"Advances in Silicon Chemistry"
Gerald L. Larson, Editor
VP, Research Products
Gelest, Inc.
11 East Steel Road
Morrisville, PA 19067

IODOTRIMETHYLSILANE

George A. Olah, G. K. Surya Prakash,
and Ramesh Krishnamurti

Advances in Silicon Chemistry,
Volume 1, pages 1–64.

ISBN: 1-55938-176-0

1. INTRODUCTION

The use of functionalized organosilicon reagents (R_3SiX, X=electron withdrawing substituent) in organic synthesis has experienced rapid growth in the past two decades.[1,2] These reagents have been used as versatile synthons for the formation of new carbon–carbon, carbon–oxygen, carbon–nitrogen, and carbon–halogen bonds. The success of the above-mentioned reactions is largely due to the strong electropositive character of silicon compared to carbon (electronegativity, Si: 1.64; C: 2.35).[3] Furthermore, silicon forms strong bonds with oxygen and fluorine, and relatively weak bonds with nitrogen, bromine, iodine, sulfur, and selenium (see Table I for bond strengths in Me_3SiX).[3,4] Well-known reagents (Me_3SiX) wherein the silicon atom is attached to a moderately labile Si–X bond include azidotrimethylsilane (Me_3SiN_3), cyanotrimethylsilane (Me_3SiCN), bromotrimethylsilane (Me_3SiBr), and iodotrimethylsilane (Me_3SiI). Recently, we have found trifluoromethyltrimethylsilane ($(CH_3)_3SiCF_3$) as an effective trifluoromethide equivalent for nucleophilic reactions.[5a] All of these reagents have been extensively used in organic synthesis.[1,2]

Iodotrimethylsilane reviewed in this chapter was of interest to us originally[5b]

Table I. Approximate Bond Dissociation Energy of Organosilanes

Bond	*Compound*	*Dissociation energy, [kcal/mol]*
Si–F	$Me_3Si–F$	192.6
Si–O	$Me_3Si–OMe$	126.7
	$Me_3Si–OSiMe_3$	193.8
Si–C	Me_4Si	75.9
Si–S	$(H_3Si)_2S$	~69.9
Si–N	$Me_3SiNHSiMe_3$	76.4
Si–Cl	$Me_3Si–Cl$	112.4
Si–Br	$Me_3Si–Br$	96.2
Si–I	$Me_3Si–I$	76.8

in the possible preparation of long-lived trivalent silicon cations, such as Me_3Si^+. The weak Si–I bond offered a possible advantage in the attempted ionization of iodotrimethylsilane. Although these expectations did not materialize, the studies aroused our interest in the remarkable reactivity of iodotrimethylsilane as a hard–soft reagent.

Studies reported by Olah and Ho in 1976, as well as independently by Jung et al. in 1977 opened up the synthetic utility of iodotrimethylsilane, which rapidly developed into a widely used synthetic reagent.[6a] An earlier review[6a] published in 1982 covered the synthetic utility of iodotrimethylsilane till that time.

The present chapter incorporates studies summarized in the 1982 review along with subsequent work between 1982 and 1988. A number of shorter reviews were also published on the topic in the interim.[6b–d]

Iodotrimethylsilane contains silicon as the hard acid site and iodine as the soft basic site. Consequently, it reacts rapidly with compounds containing oxygen or fluorine (hard bases) forming strong silicon–oxygen and silicon–fluorine bonds. Furthermore, due to its polarization iodotrimethylsilane can also act as an electron-deficient silylating agent, i.e., as an aprotic acid catalyst for many significant organic reactions.

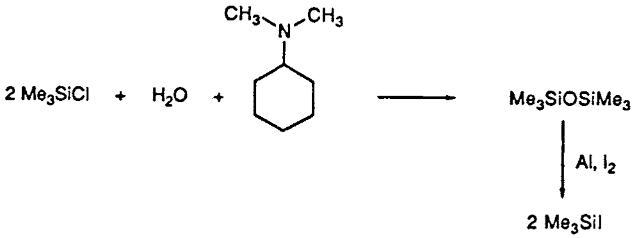
Wide interest and rapid growth in the use of the highly versatile iodotrimethylsilane made this review timely emphasizing both preparation of the reagent and its synthetic applications. For details the reader is referred to the primary literature quoted in the references.

2. PREPARATION OF IODOTRIMETHYLSILANE AND ITS EQUIVALENTS

The first preparation of iodotrimethylsilane was reported by Voronkov and Khudobin[7] in 1956 by the reaction of hexamethyldisiloxane with aluminum iodide. Pray et al.[8] obtained iodotrimethylsilane in 1948 by the iodolysis of phenyltrimethylsilane. The reactants were heated under gentle reflux under anhydrous conditions, and the iodotrimethylsilane isolated by fractional distillation of the reaction mixture.

$$Me_3SiOSiMe_3 + AlI_3 \longrightarrow 2\ Me_3SiI$$

The product is obtained as a colorless liquid on fractional distillation of the reaction mixture under strictly anhydrous conditions. The former method has subsequently been modified, and iodotrimethylsilane can be obtained in >80% yield from chlorotrimethylsilane in a two-step process.[9]

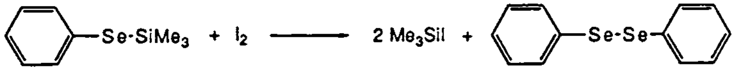


A less convenient method involves the halogen exchange between chlorotrimethylsilane and magnesium iodide.[10] However, with lithium iodide the reaction was found to work much more efficiently.[11]

$$2\,Me_3SiCl + MgI_2 \longrightarrow 2\,Me_3SiI + MgCl_2\,,$$

$$Me_3SiCl + LiI \longrightarrow Me_3SiI + LiCl$$

Detty[12] has prepared iodotrimethylsilane from phenylselenotrimethylsilane and iodine.

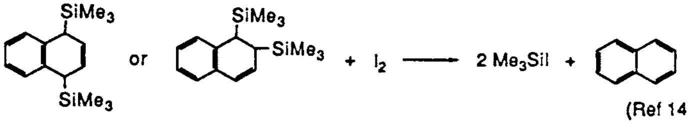


Iodotrimethylsilane can be isolated in very high yield by distillation of the reaction mixture. Diphenyldiselenide can be recycled to synthesize the starting precursor. The use of toxic organoselenides, however, represents difficulties. This approach has been adapted for the preparation of *t*-butyldimethylsilyl iodide.

Kovaleva[13] has used N-trimethylsilyldialkylamines as precursors for the preparation of iodotrimethylsilane.

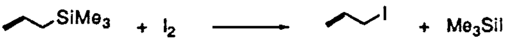
R = Et, n-Pr, n-Bu

Additional reported methods of preparation of iodotrimethylsilane starting from less readily available materials are



(Ref 14)

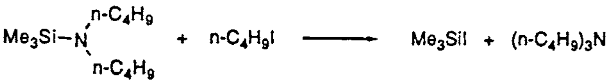
(Ref 15)


(Ref 15)

The following reactions have also been reported to yield iodotrimethylsilane as a product.

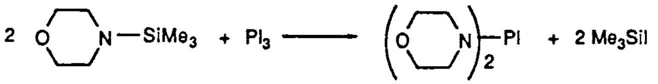
$Me_4Si + BI_3 \longrightarrow Me_3SiI + MeBI_2$ (Ref 16)

$Me_3Si{-}S{-}R + R'I \longrightarrow Me_3SiI + RSR'$ (ref 17a)


$Me_3Si{-}N(n\text{-}C_4H_9)_2 + n\text{-}C_4H_9I \longrightarrow Me_3SiI + (n\text{-}C_4H_9)_3N$ (ref 17b)

$Me_3Si{-}NH{-}SiMe_3 + AlI_3 \longrightarrow Me_3SiI$ (Ref 18)


(Ref 19)

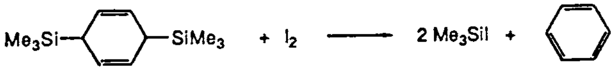

(Ref 19)

The hydrolytic susceptibility of the Si–I bond in iodotrimethylsilane can cause serious problems in reactions involving acid-sensitive compounds. Iodotrimethylsilane should be prepared fresh and used immediately, because it fumes in air and turns purple on standing (indicative of free iodine), making prolonged storage undesirable. However, storage over copper wire or copper powder in the absence of light prolongs shelf life. To circumvent this problem several *in situ* equivalents of iodotrimethylsilane were developed.

