, **77**, **79**, **82** and/or alkyl 2-trimethylsilyl-carboxylates **75**, **80**[9,99,123,153–161] (Table VI). Silylation of alkyl acetates **83**

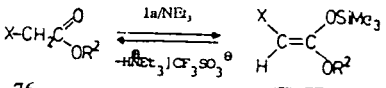
exclusively results in the formation of α-trialkylsilylated esters **84**.[9,153,162] Electrophilic attack at the carbonyl oxygen is always the first step of the reaction. Subsequently, in a step catalyzed by triflates **1**, rearrangement to the often more stable carbosilanes **75**, **80**, and **84** can occur.[153]



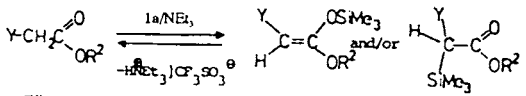
73 (Z)-74



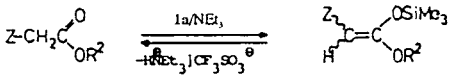
75



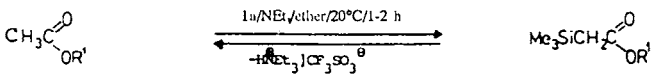
76 (Z)-77



78 79 80



81 (E+Z)-82

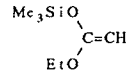


83 84 (60-65%)

R^1 = CH_2-Bu-t, n-C_6H_{11}, c-C_6H_{11}, CH_2Ph, Ph, $SiMe_3$

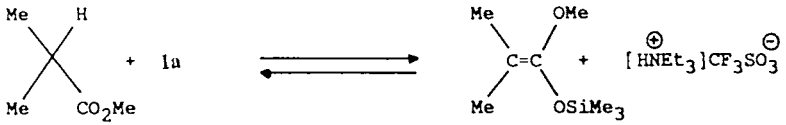
All silylations proceed at room temperature. Electron-withdrawing groups in the α-position facilitate the reaction because of increased α-CH-acidity. Alkoxy and acylamino groups slow down the reaction rate.[154–159] On the one side, the anion-destabilizing effect of these groups retards the silylation rate; on the other

Table VI. Ketenacetals **74**, **77**, **79**, **82** and Carbosilanes **75**, **80** by Silylation of Carboxylic Acid Esters with **1a–c**.

Product	R^1 or X,Y,Z	R^2	Silyl triflate	Reaction time [h]	Solvent	Yield [%]	Ratio of ketene acetal/ carbosilane	Reference
74,75a	Me	Et	**1a**	2	ether	66	14:86	9,99,153
b	Me	Et	**1b**	16	ether	28	78:22	9,99,153
c	Me	Et	**1c**	18	ether	34	72:73	153
d	Me	$SiMe_3$	**1a**	4	ether	57	24:76	9,153
e	Me	Ph	**1a**	5	ether	55	81:19	9,99,153
f	Et	Et	**1a**	4	ether	79	16:84	9,99,153
g	Et	$SiMe_3$	**1a**	2	ether	56	53:47	9,153
77a	Ph	Et	**1a**	2	ether	77	—	9,99,123,153
b	C≡N	Me	**1a**	0.3	ether	80	—	9,99,153
c	EtO_2C	Et	**1a**	1	ether	76	—	9,153
(Z+E)-**d**	CF_3	Me	**1a**	—	CH_2Cl_2	86	—	160
e		Et	**1a**	1.5	ether	65	—	9,153
79,80a	MeS	Me	**1a**	3	ether	63	52:48	154
b	MeO	Me	**1a**	5	NEt_3	45	27:73	154
c	MeO	Ph	**1a**	8	NEt_3	85	89:11	154
d	MeO	$SiMe_3$	**1a**	14	NEt_3	62	83:17	154
e	Me_3SiO	$SiMe_3$	**1a**	14	NEt_3	89	100:0	154
f	PhO	Ph	**1a**	22	NEt_3	83	100:0	154
82(Z)**a**	N=C=S	Me	**1a**	6	ether	71	—	154
(Z)-**b**	$N(SiMe_3)COCF_3$	Me	**1a**	6	ether	89	—	154,155
(Z)-**c**	$N(SiMe_3)COCF_3$	CH_2Ph	**1a**	8	NEt_3/DCE[a]	77	—	156
(Z)-**d**	$N(SiMe_3)COCF_3$	$SiMe_3$	1a	14	NEt_3/DCE	81	—	156
(Z)-**e**	$N(SiMe_3)COPh$	Me	**1a**	3	NEt_3/DCE	80	—	156
(Z+E)-**f**	$N(Me)COCF_3$	Me	**1a**	16	NEt_3	82	—	157
(Z+E)-**g**	$N(i\text{-}Pr)COCF_3$	Me	**1a**	70	NEt_3/DCE	80	—	159
(Z+E)-**i**	$N(CH_2Ph)COCF_3$	Me	**1a**	70	NEt_3/DCE	75	—	159
(Z+E)-**k**	$N(Ph)COCF_3$	Me	**1a**	60	NEt_3/DCE	81	—	158,159

[a] Ratio NEt_3/1,2-dichloroethane = 1 : 1.

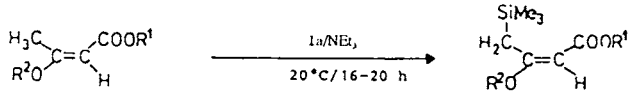
side, protodesilylation is favored due to higher basicity of the ketene acetals **80b–f**, **82b–k**. This handicap can be removed by increasing the basicity of the reaction medium (decreasing proton activity of $[HN^{\oplus}Et_3]CF_3SO_3^{\ominus}$). In this way esters **78b–f** and **81b–k** can be transformed to ketene acetals in triethylamine[154,155] or better in the more polar triethylamine/DCE 1 : 1 mixture[156,158,159] as solvents. The same effects gave rise to unfavored position of equilibrium in silylation of methyl isobutyrate **85**. Reaction with **1a** only proceeds in triethylamine. The equilibrium also can be achieved starting from ketene acetal **86** and triethylammonium triflate.[154] Steric effects are of minor importance with respect to reaction rates as can be seen from rapid silylation of isobutyric acid ethylthiolester (chapter I, 6.2.6.8).