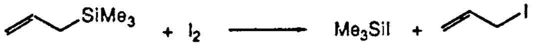
Following Sommer's method,[8] Ho and Olah[20] utilized the reaction of phenyltrimethylsilane with iodine at 110°C for the *in situ* generation of iodotrimethylsilane.

This reagent system was found to be more efficient than iodotrimethylsilane for the cleavage of esters.[20] These observations were subsequently confirmed by the work of Benkeser et al.[21] However, there are two drawbacks associated with the reagent system. The relatively high reaction temperature required for the iodolysis of phenyltrimethylsilane nullifies the inherent selectivity in some of the cleavage reactions of iodotrimethylsilane. Furthermore, an equivalent amount of iodobenzene is produced as a by-product which can be very difficult to separate from the reaction mixture. Although this problem can be circumvented in certain special cases, no simple method of separation of iodobenzene is available, except by very tedious column or gas chromatography. Therefore, Olah and others have developed alternative methods of *in situ* generation of iodotrimethylsilane or its equivalents.

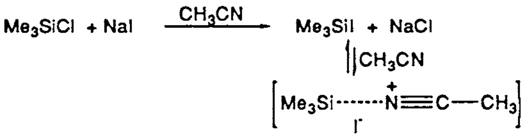
Jung and Blumenkopf[15] generated iodotrimethylsilane *in situ* from 3,6-bis-trimethylsilyl-1,4-cyclohexadiene and iodine, an extension of the earlier method of Birkofer and Kramer[14] who obtained iodotrimethylsilane from the corresponding bis-trimethylsilyldihydronaphthalene derivatives. However, this method involves the tedious synthesis of the starting diene.



Jung and Blumenkopf[15] also prepared iodotrimethylsilane from the reaction of allyltrimethylsilane with iodine, forming 1-iodopropene as by-product.



The formation of undesirable by-products and needed synthesis of precursors have led to the use of the surprisingly simple and inexpensive alternative of chlorotrimethylsilane with sodium iodide in acetonitrile solution or with lithium iodide in chloroform and carbon tetrachloride.[22-26] The mixture of chlorotrimethylsilane/sodium iodide in acetonitrile was found to be better than iodotrimethylsilane in many of its reactions with organic substrates. Schmidt and Russ[22] are to be credited with the first use of this reagent system in the reaction of carbonyl compounds. Olah et al.[23] and Morita et al.[24,25] have independently studied it on a wider scope. Machida et al.[26] have described the use of chlorotrimethylsilane and lithium iodide in chloroform and carbon tetrachloride.



Bassindale and Stoat[27] have found no evidence for the formation of N-trimethylsilylacetonitrilium iodide in the reaction mixture of Me3SiCl + NaI in acetonitrile, which was assumed previously to be involved in the reactions. Low concentrations of an intermediate polarized nitrilium complex, however, is possible.

For an ideal *in situ* reagent, there are several factors to be considered. (a) The precursor should be available readily in high yield. (b) *In situ* generation of iodotrimethylsilane should take place under mild conditions. (c) No by-products should be formed. Hexamethyldisilane fulfills all of these criteria. Hexamethyldisilane is available in high yield via the Wurtz coupling of chlorotrimethylsilane. Hexamethyldisilane is known to react with iodine to give iodotrimethylsilane in quantitative yield.[28] The reaction can be carried out in a variety of solvents.

Based on these considerations, Olah et al.[29,30] reported the use of hexamethyldisilane/iodine reagent as the most convenient *in situ* equivalent of iodotrimethylsilane. The reagent system gives no other products and the conversion is quantitative. Seitz and Ferreira[31] and Sakurai et al.[32] have independently demonstrated the utility of this reagent system.

$$Me_3SiSiMe_3 + I_2 \xrightarrow{25\text{-}61^\circ} 2\ Me_3SiI$$

3. PROPERTIES

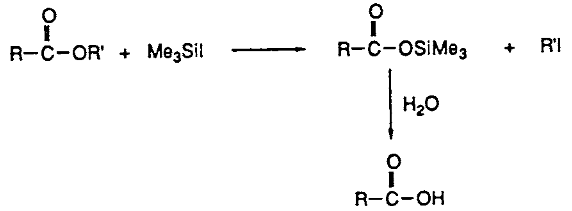
Iodotrimethylsilane is a clear, colorless liquid (bp 107°C, 106–109°C), which fumes in air (due to ready hydrolysis). The product becomes discolored on storage, particularly when exposed to light, but can be purified by distillation from copper powder. It has been well characterized by IR, Raman, ^{1}H NMR, ^{13}C NMR, ^{29}Si NMR, and by mass spectrometry.[33-36] Because of its relative instability (including light sensitivity), iodotrimethylsilane should be prepared fresh or purified before use.

4. SYNTHETIC APPLICATIONS

4.1. Esters

Carboxylic acids are usually protected as esters in organic synthesis. Generally, esters are hydrolyzed under either basic or acidic conditions.[37] Reagents for nonsaponifying hydrolysis (e.g., lithium iodide, alkylpyridines,[38] thiocyanate,[39] thiolate,[40] etc.) involve strong nucleophiles and higher reaction temperatures. Therefore, a need existed for the development of mild neutral reagents for the cleavage of esters into their carboxylic acids.

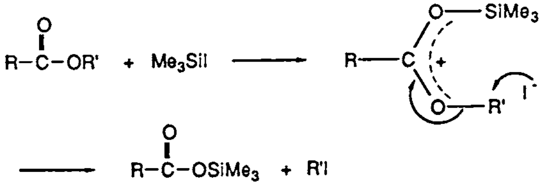
Iodotrimethylsilane was found to be an extremely efficient reagent for the dealkylation of esters under strictly neutral conditions to yield the silyl esters which then were hydrolyzed upon aqueous workup to the corresponding carboxylic acids. Cleavage of esters was reported independently by Ho and Olah,[41] and Jung and Lyster.[42] Carboxylic acids were obtained in very high yields on heating the esters with iodotrimethylsilane followed by quenching the reaction mixture with water. The reaction proceeds via O–alkyl cleavage, and thus an equivalent amount of alkyl iodide is formed.



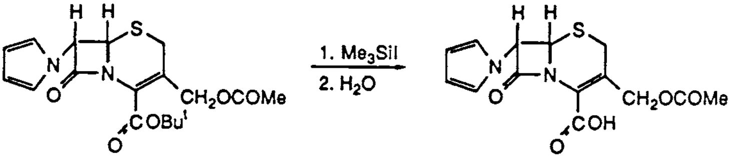
$$\mathrm{R{-}\overset{\overset{O}{\|}}{C}{-}OR' + Me_3SiI \longrightarrow R{-}\overset{\overset{O}{\|}}{C}{-}OSiMe_3 + R'I \xrightarrow{H_2O} R{-}\overset{\overset{O}{\|}}{C}{-}OH}$$

The reaction is general for all alkyl esters. Methyl and ethyl esters are cleaved cleanly in nearly quantitative yield. Even hindered esters (e.g., methyl pivalate) are cleaved by this reagent. The method also allows selectivity between various esters, because benzyl and *t*-butyl esters react at a much faster rate than the methyl, ethyl, and isopropyl esters. It is therefore possible to selectively cleave benzyl and *t*-butyl esters in the presence of methyl, ethyl, and isopropyl esters at 25°C.

The reaction rates suggest the following mechanism for nonsaponificative cleavage of esters by iodotrimethylsilane.



The selectivity of ester cleavage and the advantage of using neutral conditions is well-illustrated in the reported deprotection of the *t*-butyl ester group in the 7-pyrrolocephalosporin derivative.[43]



Because of the instability of pyrroles towards strong acids, the *t*-butyl group could not be removed by conventional acidic reagents.[44] Treatment with one equivalent of trifluoroacetic acid caused decomposition. However, reaction with iodotrimethylsilane followed by aqueous basic workup provided the free carboxylic acid. The selectivity of ester cleavage was demonstrated by the fact that the acetate group was left intact under the reaction conditions. Similar selective cleavage of the *t*-butyl group of a 1,4-dihydropyridinedicarboxylic acid diester derivative in the presence of a methyl group has been achieved with iodotrimethylsilane.[45]

Voronkov et al.[46] have cleaved (trifluorosilyl)methyl benzoate with iodotrimethylsilane.