85 86

The regioselectivity of silylation is controlled by the relative thermodynamic stabilities of ketene acetals and carbosilanes. Electron-withdrawing groups R^2 in **73** or **78** which are disadvantageous for ester mesomerism favor formation of ketene acetals **74**, **79**.[9,153,154] The latter ones also are stabilized by a conjugated system.[9,153] Bulky groups in the β-position as in **81b–k**[154–159] favor the ketene acetals. A steric preference of ketene acetals also is observed in treatment of esters **73** with **1b,c**.[9,153]

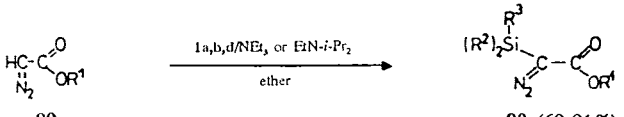
Alkyl-3-alkoxy-2-butenoates **87** are regioselectively silylated in γ-position.[161]



87 (E)-88

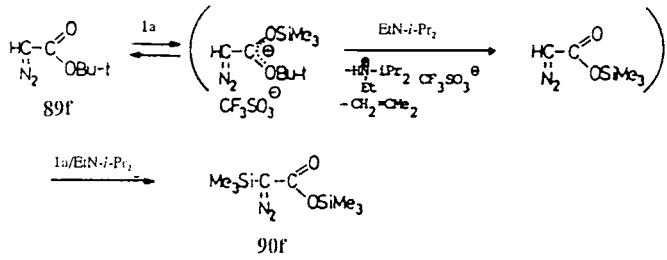
R^1, R^2 = Me, Et

Treatment of α-diazoesters **89** with **1**/triethylamine leads to the stable α-trialkylsilylesters **90**[9,153,163] possibly via O-silylation as can be deduced from formation of **90f** in the reaction with the *tert*-butyl ester **89f**.[163]



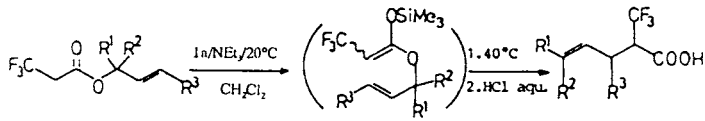
89 **90** (68-91%)

89/90	R^1	R^2	R^3
a	Me	Me	Me
b	Me	Me	*t*-Bu
c	Me	*i*-Pr	*i*-Pr
d	Et	Me	*t*-Bu
e	Et	*i*-Pr	*i*-Pr



In reactions with triflates **1b,c** 24 h are required,[163] whereas silylations with **1a** are complete within 30 min at 0–20°C.[9,153] Diazophosphonates react in an analogous manner.[163]

Ketene acetals **92**, which are prepared *in situ* from allylcarboxylates **91**, rearrange to the β,γ-unsaturated silylesters, (acids **93**) under mild conditions:[164]

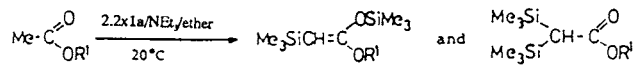


91 92 93 (74-100%)

R^1, R^2, R^3 = H, Me

Ketene acetals produced *in situ* from O-acylcyanohydrins are cyclized to yield 3-hydroxy- or 3-aminodihydrofuran-2-ones.[165,165a]

With excess **1a** disilylation of alkylacetates occurs. The alkyl bis(trimethylsilyl)acetates **95** are the predominant products in these reactions.[153]

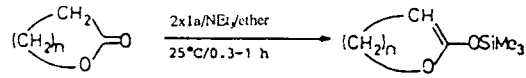


94 ~20:80 **95**

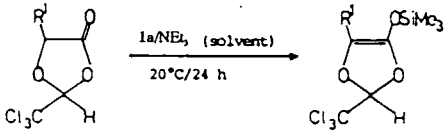
R^1 = Me,Et,*i*-Pr,CH_2Ph,$SiMe_3$ besides: $Me_3SiCH_2COOR^1$

84

6.2.6.6. With Lactones. As expected lactones **96** react significantly more rapidly with **1a** than esters to give the bissilylated ketene acetals **97**.[9,127,153,166] Monosilylated products cannot be obtained. In the same manner, although much more slowly, dioxolanones **98** are converted to the dioxolenes **99**.[154,167]



96 n=2,3,5 **97**



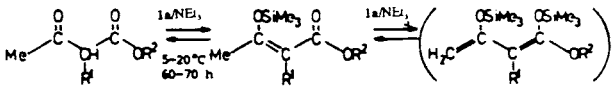
R^1 = $SiMe_3$ (91%)
R^1 = Ph (69%)

98 99

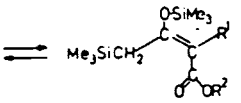
R^1 = H, Ph

Silylation of oxetan-2-one results in ring cleavage.[9,153]

6.2.6.7. With Alkyl-β-Ketocarboxylates. Via alkyl-3-trimethylsiloxy crotonoates **101** alkyl acetoacetates **100** are converted to 4-trimethylsiloxy-2-alkenoic acid esters **102** under thermodynamic control.[37] With four equivalents **1a** the trisilylated esters are achieved.[37] In order to suppress protodesilylation triethylamine is employed as solvent.

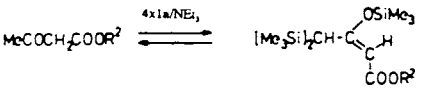


100 **101**



R^1 = H, Me
R^2 = Et, *i*-Pr, CH_2-Ph

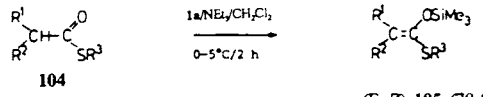
(E)-**102** (44-60%)



100 (E)-**103** (54-56%)

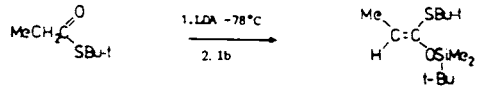
R^2 = Me, Et

6.2.6.8. With S-Alkylthiocarboxylates. Presumably because of their higher α-CH-acidity esters **104** react more rapidly with **1a**/triethylamine than do alkyl carboxylates. The lower nucleophilic character of the carbonyl oxygen does not affect the reaction rate. In view of lower mesomerism—compared with alkyl carboxylates—regioselective silylation to give ketene acetals **105** is observed.[168] In spite of steric hindrance, ester **104d** is smoothly converted to **105d** (see chapter I ,6.2.6.5). The thermodynamically less stable Z-isomers can be synthesized by silylation of lithio-S-alkylthiocarboxylates.[169]



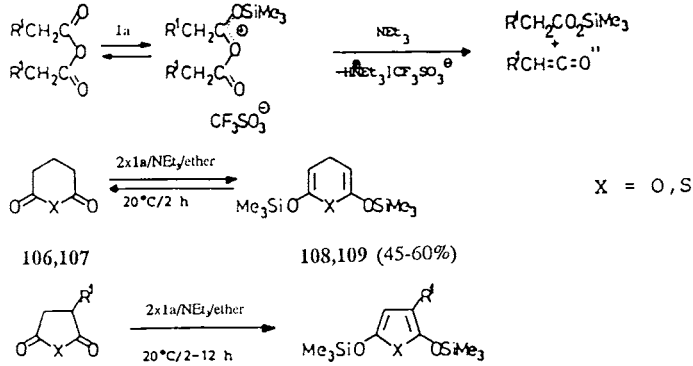
104 (E+Z)-105 (78-81%)

104,105	R^1	R^2	R^3
a	H	H	Et
b	Me	H	Et
c	Et	H	Et
d	Me	Me	Et
e	Ph	H	Et
f	Cl	H	Et
g	H	H	*t*-Bu
h	Me	H	*t*-Bu



104h 105i

6.2.6.9. With Carboxylic and Thiocarboxylic Acid Anhydrides. Siloxonium salts formed as intermediates from carboxylic acid anhydrides and **1a** are cleaved by triethylamine. Trimethylsilyl carboxylates are one of the reaction products.[170] In the reactions with cyclic dicarboxylic acid anhydrides proton abstraction is more rapid so the (thio)pyranes **108**,[170] **109**,[171] furans **112**,[170] and thiophenes **113**[170,172] result in the bissilylation of glutaric **106** and succinic **110** acid anhydrides, as well as their thioderivatives **107**, **111**.

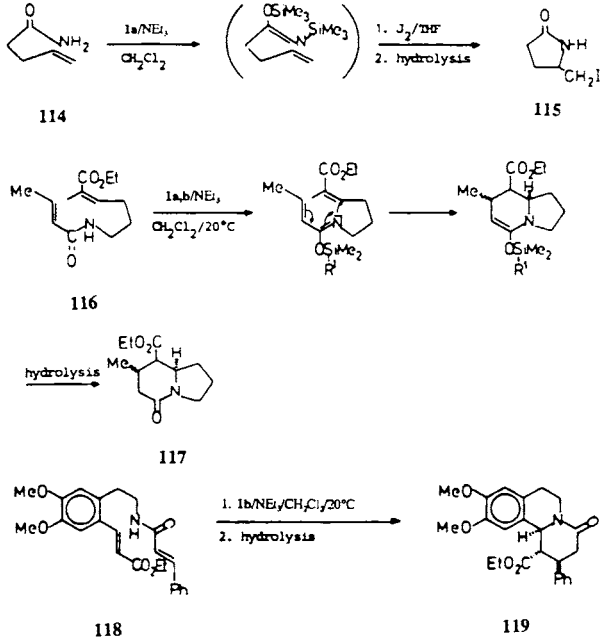


106,107 108,109 (45-60%)

110,111 112,113 (52-78%)

110,112 (X=O)	R^1	111,113 (X=S)	R^1
a	H	a	H
b	Me	b	Me
c	Ph		

6.2.6.10. With Carboxylic Acid Amides. Lactams, Ureas, Imides and Vinylogous Carboxylic Acid Amides. With primary and secondary carboxylic acid amides triflate **1a,b** form N, O-bis(trialkylsilyl)- or O-(trialkylsilyl)imino acid esters.[123,173,174] This conversion is of particular interest for iodolactamization of alkeneamides **114**[173] and synthesis of indolizines **117**, as well as chinolizidines **119** from amides of the types **116**, **118**.[174]



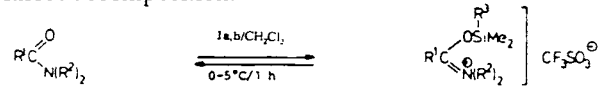
114 **115**

116

117

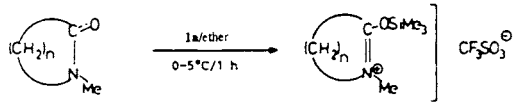
118 **119**

N,N-Dialkylcarboxylic acid amides **120**,[9,55,123,175,175a] N-alkyl lactams of ring size ≥5 **122**,[9,55] and N,N'-tetraalkylureas **124**[55] react with **1a,b** in an exothermic manner to yield O-trialkylsilyliminium salts **121**, **123**, and **125**. The constitution of these salts (see chapter I ,5) was first proved by ^{1}H NMR[9], and later by ^{29}Si and ^{13}C NMR spectroscopy.[55,175a] At about 100°C, the mainly crystalline triflates **121** dissociate into the starting components. Therefore, lower species of this kind can be distilled without decomposition.[176]

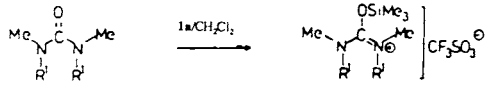


120 **121** (~100%)

120/121	R^1	R^2	R^3	120/121	R^1	R^2	R^3
a	H	Me	Me	**e**	*i*-Pr	Me	Me
b	H	Me	*t*-Bu	**f**	Me	*i*-Pr	Me
c	Me	Me	Me	**g**	$PhCH_2$	Me	Me
d	Et	Me	Me	**h**	CH_2CN	Me	Me



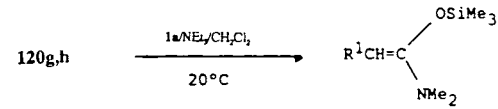
122 n=3,4,5 **123** (~100%)



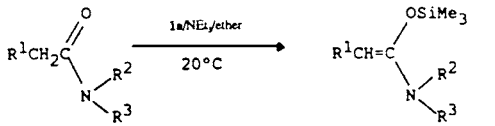
124 **125**

124/125	R^1	R^1
a	Me	Me
b	$-(CH_2)_2-$	
c	$-(CH_2)_3-$	

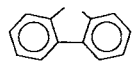
The ability to form iminium triflates **121**, **123**, and **125** decreases in the order HMPA>N-methyl-2-pyridone> DMPU> N-methyl-2-pyrrolidone> DMF> DMEU.[55] As a consequence of lower α-CH-acidity in iminium triflates proton abstraction to give ketene-O,N-acetals **126** with triethylamine only succeeds in the case of electron-withdrawing groups in the α-position[9] or N-arylsubstitution,[170] which decreases amide mesomerism.



R^1 = Ph, CN **126g,h**

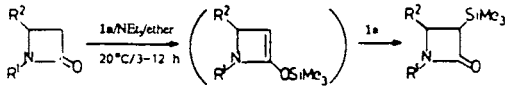


127 (E+Z)-**126** (50-68%)

126	R^1	R^2	R^3
i	$SiMe_3$[a]	Ph	Ph
k	Me	Ph	Ph
l	Et	Ph	Ph
m	H		
n	H		

[a]from N,N-diphenyl acetamide.