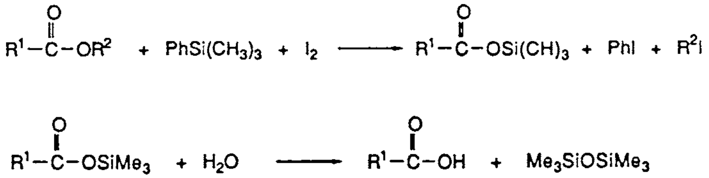
$$\mathrm{C_6H_5COOCH_2SiF_3 + ISiMe_3 \longrightarrow C_6H_5COOSiMe_3 + ICH_2SiF_3}$$

They were also able to obtain the reactive monomer bis(trimethylsilyl)-tetraphthalate by the cleavage of diethylterephthalate.[46]

$$C_2H_5OOCC_6H_4COOC_2H_5 + 2\,ISiMe_3 \longrightarrow Me_3SiOOCC_6H_4COOSiMe_3 + 2\,C_2H_5I$$

From the mechanism of the reactions, it was quite clear that the aryl esters will not be cleaved by iodotrimethylsilane. This was found to be true experimentally thus allowing 100% selectivity of cleavage between aryl and alkyl esters.

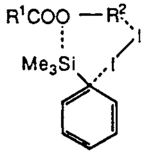
Because of the previously mentioned difficulties associated with the handling of iodotrimethylsilane, the phenyltrimethylsilane/iodine reagent was also used for the cleavage of esters.[20,47]



$$R^1-\overset{O}{\overset{\|}{C}}-OR^2 + PhSi(CH_3)_3 + I_2 \longrightarrow R^1-\overset{O}{\overset{\|}{C}}-OSi(CH)_3 + PhI + R^2I$$

$$R^1-\overset{O}{\overset{\|}{C}}-OSiMe_3 + H_2O \longrightarrow R^1-\overset{O}{\overset{\|}{C}}-OH + Me_3SiOSiMe_3$$

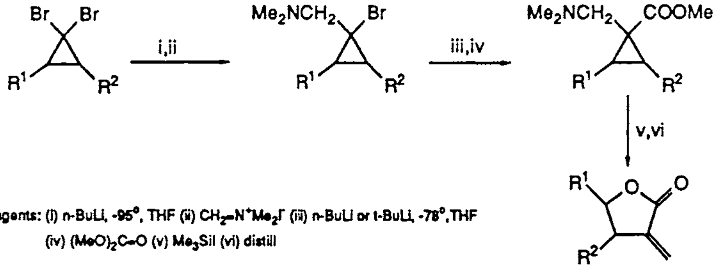
A concerted mechanism was suggested for the cleavage, rather than the *in situ* generation of iodotrimethylsilane and its subsequent reaction with the esters.



Subsequently, significant attention has been focused on the dealkylation of esters with *in situ* generated iodotrimethylsilane, such as chlorotrimethylsilane/sodium iodide reagent in acetonitrile. When chlorotrimethylsilane is added to an acetonitrile solution of sodium iodide, a yellow solution is obtained with immediate precipitation of sodium chloride. Concurrently, other groups had also reported dealkylation of esters and other transformations with chlorotrimethylsilane/sodium iodide reagent.[22–25] The cleavage of esters is slightly slower with this reagent than with iodotrimethylsilane. Allyltrimethylsilane and 3,6-trimethylsilyl-1,4-cyclohexa-2,5-diene have also been used as *in situ* precursors of iodotrimethylsilane[15] for the cleavage of esters.

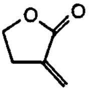
After the initial report on the use of *in situ* generated iodotrimethylsilane from hexamethyldisilane/iodine,[29] a more detailed report of the utility of the hexamethyldisilane/iodine reagent for dealkylation of esters appeared.[30] It was observed that the reaction with esters is catalyzed by excess iodine in the reaction mixture. Other groups[31,32] have also independently utilized hexamethyldisilane/iodine reagent for the cleavage of esters and other transformations.

An elegant application of nonsaponifying hydrolysis of esters has been demonstrated in the synthesis of α-methylene-γ-butyrolactones from the corresponding 1-(N,N-dimethylaminomethyl)cyclopropanecarboxylate esters.[48] Because of the interesting physiological properties of several terpenes containing the α-methylene-γ-butyrolactone functionality, there have been many reports on the synthesis of this class of compounds.[49] Use of iodotrimethylsilane for this purpose can be illustrated.

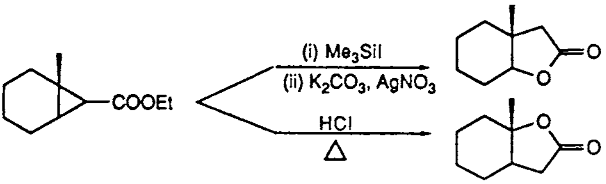


Reagents: (i) n-BuLi, -95°, THF (ii) $CH_2=N^+Me_2I^-$ (iii) n-BuLi or t-BuLi, -78°,THF (iv) $(MeO)_2C=O$ (v) Me_3SiI (vi) distill

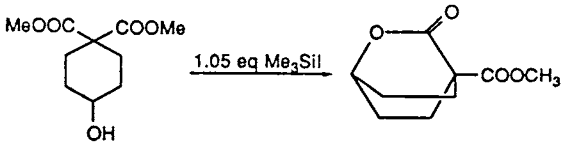
The starting dialkylaminocarboxylate ester undergoes dealkylation of the ester group followed by rearrangement in a highly stereoselective and regioselective manner. The reaction takes place by treating the ester with iodotrimethylsilane, followed by distillative thermolysis of the resulting quaternary ammonium salt. This sequence of reactions was used for the synthesis of the highly unstable hemiterpene lactone, tulipalin.



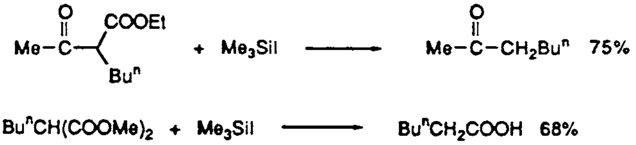
This synthetic methodology is a significant improvement over corresponding methods utilizing strongly acidic, aqueous conditions.[50] Such a ring expansion of a cyclopropane ester to butyrolactone catalyzed by iodotrimethylsilane has been employed to obtain regiocontrol in the product.[51a] Exactly opposite regiochemistry was observed in the case of the HCl-induced reaction.



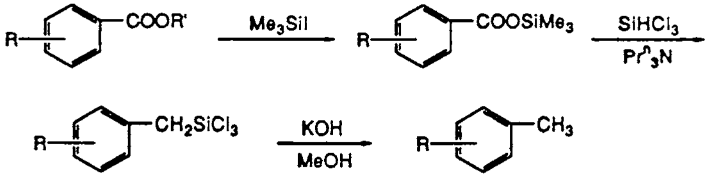
An unusual transannular lactone formation was observed in the case of 1,1-dicarbomethoxy-4-cyclohexanol with iodotrimethylsilane.[51b]



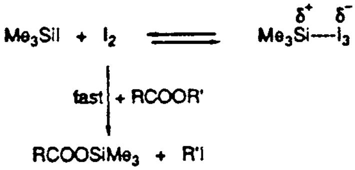
The dealkylation of esters has been used to synthesize trimethylsilylethyl oxalate by reaction of diethyloxalate with iodotrimethylsilane.[52] In another report, it was shown that β-keto esters and gem diesters undergo decarbo-alkoxylation on heating with iodotrimethylsilane.[53] Thus ketones and monocarboxylic acids, respectively, are obtained on workup. This procedure is a good alternative to the method of Krapcho which involves the heating of esters in wet dimethylsulfoxide in the presence or absence of alkali metal salts.[54]



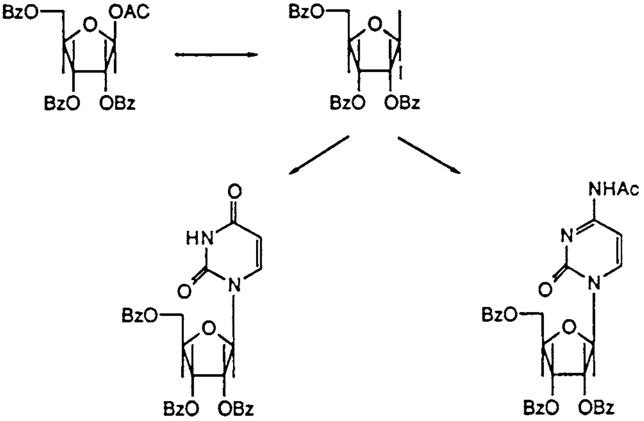
The known formation of silyl esters as intermediates has been exploited for the reduction of alkylbenzoates to the corresponding methylated aromatic compound in a three-step sequence.[17]



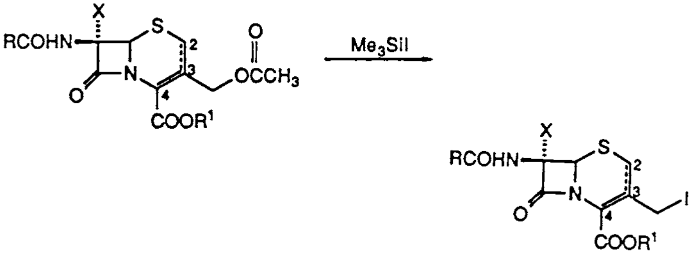
The catalytic effect of iodine on the reaction of esters with iodotrimethylsilane has been studied in detail. The following mechanism has been proposed.