In azetidinones **128** due to ring strain substitution in position 3 takes place:[177]

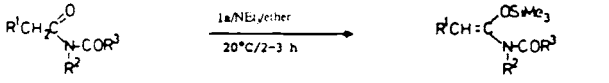


128 **129**

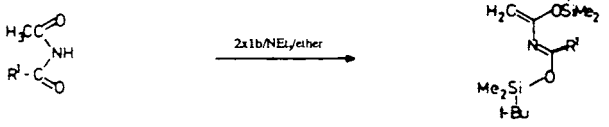
R^1 = Ph, $SiMe_3$

R^2 = H, Ph

N,N-Diarylamides **127**, carboxylic acid imides[170,178,179] and N-acyl lactams **130**[170] as well as dicarboxylic acid imides **132**,[171] **134**[154,167] are transformed to ketene-O,N-acetals **131**, **133**, and **135** under mild conditions. Succinimides **136** are converted to 2,5-bis(trimethylsiloxy) pyrrols **137** by **1a**/NEt_3 supported by formation of the aromatic system.[9] Electron-withdrawing substituents on nitrogen lower the reaction rate.[170,180]



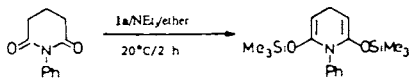
130 **131** (50-66%)



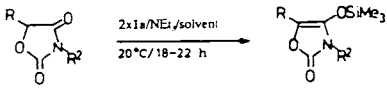
130g,h **131g,h** (81-86%)

R^1 = H, Me

130/131	R^1	R^2	R^3
a	H	Me	Me
b	H	Me	OEt
c		$-(CH_2)_2-$	Me
d		$-(CH_2)_3-$	Me
e		$-(CH_2)_4-$	Me
f		$-(CH_2)_4-$	OEt



132 **133** (57%)

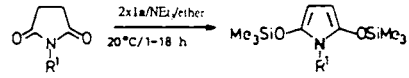


134 **135** (81-90%)

R^1 = H

R^2 = Me, n-Pr, Ph

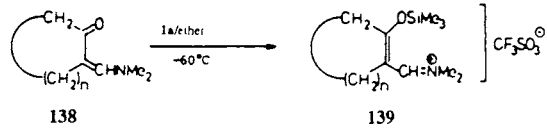
R^1 = $SiMe_3$



136 137 (46-82%)

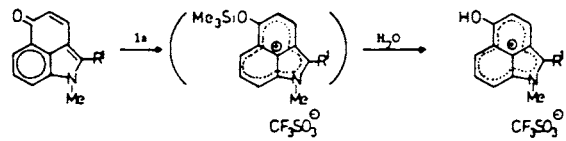
R^1 = Me, Et, CH_2Ph, Ph, $SiMe_3$, $OSiMe_3$, CO_2Me, CO_2Et, COPh

As expected **1a** reacts with vinylogous N,N-disubstituted amides **138**, **140** to give iminium triflates **139**, **141** in quantitative yields:[181–184]



138 139

n = 2,3,4

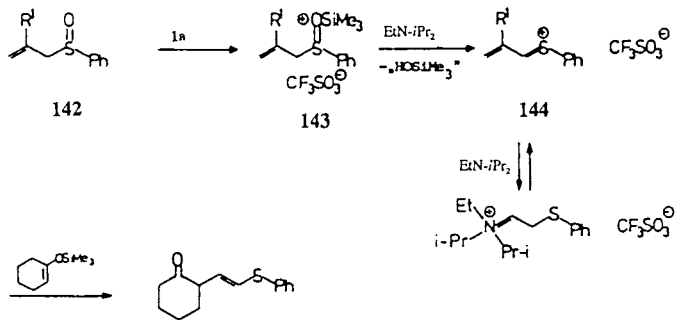


140 141

R^1 = H, Ph

6.2.6.11. With Sulfoxides (Silyl-Pummerer Reaction) and Sulfones. Sulfoxides react rapidly with **1a** to give sulfoxonium triflates (e.g., **143**). In the presence of triethylamine, silanol is eliminated and thionium triflates are formed as intermediates.

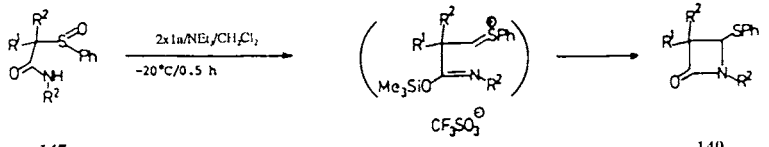
Allylsulfoxides **142** in the presence of silyl enol ethers as nucleophiles and **1a** give Michael adducts **145** via thionium salts **144** in a Pummerer reaction.[185,186] 1,2-Addition is of little importance, if sulfoxides are unsubstituted on the terminal carbon.[185] 1,4-Addition of the nitrogen base decreases the yield. With other Lewis acids much lower yields result.[186]



142 143 144

145

In a similar conversion using β-ketosulfoxides only, low yields of 1,2-adducts with thionium salts are obtained. Further research work will be necessary to obtain the optimal reaction conditions.[187] By intramolecular 1,2-addition to thionium ions **148** a synthesis of β-lactams **149** could be realized from α-sulfoxy carboxylic acid amides.[188]

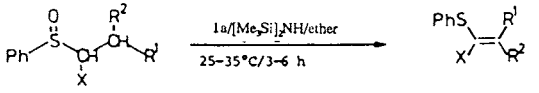


147 148 149 (11-51%)

R^1 = H, Me

R^2 = OCH_2Ph, H

In an eliminative deoxygenation of sulfoxides with anion stabilizing groups in the α-position systems **150** were transformed to vinylsulfides **151**.[189]

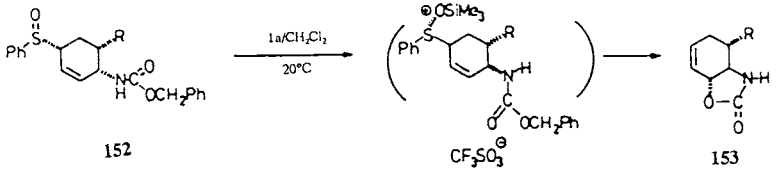


150 151 (73-85%)

X = CN, CO_2Et

R^1,R^2 = H, Me, Et

Sulfoxycarbamate **152** upon treatment with **1a** was converted to bicyclic carbamate **153**. This transformation seems to be without precedent.[190]

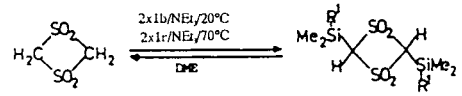


152 153

Little is known about the silylation of sulfones by **1**. The 1,3-disulfone **154** reacts with trimethylsilylnonaflate (**1r**)/NEt_3 or **1s**/NEt_3 to yield the bis(silyl)sulfones trans-**155a** and cis/trans-**155b**. The introduction of a third trimethylsilyl group by **1r** proceeds much more slowly. The resulting **156a** or **155a** can be persilylated to **157a** after lithiation and reaction with **1r**.[18,191a,b]

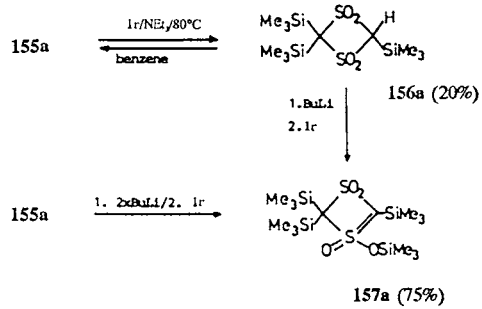
Presumably, silylation is initiated by an electrophilic attack on the sulfonyl oxygen, continued by a rapid **1r**,**s** catalyzed rearrangement to the carbon silylated

derivatives **155, 156.** Indications are that the isomerization of cis-**155a** to trans-**155a** catalyzed by **1r** and the low yield of **156a** are due to protodesilylation.