So far, we have only considered the cleavage reaction forming the carboxylic group as the free acid. The fact that the reaction also gives an alkyl iodide has been exploited in carbohydrate chemistry for the synthesis of nucleosides.[55] A glycosyl iodide was prepared by the reaction of a suitably blocked sugar derivative bearing an anomeric ester with iodotrimethylsilane. Reaction of the glycosyl iodide with some pyrimidine and purine nucleobases provided the corresponding nucleosides. Thus, 1-O-acetyl-2,3,5-tri-O-benzoyl-β-D-ribofuranose was reacted with iodotrimethylsilane, and the resulting product coupled with silylated uracil to form 1-(2,3,5-tri-O-benzoyl-β-D-ribofuranosyl)uracil. Similarly, coupling with silylated cytosine, followed by acetylation yielded 1-(2,3,5-tri-O-benzoyl-β-D-ribofuranosyl)-4-acetamido-2(1H)-pyrimidinone.



There are several reports in the literature on the cleavage of cephalosporin esters,[56–60] related cephem derivatives,[61] and β-lactam antibiotic esters[62] with iodotrimethylsilane or its derivatives. For example, very high yields (≥95%) of 3-iodomethyl cephalosporin esters was obtained from 3-acetoxymethyl cephalosporin esters.[56] In this reaction, the integrity of double bonds at Δ^2- and Δ^3-cephems was retained.



The formation of silyl ester intermediates in the dealkylation of esters has been exploited to develop iodotrimethylsilane-mediated mild and neutral transesterification of esters,[63] the overall reaction being a composite of two successive transesterifications.

$$R^1COOR^2 \xrightarrow[-R^2I]{Me_3SiI/I_2} R^1COOSiMe_3 \xrightarrow[-[Me_3SiOH]]{R^3OH} R^1COOR^3$$

The transesterification procedure is general for aryl, alkyl, and α,β-unsaturated carboxylic acid esters. Even hindered esters such as methyl pivalate underwent transesterification in good yield. However, the scope of the reaction is limited to primary and secondary aliphatic alcohols.

Alkyl silyl ethers can be used in place of alcohols in the second step.

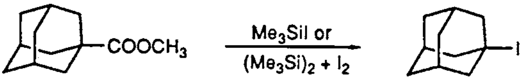
$$R'COOSiMe_3 + R^3OSiMe_3 \longrightarrow R'COOR^3 + Me_3SiOSiMe_3$$

In their report on the dealkylation of esters, Jung and Lyster[42] described the formation of acyl iodides in high yield on prolonged exposure of esters to excess iodotrimethylsilane.

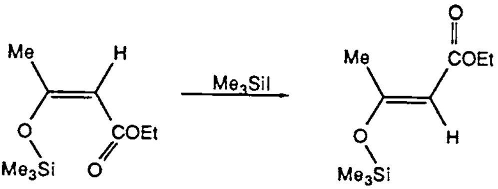
$$RCOOR' + Me_3SiI \longrightarrow RCOOSiMe_3 + Me_3SiI \longrightarrow RCOI + (Me_3Si)_2O$$

Ethyl palmitate was converted to palmitoyl iodide in 70% yield on reaction with 2.5 eq of iodotrimethylsilane for 3 days at 75°C.

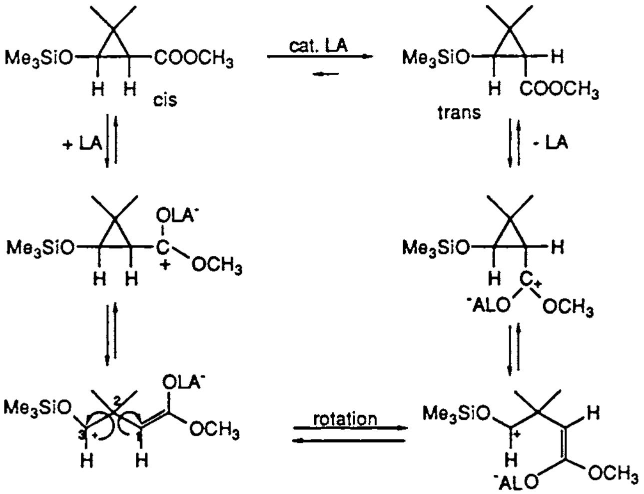
During studies on the reaction of methyl-1-adamantanecarboxylate with hexamethyldisilane/iodine reagent, it was observed by Olah et al.[64] that some 1-iodoadamantane is formed on prolonged heating of the reaction mixture. By heating methyl 1-adamantanecarboxylate with 2 eq of hexamethyldisilane/iodine in the absence of solvent (~107°C, bp of Me3SiI), 1-iodoadamantane was obtained in 70% yield. The reaction is in fact general for tertiary alkyl esters. Consequently, a general procedure has been developed[64] for the halodecarboxylation of ester and acids (via the corresponding silyl esters and acyl chlorides).



Although esters in general are cleaved by iodotrimethylsilane, it was observed that *cis–trans* isomerization of certain crotonic acid esters can be catalyzed by iodotrimethylsilane at 100°C.[65] Thus, a mixture of 86% *cis*- and 14% *trans*-β-trimethylsilyloxy crotonic acid esters was transformed on heating with catalytic amounts of iodotrimethylsilane at 100°C for 2 h into 98% of the *trans* product, which is thermodynamically more stable.



Similar results have been reported by other groups using halotrimethylsilanes.[66] Not only reaction of unsaturated esters, even *cis–trans* isomerization of cyclopropanecarboxylic acid esters have been achieved using iodotrimethylsilane[67] and related Lewis acid type catalysts. The mechanism of the reactions can be depicted as



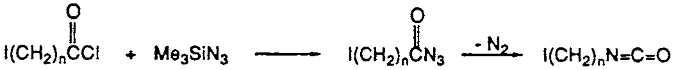
4.2. Lactones, Carbonates, Lactams, and Sulfones

The facile cleavage of esters with iodotrimethylsilane implied that lactones (especially with 4-, 5-, and 6-membered rings) should cleave at appreciably faster rates. Such cleavage of lactones provides an entry into ω-iodocarboxylic acids, which are highly versatile bifunctional synthons.

Voronkov et al.[68] initially reported the reaction of γ-butyrolactone with iodotrimethylsilane.

This reaction was further developed by Kricheldorf,[69] who treated a wide variety of lactones with iodotrimethylsilane and also with bromotrimethylsilane. Iodotrimethylsilane was found to be much more reactive than bromotrimethylsilane. These observations are consistent with the results of the cleavage of esters.

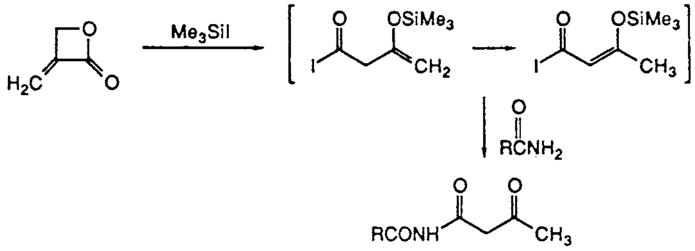
The iodoalkyl esters and acids function as powerful alkylating agents. The iodo group could be converted to other functional groups such as hydroxyl, mercapto, amino, etc. The bifunctional acids and acid chlorides are important starting materials for a large number of industrially useful compounds. One of this class of compounds are the ω-haloalkyl isocyanates, obtained from the corresponding acyl chlorides by reaction with azidotrimethylsilane followed by rearrangement of the intermediate acyl azide.