R^1 = Me, *t*-Bu

155a (69%), **155b**

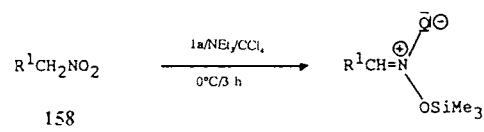


157a (75%)

SO_2 ligands in tungsten and molybdenum complexes are silylated with **1a** on oxygen.[192]

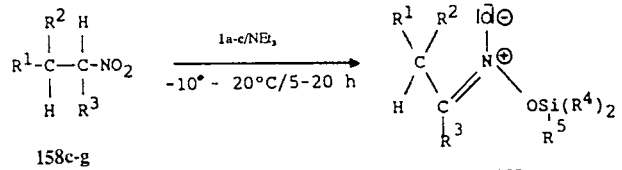
6.2.6.12. With Nitroalkanes and Nitrosamines In the first reaction step silyl nitronates **159** are produced from nitroalkanes **158** and triflates **1**/NEt_3. Nitronates **159** with β-CH bonds cannot be isolated, so they undergo a rapid further silylation by **1**/NEt_3 to yield nitrosoacetals **160.** Under usual reaction conditions (5% excess of **1**) these, however, are rearranged to (E/Z)-2-(trialkylsiloxy) oxime-O-trialkylsilylethers **161.** This new rearrangement is facilitated by cation stabilizing substituents in the β-position. As a result of greater thermodynamic stability of the intermediate products **160** bulky groups on silicon have an advantageous effect on the yields.[9,193]

In the silylation with exactly two equivalents of **1a–c** and a simultaneous excess of triethylamine, nitrosoacetals **160** can be isolated in crude yields of about 95–100%. Products **160** with bulky groups on silicon can be distilled without decomposition.[194]



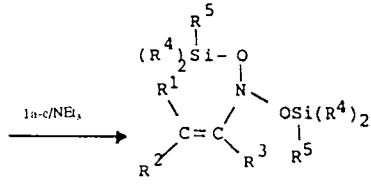
158 **159**

158/159	a	b
R^1	Ph	CO_2Me

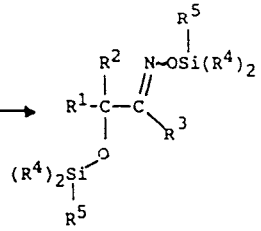


158c-g

159



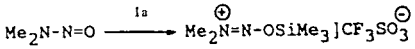
160



(E+Z)-161c-g (25-84%)

158/161	c	d	e	f	g	h	j	k	l	m	n	o	p	q
R^1	H	Me	Me	H	H	Et	Et	*n*-Pr	*n*-C_5H_{11}	Ph	Ph	H	$OSiMe_3$	H
R^2	H	H	H	H	H	H	H	H	H	H	H	H	H	H
R^3	H	H	H	Me	Me	H	H	H	H	H	H	CH_2Ph	H	CH_2OSiMe_3
R^4	Me	Me	Et	Me	Me	Me	Me	Me	Me	Me	Me	Me	Me	Me
R^5	Me	Me	Et	Me	*t*-Bu	Me	*t*-Bu	Me	Me	Me	*t*-Bu	Me	Me	Me

Little work has been done on the silylation of nitroso compounds. From **162** and **1a** the siloxonium triflate **163** is generated.[195]



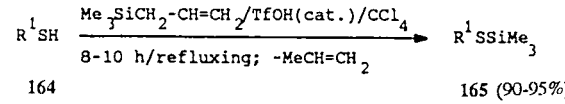
162 163

Concerning the reactions of **1a,b** with epoxynitrones,[31,98] see chapter I ,6.2.2.

6.3. With Sulfur Nucleophiles

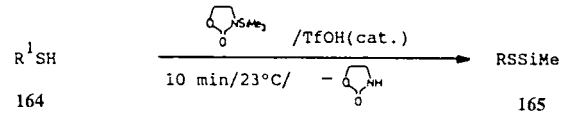
Reactions of the hard Si-electrophiles **1** with soft S-nucleophiles proceed much more slowly than with the O-analogues. Thus, conversion of alkane thiols **164** into their silylthioethers **165** by **1a**, prepared *in situ* from allyltrimethylsilane and catalytic amounts of trifluoromethanesulfonic acid, requires heating for several hours in tetrachloromethane, whereas alcohols are immediately silylated.[22] With 2-trimethylsilyl-1,3-oxazolidin-2-one as a silyl source the reaction time can be shortened, provided the reaction is carried out in the absence of solvent.[27] Nafion-TMS (**1u**) can also be used for the silylation of mercaptans.[15]

In contrast to carboxylic acid amides, both N,N-dialkylthioamides and N-alkylthiolactams react sluggishly with **1a**. Under the usual conditions employed (20°C,



164 165 (90-95%)

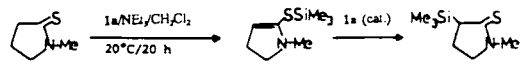
R^1 = CH_2Ph, Ph, 3-MeC_6H_4



164 165

R^1 = Et, n-Bu, Ph, $Me_3SiO_2CCH_2CH_2$

small excess of **1a**) only low yields of the thermodynamically more stable carbosilanes **167** were obtained, e.g.,[177]



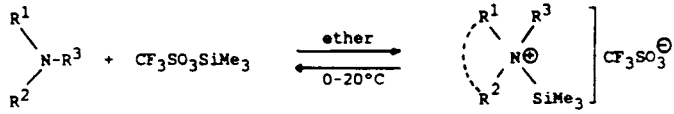
166 167

6.4. With Nitrogen Nucleophiles

6.4.1. With Tertiary Amines, Azaarenes, and Imines:

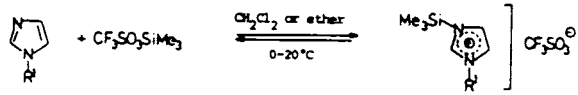
Synthesis of Silyl Ammonium - and Iminium Salts[15,96]

Tertiary aliphatic amines **168**[9,52,197] and azaarenes **170**, **172**[9,54,55,145,198–200] react with **1a,b** under equilibrating conditions to form crystalline compounds of definite melting points, which are sublimable without decomposition. By means of IR,[9,52] ^{1}H NMR,[52,54,145,199] ^{29}Si NMR,[55,199] ^{13}C NMR[198,199] conductivity[9,52] and conductivity titration,[199] it was concluded that the N-silylammonium salt structure **169** was the most logical:



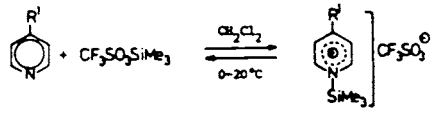
168 1a 169

R^1,R^2,R^3 see Table VII



170 1a 171

R^1 = Me, $SiMe_3$



172 173

R^1 = H, NMe_2

The IR spectra of salts **169** and **171** measured in $CDCl_3$ solution show characteristic ν_s and ν_{as} frequencies of the triflate anion[201] at 1030 and 1170 cm^{-1}. Increasing the bulkiness of substituents R^1-R^3 (for example, **169d,f**, Table VII) gives rise to absorptions of trimethylsilyltriflate as well.[52] This indicates that bulky substituents destabilize salts **169**. In $CDCl_3$ solution some dissociation into the reactants **168** and **1a** occurs. Similar conclusions are to be deduced from ^{1}H NMR ($CDCl_3$)[52,54,199] and ^{29}Si NMR spectra.[55,199] In accordance with increasing thermodynamic stability deshielding of NCH_2-R and $SiCH_3$ signals in ^{1}H NMR are observed (Table VII). The sublimation temperature,[52] which can also be considered as a rough criterion for thermodynamic stability, falls with increasing size of the groups R^1,R^2,R^3 (Table VII). According to these data quaternary salts **169a,e** and **171a** display the highest, and N-trimethylsilyltriethylammonium triflate **169d** the lowest stability. In accordance with this order of dissociation of Si–N bonds, silylation with **1a** proceeds much faster in the presence of NEt_3 (**168d**) than with trimethylamine (**168a**), N-methylpyrrolidine (**168e**), or N-methylimidazole (**170a**) as auxiliary bases (for experimental proof see chapter I, 6.5.2). From ^{29}Si NMR

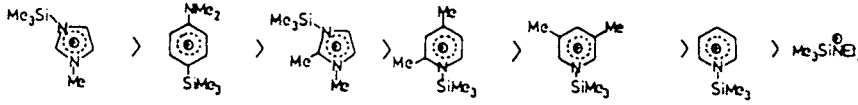
Table VII. ^{1}H NMR Data ($CDCl_3$) and Sublimation Temperatures of Silylammonium Triflates **169,171**[52]

				^{1}H-NMR ($CDCl_3$) δ ppm						
Salt **169**	R^1	R^2	R^3	NCH_2R **168**	NCH_2R **169**	*Δ ppm*	$SiMe_3$[a]	*Δ ppm*	*Sublimation temperature [°C/torr]*	*mp [°C]*
a	Me	Me	Me	2.26	3.23	0.97	0.75	0.25	45/12	161
b	Et	Me	Me	2.23	2.65	0.42	0.58	0.08	40/12	127
c	Et	Et	Me	2.20	2.36	0.16	0.54	0.04	25/12	110
d	Et	Et	Et	2.55	2.55	0.00	0.50	0.00	20/12	58
e	$-(CH_2)_4-$		Me	2.46	2.88	0.42	0.60	0.10	60/0.05	180
f	$-(CH_2)_5-$		Me	2.17	2.40	0.23	0.54	0.04	50/12	134
171b	Me_3Si	—	—	7.60[b]	8.58	0.98	0.60	0.10	120/0.01	155

[a] $CF_3SO_3SiMe_3$: δppm $SiCH_3$ = 0.50.

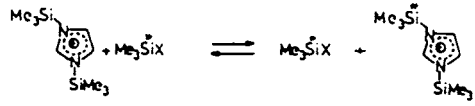
[b] δ ppm 11[2].

data and competitive reactions of amines with N-trimethylsilylammonium salts **171, 173,** the following order of decreasing stability has been established.[55]



171a 173b 171c 173c 173d 173a 169c

Silyl exchange reactions take their course via a dissociation-reassociation mechanism (see also sublimation) as it was proved during studies on reactivity of silylation agents.[54]



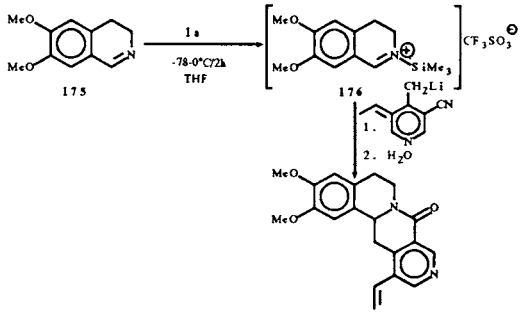
171b

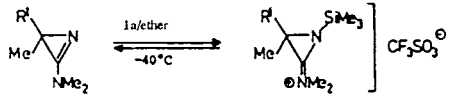
X = ClO_4, CF_3SO_3, J, Br, Cl

Triflates **1o** and **1a** with NEt_3 or pyridine form the following adducts:[17]

Phenylthiohydroxylamines react selectively with alkenes in a nitrile as solvent in the presence of **1a** to give N-(β-phenylthioalkyl)amidines. In the absence of nitriles amines are formed.[201a]

Besides their role as intermediates in silylation processes N-(trimethylsilyl)- and N-(tert-butyldimethylsilyl)pyridinium triflates **173a,e**[202,203] as well as N-(trimethylsilyl)pyrimidinium triflate **174**[204] have achieved importance in the regioselective introduction of nucleophiles in the 4-position of these azaheterocycles. Transformation of imines **175** into salts **176** by **1a** is used to activate the heterocycle



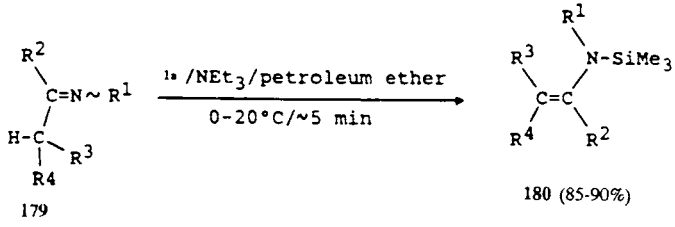


177 178

towards nucleophilic addition.[206] Without any ring cleavage dimethylamino azirines **177** are quaternized to yield the salts **178**.[205]

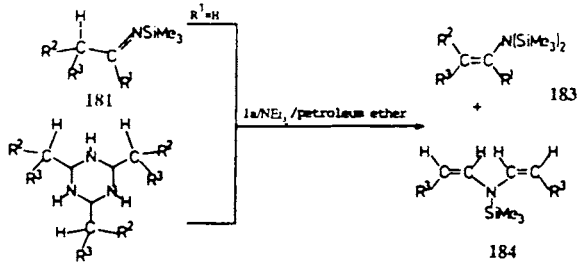
6.4.2. *With Imines—Synthesis of N-Trialkylsilylenamines and Imino Esters*

Compared to other procedures a superior method in synthesizing N-trimethylsilylenamines **180** is the regioselective silylation of ketimines and aldimines by **1a**/NEt_3. Independent of the amino component yields of 85–90% are achieved. As a result of the thermodynamic reaction control only E-isomers are formed.[207] N,N-bis(trimethylsilyl)enamines **183** derived from ketones can be prepared from ketimines **181**. In the synthesis of aldo-N,N-bis(trimethylsilyl) enamines **183** instead of difficultly obtainable monomeric aldimines 2,4,6-trialkylhexahydro-s-triazines **182** were selected as starting materials. Thus, divinylamines **184** are also formed in their silylations, yields being only about 50%.[208]