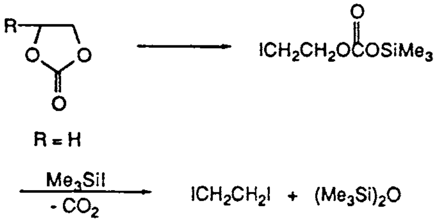
$$I(CH_2)_n\overset{O}{\overset{\|}{C}}Cl + Me_3SiN_3 \longrightarrow I(CH_2)_n\overset{O}{\overset{\|}{C}}N_3 \xrightarrow{-N_2} I(CH_2)_nN{=}C{=}O$$

Deslongchamps and Guay[70a] have used the lactone cleavage procedure in the synthesis of conformationally rigid *cis*- and *trans*-tricyclic monoacetals and dithioacetals. Lactones are also cleaved very efficiently with chlorotrimethylsilane/sodium iodide reagent system.[29]

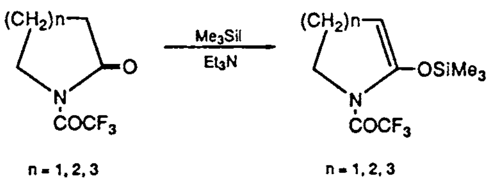
Yamamoto et al.[70b] have used diketene/iodotrimethylsilane as an efficient N-acetoacetylating agent for carboxamides. Diketene, which is a methylene-butyrolactone, undergoes unusual ring oxygen carbon cleavage to provide the acyl iodide adduct, which subsequently acetoacylates the carboxamides.



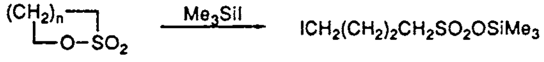
Cyclic carbonates were also found to react readily with iodotrimethylsilane, yielding 1,2-diiodoalkanes.



Lactams in the presence of iodotrimethylsilane and triethylamine led to lactam enol silyl ethers.[71a] This is interesting since direct silylation of lactam enolates gives C-silylation.[71b,c]



Even certain sultones are cleaved by iodotrimethylsilane to the corresponding ω-iodo-alkyltrimethylsulfonates[72] without further reaction.



The carbamate function is a commonly used protecting group for primary and secondary amines. Whereas many groups have been developed for the protection of amines, carbamates are very convenient in that the free amines can be recovered with ease. Simple alkyl carbamates can be synthesized very easily, but require highly acidic reagents for deprotection to form the starting amines. The reagents commonly used for the cleavage of alkyl carbamates are strong base and strong acid. However, benzyl carbamates can be easily cleaved with acid,[73] or hydrogenolysis,[74] or photolysis.[75] *t*-Butyl carbamates can also be cleaved very readily with dilute acid.

Based on the analogy with the reaction of esters, iodotrimethylsilane has proven to be a very general reagent for the conversion of carbamates into the corresponding free amines, via the trimethylsilyl carbamates, as shown by Jung and Lyster.[76]

$$R^1R^2NCOOR^3 + Me_3SiI \xrightarrow{-R^3I} R^1R^2NCOOSiMe_3$$

$$\xrightarrow[-Me_3SiOMe]{MeOH} \left[R^1R^2NCOOH\right] \xrightarrow{-CO_2} R^1R^2NH$$

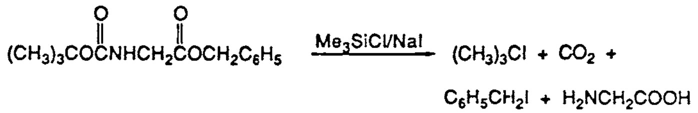
The first step is a transesterification reaction in which the alkyl carbamate is converted to the trimethylsilyl carbamate. Treatment with methanol yields the free carbamic acid, which spontaneously loses CO_2 to provide the free amine. The reaction is equally applicable to unsubstituted, monosubstituted, and disubstituted carbamates. This method allows the deprotection of amines which are highly sensitive to either acidic or alkaline reaction conditions.

Because of the presence of a lone pair of electrons on the nitrogen, the carbamyl group is more polarized, thus facilitating the interaction of the carbonyl oxygen with silicon. For this reason, the carbamates react at a faster rate with iodotrimethylsilane than do the corresponding esters.

The chlorotrimethylsilane/sodium iodide/acetonitrile reagent was also shown capable of converting alkyl carbamates into the corresponding amines in high yields.[23]

As is the case with esters, benzyl and *t*-butyl carbamates are cleaved faster than the methyl and ethyl derivatives. Benzyl carbamates are cleaved almost instantaneously at 25°C, as are the *t*-butyl carbamates. On the other hand, methyl carbamates require heating under reflux for 24 h for complete cleavage to the corresponding amines. The reaction rate with chlorotrimethylsilane/sodium iodide is slower than with iodotrimethylsilane.

When benzyl N-*t*-butoxycarbonyl glycine was treated with chlorotrimethylsilane/sodium iodide, glycine was obtained via the deprotection of both the ester and carbamate groups.

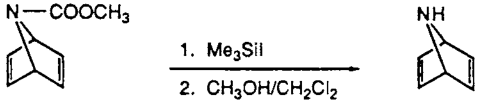


$$(CH_3)_3CO\overset{\overset{O}{\|}}{C}NHCH_2\overset{\overset{O}{\|}}{C}OCH_2C_6H_5 \xrightarrow{Me_3SiCl/NaI} (CH_3)_3CI + CO_2 + C_6H_5CH_2I + H_2NCH_2COOH$$

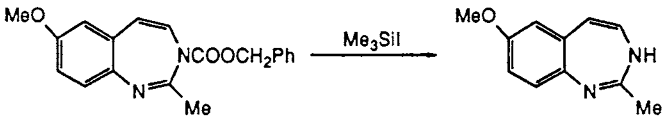
Seitz and Ferreira[31] using the hexamethyldisilane/iodine reagent have also shown that the *t*-butoxycarbonyl group can be removed under mild conditions from N-(*t*-butoxycarbonyl)-L-valine in 83% yield with no racemization of the product. The results[30] with the hexamethyldisilane/iodine reagent indicate that this reagent is very selective compared with chlorotrimethylsilane/sodium iodide. For example, carbamates can be cleaved cleanly in the presence of a benzyl ester.

$$\text{Boc-Gly-OBzl} \xrightarrow[\text{5 min}]{Me_3SiSiMe_3/I_2} \text{Gly-OBzl} \xrightarrow[\text{15 min}]{Me_3SiSiMe_3/I_2} \text{Gly}$$

Vogel and co-workers[77] have used iodotrimethylsilane to prepare 7-azanorbornadiene from 7-N-carbomethoxy azanorbornadiene.



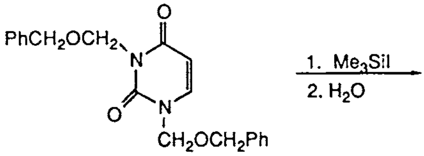
Kurita et al.[78] have provided the first example of a 1,3-benzodiazepine derivative by the iodotrimethylsilane-induced decarboxylative cleavage of 3-benzyloxycarbonyl-3H-1,3-benzodiazepine. The method[78] was also utilized for the preparation of 1,3-thienodiazepines.



Iodotrimethylsilane is a very attractive reagent in peptide synthesis, because esters and carbamates are the most common blocking groups used. The acid-catalyzed deblocking of peptides results in the formation of *t*-butyl and benzyl carbocations, which often leads to tertiary butylation and benzylation of the aromatic rings in the peptide chain. This alkylation reaction does not occur upon deblocking of peptides with iodotrimethylsilane, because the alkyl groups are cleared as alkyl iodides via an SN2 mechanism, thereby circumventing the formation of highly reactive carbocations.

Lott et al.[79] have examined in detail the reaction of several N-benzyloxy and N-*t*-butoxycarbonyl peptides with iodotrimethylsilane, by following the reaction by ^{1}H NMR. The reagent was found to be very selective. O-Benzyltyrosine was cleaved without the formation of any rearrangement products. Furthermore, none of the side-chain protecting groups were affected by treatment with iodotrimethylsilane. This method will probably find wide use in solid-phase peptide syntheses as well.

Kundu[80] has used iodotrimethylsilane to deblock the N-protected groups of uracil derivatives. N-Benzyloxymethyl substituted uracil derivatives were cleaved to free uracil in moderate to good yields.