179 180 (85-90%)

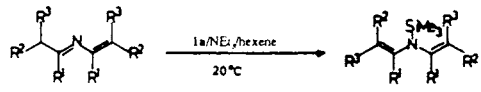
179/180	a	b	c	d	e	f	g	h	i	k	l
R^1	Me	*i*-Pr	*t*-Bu	Me	Et	Ph	Ph	Ph	$PhCH_2$	Ph	Ph
R^2	Ph	Ph	Ph	Et	Et	$(CH_2)_4$	Et	H	H	Et	Me
R^3	H	H	H	Me	Me		Me	Et	Me	H	Me
R^4	H	H	H	H	H	H	H	Et	H	H	H



181 182 183 184

181,182,183	a	b	c	d	e	f	g	h	i
R^1	Ph	Ph	C_5H_{11}	*n*-Bu	H	H	H	H	H
R^2	H	H	H	H	H	H	H	Me	H
R^3	H	*n*-Pr	H	n-Pr	H	Me	Et	Ph	$SiMe_3$

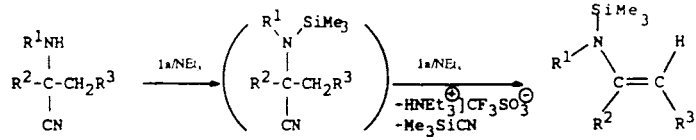
To synthesize higher substituted divinylamines **184** silylation of 2-aza-1,3-dienes **185** with **1a**/NEt_3 is most convenient.[209]



185 184

184,185	a	b	c	d	e
R^1	Ph	Ph	4-MeC_6H_4	H	*n*-Pr
R^2	Me	Et	Me	Me	Et
R^3	H	H	H	Me	H

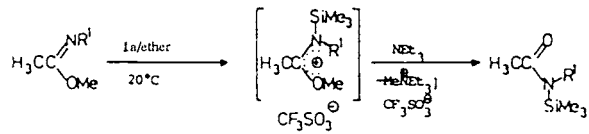
In a general approach the synthesis of N-silyl- and N,N-bis(trimethylsilyl)enamines **187** are accomplished by the reaction of N-alkyl and N-unsubstituted α-amino nitriles **186** with two to three equivalents of **1a**/NEt_3. Because of the high silylation ability of **1a** elimination of cyanide as cyanotrimethylsilane is achieved even at room temperature in petroleum ether.[210]



186 (E)-187 (80-90%)

187	a	b	c	d	e	f	g	h	i	k
R^1	Ph	Ph	Ph	Me	$SiMe_3$	$SiMe_3$	$SiMe_3$	$SiMe_3$	$SiMe_3$	$SiMe_3$
R^2	H	Me	$(CH_2)_4$	$(CH_2)_4$	H	H	Me	Et	$(CH_2)_3$	$(CH_2)_4$
R^3	Me	Me			H	Et	H	H		

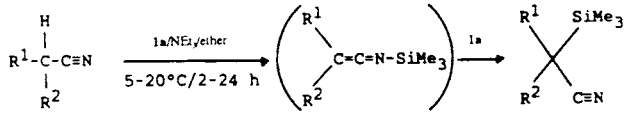
Treatment of α-aminopropionitrile with **1a**/NEt_3 results in silylation at the β-carbon.[210] N-alkylimidates **188** undergo silylative dealkylation in the reaction with **1a**/NEt_3 to yield carboxylic acid amides **189**.[9]



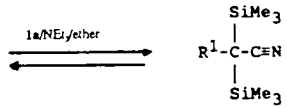
188 189

6.4.3. With Nitriles

Carboxylic acid nitriles **190** are monosilylated or disilylated by **1a**/NEt_3 to give the derivatives **191, 192.** Because of increasing CH-acidity the second silylation step proceeds with a higher reaction rate.[197] Acetonitrile **190a** is transformed into a mixture of silatautomers **193a,b.** The intermediates could not be isolated.[197] As in the reaction with esters the conversion may start with electrophilic attack on nitrogen although the existence of N-trimethylsilylnitrilium salts could not be established.[175a] The resulting N-trimethylsilylketene-imines thereafter are rearranged to the thermodynamically more stable carbosilanes **191, 192.**

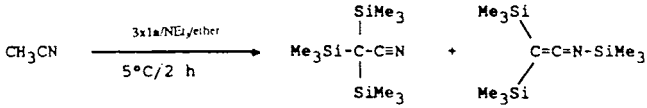


190 **191** (34-80%)



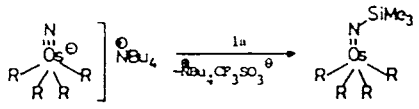
192 (33-65%) R^1 = Me, Cl

191	b	c	d	e
R^1	H	H	Me	H
R^2	CN	Ph	Ph	OMe



193a (73%) **193b**

Anionic nitrido osmium **194** as well as ruthenium complexes are converted to N-trimethylsilylimino derivatives **195** by **1a**,[211,211a] e.g.,

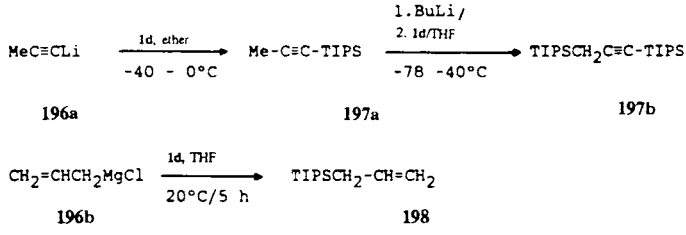


194 **195**

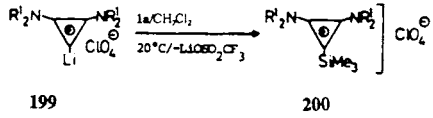
6.5. With Carbon Nucleophiles

6.5.1. With Carbanions

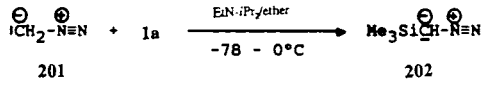
The triisopropylsilyl group, as a result of strong steric screening of α and also β atoms, leads to stereo and regio control in synthesis.[212] It is best introduced by reaction of carbanions with the triflate **1d** (TIPS-triflate).[212–214]



Ergolins silylated in position 2 are formed from 2-lithio derivatives by capturing with triflate **1b**.[215] The first silyl cyclopropenylium cation **200** was synthesized by reaction of the carbenoid **199** with **1a**.[216]



Trimethylsilyldiazomethane (**202**) is easily prepared in a 74% yield by addition of **1a** to an ethereal solution of diazomethane (**201**).[216a]