4.3. Phosphine Oxides, Halophosphines, Phosphoramides, and Phosphorous Amides

It was suggested[81,82] that in the presence of nonbonded electron pair donors, silicon–iodine bonds may be ionized to yield complex cations containing silicon(IV). Phosphine oxides and phosphoramides are such compounds. Beattie and Parrett[83] were able to isolate a crystalline adduct between trimethylphosphine oxide and iodotrimethylsilane. The structure was formulated as $Me_3P^+–O–SiMe_3I^-$.

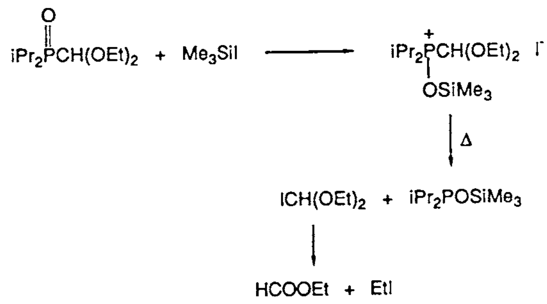
The adduct was characterized by IR spectroscopy and conductivity measurements. Other researchers later prepared more tris[alkyl or aryl] trimethylsilyloxyphosphonium iodides by the reaction of the corresponding phosphine oxides with iodotrimethylsilane.[84,85]

Similar ionic adducts have been isolated by the reaction of iodotrimethylsilane and bromotrimethylsilane with tris(dimethylamino) phosphine oxide.[85]

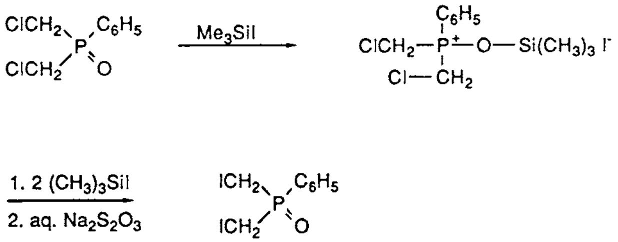
$$(Me_2N)_3P{=}O \;+\; Me_3SiX \longrightarrow [(Me_2N)_3POSiMe_3]^+X^-$$

Conductomeric studies showed that the equilibrium for formation of these adducts in dichloromethane lies well to the right. These results were also confirmed by ^{31}P NMR studies. The kinetic characteristics of reactions involving hexamethylphosphoric triamide-catalyzed racemization or substitution of silicon halides can be interpreted in terms of such phosphonium intermediates.[86–88]

Livantsov et al.[89] have shown that phosphorylated formals react with iodotrimethylsilane to provide the corresponding O-silylated onium ion which upon heating at 120–130°C under reduced pressure cleaves to silylphosphinite and α-iodoacetal. The latter decomposes to ethyl formate and ethyl iodide



Because of the potential of these trimethylsiloxyphosphonium salts in organic synthesis, the studies have been extended to alkylphosphine oxides bearing substituents on the alkyl group, with some interesting results.[90] When bis[chloromethyl]phenyltrimethylsilyloxyphosphonium iodide was treated with iodotrimethylsilane, halide exchange was observed.



In addition to chlorine, bromine and tosylate groups can also undergo displacement with iodotrimethylsilane.

$$(X\text{-}CH_2)_3P{=}O \xrightarrow{(CH_3)_3SiI} (I\text{-}CH_2)_3P{=}O$$

$X = Cl, Br, O\text{-}Tos$

These studies have been extended to chlorophosphines and chlorophosphoranes.

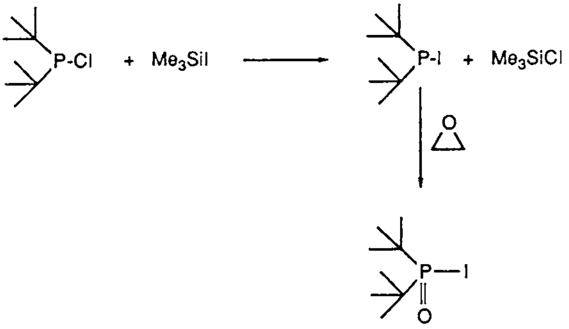
$$R_{3-n}PCl_n + n\ Me_3SiI \longrightarrow R_{3-n}PI_n + n\ Me_3SiCl$$

$$R_{5-n}PCl_n + n\ Me_3SiI \longrightarrow R_{5-n}PI_n + n\ Me_3SiCl$$

This method allows the preparation of iodophosphines and iodophosphoranes under mild, neutral conditions in high yields, compared to the usual metal–iodide exchange method,[91a] which gives relatively lower yields and necessitates a tedious workup, due to the sensitivity of the products towards moisture and oxygen. In one case, trimethylsilylallylphosphine was prepared by reacting allylphosphine with iodotrimethylsilane.[91b]

The exchange reaction allows the facile preparation of diphenylphosphinous iodide, ethanephosphonous diiodide and related iodides, which could not be prepared using metal iodides, but were prepared by cleavage of dimeric and tetrameric starting materials containing a phosphorous–phosphorous bond.[92,93] Some of these iodophosphines and iodophosphoranes are finding increasing utility as reagents in organic synthesis.[94,95]

Gomelya and Feshchenko[96] have prepared the sterically hindered di-*tert*-butylphosphinous iodide by reacting di-*tert*-butylphosphinous chloride with iodotrimethylsilane in benzene. The hindered iodide was subsequently employed for the preparation of the hitherto unknown di-*tert*-butylphosphinic iodide



Iodotrimethylsilane also reacts with triaminophosphine imides and their derivatives. N-Chlorohexaethylphosphorimidic triamide reacts with iodotrimethylsilane in ether solution at 20°C to provide tris(diethylamino)(diiodoamino)phosphonium chloride, N-silylphosphorimidic triamide, and chlorotrimethylsilane.[97]

$$2\ [(C_2H_5)_2N]_3P{=}N\text{-}Cl + 2\ Me_3SiI \longrightarrow [(C_2H_5)_2N]_3P^{+}NI_2 + [(C_2H_5)_2N]_3P{=}N\text{-}SiMe_3 + Me_3SiCl$$

Facile iodide-ion exchange has been observed with phosphonium bromides on treatment with iodotrimethylsilane.[98]

Cybryk et al.[99] have observed facile interaction of iodotrimethylsilane and related derivatives with phosphorous triamides. At low temperatures (below –50°C), ^{31}P NMR spectra and conductometric measurements indicated an equilibrium involving phosphonium ion.

$$(Me_2N)_3P + Me_3SiI \rightleftharpoons (Me_2N)_3P^{+}SiMe_3\ I^{-}$$

At higher temperatures, the reaction provides the iodophosphorous diamide which subsequently interacts with the phosphorous triamide to provide an Arbuzov-type intermediate.

$$(Me_2N)_3P + Me_3SiI \rightleftharpoons (Me_2N)_2P\text{-}I + Me_2NSiMe_3$$

$$(Me_2N)_3P + (Me_2N)_2PI \rightleftharpoons [(Me_2N)_3\overset{+}{P}\text{-}P(NMe_2)_2]I^{-}$$

4.4. Phosphonates, Phosphonate Esters, and Phosphorous(III) Compounds

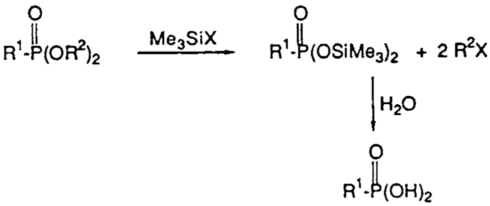
Phosphonate and phosphate esters are of particular importance in synthesis, because of their utilization as intermediates in the synthesis of oligonucleotides, and for the synthesis of phosphonate analogues of biological phosphate esters. One of the crucial steps in the synthesis of these compounds is the dealkylation of the esters to yield the free acids.

Although aryl phosphonates can be cleaved with hydroxide,[100] and benzylic esters can be cleaved by hydrogenolysis,[101] there is no general method available for the dealkylation of simple alkyl esters.[102] It should be noted that 2-cyanoethyl esters and 2,2,2-trichloroethyl esters[103] can yield free acids by treatment with ammonium hydroxide and Zn dust, respectively, but they constitute rather special cases. Simple alkyl esters are usually cleaved under harsh conditions by treatment with concentrated hydrochloric acid at high temperatures.[104] It was imperative, therefore, to find mild and neutral reagents to cleave phosphate and phosphonate esters, in order to prepare the free acids containing other acid-sensitive functional groups, or to prepare phosphonic acid derivatives of nucleosides, lipids, and carbohydrates.

The use of halotrialkylsilanes for the cleavage of phosphonates was initially investigated by Voronkov and Zgonnik[105] and Schwarz and Schoeller,[106] and later on by Rabinowitz.[107] They found that some phosphonate and phosphate esters undergo transesterification to the corresponding trialkylsilyl esters on treatment with chlorotrialkylsilanes. It was also observed that the silyl esters could be converted to the free phosphonic acids on quenching with water, thus providing an entry to phosphonic acids and phosphoric acids under mild, neutral conditions.

Chlorosilanes require higher temperatures and long reaction times for the transesterification. It was discovered by Voronkov and Zgonnik,[105] Rundinskas et al.,[108] and McKenna et al.[109] that bromotrimethyl(ethyl)silane offered a dramatic reduction in the time and temperature of the transesterification. Therefore, it was anticipated that iodotrimethylsilane and its *in situ* equivalents would be even more reactive reagents than bromotrimethylsilane. This expectation has been borne out by the simultaneous publications of Morita et al.,[24] Machida et al.,[26] Zygmunt et al.,[110] and Blackburn[111]. Whereas Morita and Machida used chlorotrimethylsilane with sodium iodide and lithium iodide, respectively, Zygmunt et al.[110] and Blackburn and Ingelson[111] achieved the same results with iodotrimethylsilane. All of these reagents are equally effective for the dealkylation of dialkylphosphonates.

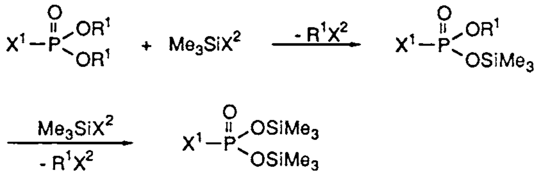
Initially, bis(trimethylsilyl)phosphonates are produced which were subsequently converted into free phosphonic acids by treatment with water or methanol. The phosphonic acids were isolated as salts by reaction with aniline or *p*-anisidine. The reaction can be depicted in general as



An examination of the data shows that dialkylphosphonates are selectively cleaved in the presence of other functional groups such as carboxylate esters, carbon–carbon multiple bonds, and haloalkyl groups (although some halogen exchange has been reported). It is especially valuable for dealkylation of acylphosphonate and aroylphosphonate esters. Dealkylation of 2-oxoalkanephosphonate esters has been studied in detail by Zygmunt et al.[110] Several patents[112,113] report the cleavage of phosphonate esters with iodotrimethylsilane resulting in industrially important compounds.

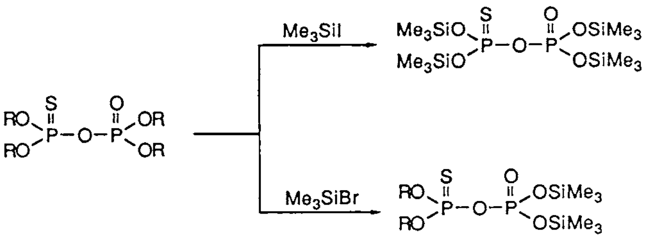
The dealkylation reaction is general for alkyl esters, but aryl esters cannot be cleaved as expected from earlier observations with carboxylate esters.[41,42] The selectivity for hydrolysis of alkyl vs. aryl phosphate esters is complementary to the variety of methods available for the selective cleavage of aryl esters. On the other hand, iodotrimethylsilane cannot be used for achieving selectivity between various alkyl groups in mixed phosphonate esters. McKenna and Schmidhauser[114] has shown that such selectivity is possible with bromotrimethylsilane. Recently, Takeuchi et al.[115] have demonstrated the stepwise and selective dealkylation of phosphotriesters with phenylthiotrimethylsilane.

Chojnowski et al.[116] have studied the transesterification of compounds of the general formula $X^1P(O)(OR')_2$, where X^1 denotes a reactive ligand attached to phosphorus. These compounds may be of biochemical interest. They found that O,O-dialkylphosphorochloridates, bromidates, thiolates, and O,O-dialkylphosphoramidates react with iodotrimethylsilane to yield the corresponding trimethylsilyl esters without altering the P–Cl, P–Br, P–S, and P–N bonds. The reaction was shown to proceed in a stepwise manner, thus allowing the preparation of mixed silyl alkyl esters.



X^1 = Cl, Br, NR_2, NHR, NH_2, SR, H X^2 = I, Br

The reaction could also be used for esters of polyphosphoric acid, with preservation of the P–O–P bond.

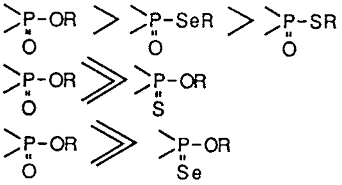


These reactions show that the nature of the product can be altered by changing from the less reactive bromotrimethylsilane to the more reactive iodotrimethylsilane. This indicates the lower reactivity of the thionophosphoryl moiety relative to the phosphate, towards halotrimethylsilane reagents.

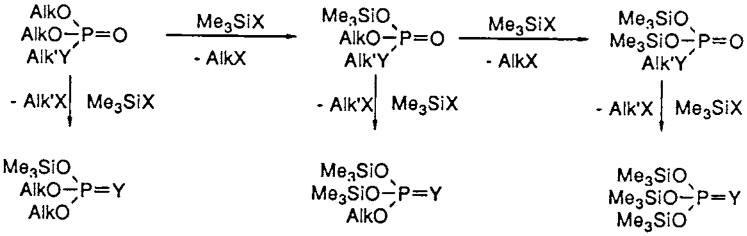
The synthetic and mechanistic aspects of the reaction of iodotrimethylsilane with thio and seleno analogs of phosphate and phosphonate esters have been examined in detail by Borecka et al.[117] They have studied the reaction of iodotrimethylsilane with various esters of phosphorothioic and phosphoroselenoic acids of general structures $(RO)_2(RY)P{=}O$ and $(RO_3)P{=}Y$, where Y=S, Se and R=alkyl.

The reactions resulted in the replacement of alkyl groups by trimethylsilyl groups, as expected from our previous knowledge about the behavior of phosphonate esters. No S-trimethylsilyl and Se-trimethylsilyl substituted esters were detected among the reaction products. Thus, the transesterification of O–R, S–R and Se–R esters always leads to the corresponding $O–SiMe_3$ ester containing the thiophosphoryl and selenophosphoryl groups.

From the large number of different esters studied, the following order of reactivity towards iodotrimethylsilane was established.

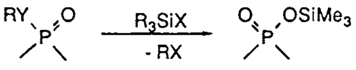


The two types of transesterification reactions observed with iodotrimethylsilane are depicted below.



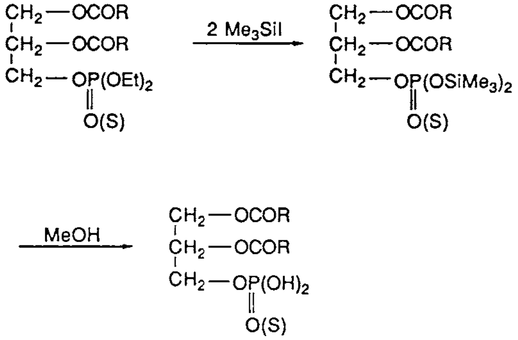
X = Br, I; Y = S, Se

Again, as expected, iodotrimethylsilane was shown to be much more reactive than bromotrimethylsilane. The general order of reactivity for the reaction is Y = O > Se > S.



is Y = O > Se > S

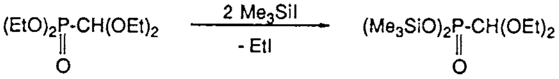
The transesterification of phosphoryl and thiophosphoryl compounds has been applied to the synthesis of phosphatidic acids.[118]



$$\begin{array}{l}CH_2{-}OCOR\\ CH_2{-}OCOR\\ CH_2{-}\underset{\underset{O(S)}{\|}}{O}P(OEt)_2\end{array} \xrightarrow{2\,Me_3SiI} \begin{array}{l}CH_2{-}OCOR\\ CH_2{-}OCOR\\ CH_2{-}\underset{\underset{O(S)}{\|}}{O}P(OSiMe_3)_2\end{array} \xrightarrow{MeOH} \begin{array}{l}CH_2{-}OCOR\\ CH_2{-}OCOR\\ CH_2{-}\underset{\underset{O(S)}{\|}}{O}P(OH)_2\end{array}$$

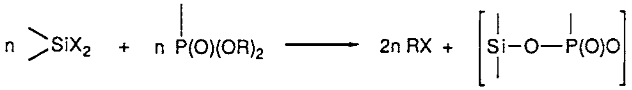
This reaction highlights the selectivity between carboxylic-ester and phosphate-ester cleavage. This methodology significantly simplifies the synthesis of phosphatidic acids, providing new possibilities in the chemistry of phospholipids.