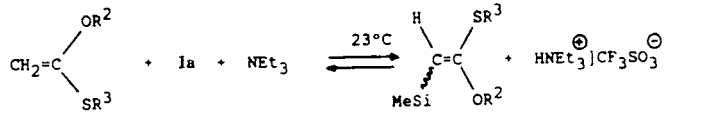
6.5.2. With Olefinic Systems

The synthesis of vinylsilanes[2–4] by direct electrophilic silylation of alkenes had never proven successful. As indicated by 1,3-(O→C)trialkylsilyl shift in silyl ketene acetals to give α-trialkylsilyl carboxylates (see chapter I ,6.2.6.5), the silylation potential of **1** should be sufficient for electrophilic attack on activated double bonds. Indeed ketene-O,O- and ketene-O,S-acetals **203, 205** are silylated by **1a** to yield the C-silylated acetals **204, 206** if protodesilylation is suppressed by low solubility and deactivation of simultaneously formed triethylammonium triflate. To achieve these requirements NEt_3, or better because of higher reaction rates, a 1:1 NEt_3/DCE mixture is used as solvent (Table VIII).[217,218]

Table VIII. Silylation of Ketene-O,O and -O,S-Acetals by **1a** at 23°C in NEt_3 (Method A) or NEt_3/DCE 1:1 Mixture (Method B)[217,218]

Product	R^1	R^2	R^3	*Method*	*Reaction time [h]*	*Yield [%]*
204a	H	Me	—	A	0.5	86
b	H	Et	—	A	1.5	71
c	H	*n*-Pr	—	A	15	81
d	H	*i*-Bu	—	A	16	84
e	H	$(CH_2)_2OMe$	—	A	0.2	76
f	H	$CH(Me)CH_2OMe$	—	A	3	83
				B	1	85
g	H	Ph	—	A	42	54
				B	14	68
h	Me	Et	—	A	68	30
				B	17	49
i	Cl	$(CH_2)_2OMe$	—	A	4	80
(E+Z)-**20 6a**	—	Et	Et	A	90	60
				B	20	76
b	—	$SiMe_3$	Et	A	53	54
c	—	$SiMe_3$	*t*-Bu	A	120	9

203 204



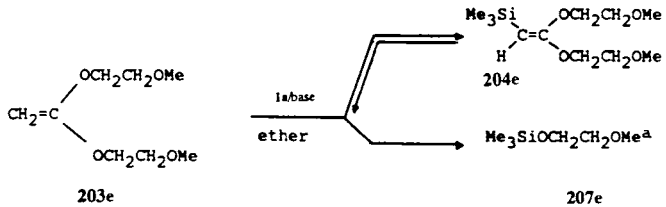
205 (E+Z)-**206** E:Z ~ 80:20

The rate increasing effect of DCE as cosolvent is particularly shown by examples **204g,h** and **206c**. Bulky alkoxy (alkylthio) groups (**204d, 206c**) or electron-withdrawing substituents on oxygen (**204g**) decrease the rate. In the same manner it is affected by enhanced basicity (**204h**). The yields are limited by "vinylether"-cleavage competing in cases of small alkoxy groups. This reaction is initiated by an electrophilic attack of the hard Lewis acid **1a** at the ether oxygen. It competes especially well in the presence of bases, which cannot form any adducts with the triflate **1a**. On the other hand, utilizing nitrogen bases which form very stable

Table IX. Yields of 2-Trimethylsilylketene Acetal **204e** and Methyl (2-trimethylsiloxy)ethyl Ether **207e** in the Silylation of Ketene Acetal **203e** in the Presence of Different Bases (Ether, 23°C).

		Yields [%]	
Base	*Reaction time [h]*	*Silylketene acetal* **204e**	*Ether* **207e**
NEt_3	0.5	78	0
NPr_3	0.5	80	0
N-Trimethylsilylimidazole	17	10	0
DBU	17	20	0
N-methylimidazole	17	16	0
N,N-dicyclohexyl-3-pentylamine[219]	5	0	67
N-ethyldiisopropyamine	0.5	0	29
Sodium hydride	1	0	57

N-silylammonium salts, ether cleavage does not occur but the rate of carbon silylation decreases drastically as well (Table XI), [218] e.g.;



203e **207e**

[a]The tarry side products were not characterized.

Table IX displays the superiority of NEt_3 (or tri-*n*-propylamine) as auxiliary base.

6.5.3. *With Aromatics*

The electrophilic aromatic silylation is another reaction that was not successful until now. Experiments with donor–acceptor complexes of triflates **1** and boron halides in the presence of 2,4,6-tri-*tert*-butylpyridine gave no signs for the electrophilic silylations of activated aromatic hydrocarbons.[19] High electrophilicity and the simultaneous effective suppression of protodesilylation are required to achieve the substitution reaction. Because both requirements are opposite to each other, electrophilic substitution with **1a** only has been achieved with electron-rich heterocycles such as pyrroles and indoles. No reaction takes place with furan or alkylfurans.

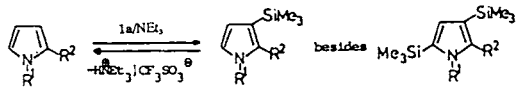
Pyrroles **208** and indoles **211** are silylated in the 3-position in TEA as solvent

Table X. Trimethylsilylation of Pyrroles **208** and Indoles **211** by **1a** in NEt_3 at Room Temperature.[220–222]

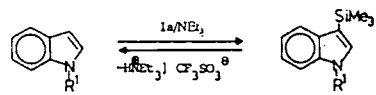
Educt	R^1	R^2	*Products*	*Reaction time [h]*	*Yield [%]*
208a	Me	H	**209a**[a]	14	70
			210a		8
208b	Et	H	**209b**	18	60
208c	$PhCH_2$	H	**209c**	23	55
208d	Me	Me	**209d**	16	61
211a	Me	—	**212a**	17	81
211b	$PhCH_2$	—	**212b**	22	69
211c	$SiMe_3$	—	**212c**	192	54

[a]Contains 9% 1-methyl-2-trimethylsilylpyrrol.

(Table X). Longer reaction times are necessary as a result of decreased electrophilic potential of **1a**.[220–222] Substitution is controlled by electron density and so the silyl group enters the β-position, i.e., the hard center in pyrroles **208**. 2,4-Disilylation is found, but to a lesser degree.[221]

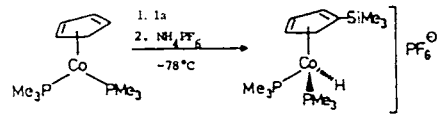


208 209 210



211 212

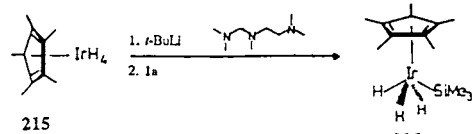
Electrophilic silylation of the cyclopentadiene anion in the cobalt complex **213** to yield **214** has been reported.[223]



213 214

6.6. With Metalo Nucleophiles

Hydride complexes of rhenium[224] and iridium[225,226] e.g., **215** after deprotonation by *tert*-butyllithium, are transformed to the trimethylsilyl derivatives (e.g., **216**) by **1a**.



215 216

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