Similar to phosphonates, phosphorous(V) substituted formals also react with iodotrimethylsilane.[89]



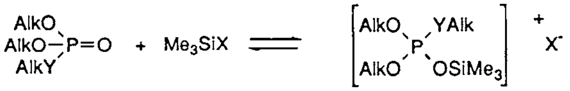
$$(EtO)_2\underset{\underset{O}{\|}}{P}\text{-}CH(OEt)_2 \xrightarrow[-\,EtI]{2\,Me_3SiI} (Me_3SiO)_2\underset{\underset{O}{\|}}{P}\text{-}CH(OEt)_2$$

Finally, these transesterifications have potential for the synthesis of silicon and phosphorous containing polymers.[119]



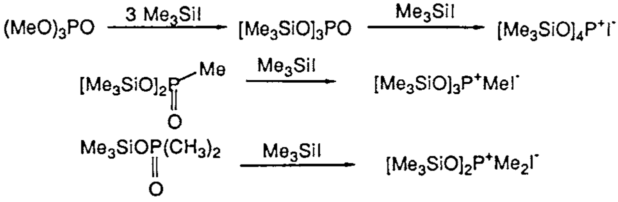
$$n\ {>}SiX_2 + n\ \overset{|}{P}(O)(OR)_2 \longrightarrow 2n\,RX + \left[\overset{|}{\underset{|}{Si}}{-}O{-}\overset{|}{P}(O)O\right]$$

Regarding the mechanism of dealkylation of phosphonate and phosphate esters, the reaction involves, as the first step, the nucleophilic attack by the phosphoryl oxygen on silicon, resulting in the formation of the phosphonium salt intermediate. This is analogous to the previously discussed reaction of phosphine oxides and phosphoramides with iodotrimethylsilane.



$$\begin{array}{l}AlkO\\ AlkO{-}P{=}O\\ AlkY\end{array} + Me_3SiX \rightleftharpoons \left[\begin{array}{c}AlkO\quad YAlk\\ P\\ AlkO\quad OSiMe_3\end{array}\right]^+ X^-$$

Such adducts have been isolated from tris(trimethylsilyl)phosphate and also from the silyl esters of methylphosphonic and dimethylphosphonic acid.[120]

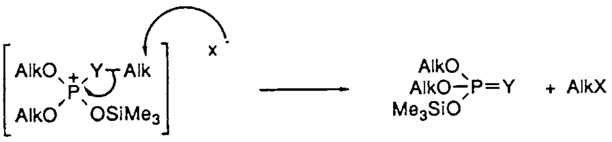


$$(MeO)_3PO \xrightarrow{3\,Me_3SiI} [Me_3SiO]_3PO \xrightarrow{Me_3SiI} [Me_3SiO]_4P^+I^-$$

$$[Me_3SiO]_2\underset{\underset{O}{\|}}{P}{-}Me \xrightarrow{Me_3SiI} [Me_3SiO]_3P^+MeI^-$$

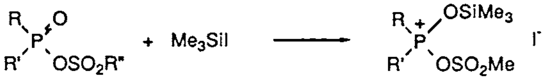
$$Me_3SiO\underset{\underset{O}{\|}}{P}(CH_3)_2 \xrightarrow{Me_3SiI} [Me_3SiO]_2P^+Me_2I^-$$

The second step involves the attack of halide on one of the alkyl groups to yield alkyl halide and the corresponding trimethylsilyl ester.

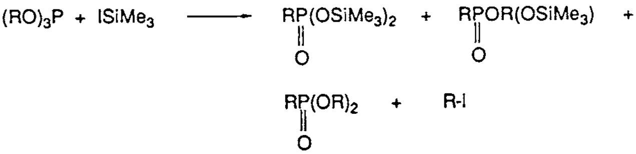


The overall reaction thus involves the initial, reversible formation of a phosphonium salt intermediate in a fast step, followed by slow dealkylation. It was shown by ^{31}P NMR studies that in the reaction of iodotrimethylsilane with an ester bearing a P=O phosphoryl group, the equilibrium for the formation of the phosphonium salt lies well towards the intermediate, thus enabling its direct observation. The mechanistic proposals were also confirmed by conductance studies on the reaction system, and also by investigation of the stereochemical course of the corresponding reaction of an optically active model thiophosphonate, where complete racemization was observed.

Mixed anhydrides of phosphorous acids also react with iodotrimethylsilane to give the corresponding onium ions.[121] Such ions have been characterized by ^{31}P NMR spectroscopy.



Many phosphites and monothiophosphites also undergo reactions with iodotrimethylsilane, and these have been elegantly investigated by Chojnowski et al.[122,123] using ^{31}P NMR spectroscopy. For example, the reaction of trialkylphosphite with iodotrimethylsilane leads to O-trimethylsilyl esters of alkylphosphonic acid. The reaction sequence is as follows:



$$(RO)_3P + ISiMe_3 \longrightarrow RP(=O)(OSiMe_3)_2 + RP(=O)OR(OSiMe_3) + RP(=O)(OR)_2 + R\text{-}I$$

If the reaction is performed at low temperatures initial formation of dialkyliodophosphite can be observed.

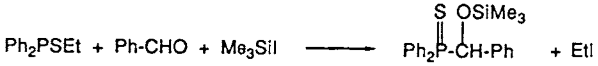
$$(RO)_3P + Me_3SiI \longrightarrow (RO)_2PI + Me_3SiOR$$

$$R = Me$$

Iodotrimethylsilane also reacts with dialkylphosphinothioites to provide the isomerized phosphine sulfide and other products.[124]

$$R_1R_2PSEt + Me_3SiI \longrightarrow R_1R_2\overset{S}{\overset{\|}{P}}Et$$

The above reaction has been employed to condense benzaldehyde with diphenylphosphenothioite and iodotrimethylsilane.[125]



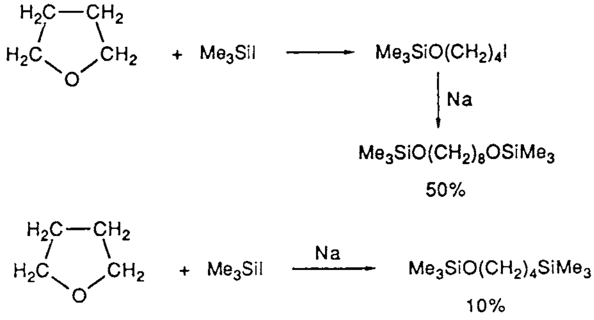
$$Ph_2PSEt + Ph\text{-}CHO + Me_3SiI \longrightarrow Ph_2\overset{S}{\overset{\|}{P}}\text{-}\overset{OSiMe_3}{\overset{|}{C}}H\text{-}Ph + EtI$$

4.5. Ethers

The first indication of the reaction of iodotrimethylsilane with ethers can be attributed to Kruerke,[10] who observed the cleavage of diethyl ether being used as a solvent during the attempted preparation of iodotrimethylsilane by halide exchange of chlorotrimethylsilane with magnesium iodide.

This investigator also studied the reaction of tetrahydrofuran with iodotrimethylsilane, but did not characterize the product. Voronkov et al.[126] examined the reaction of tetrahydrofuran in detail. At 60°C, trimethyl-(4-iodobutoxy)silane was obtained in quantitative yield.

They also observed that in the presence of sodium, the nature of the products was entirely different.



This reaction provides a convenient synthesis of 1,8-octanediol. The reaction has also been studied with Li, K, and Mg.[127] It was also observed that the unstable trimethyl-(4-iodobutoxy)silane reacts with iodotrimethylsilane to yield 1,4-diiodobutane in 85% yield.

$$Me_3SiI + Me_3SiO(CH_2)_4I \longrightarrow I(CH_2)_4I + Me_3SiOSiMe_3$$

The analogous reaction with tetrahydropyran was conducted at a slightly higher temperature (90°C), with the formation of a mixture of (5-iodopentyloxy)-trimethylsilane and 1,5-diiodopentane.[128]

Although the dealkylation reaction of chlorosilanes and bromosilanes with alkyl and alkyl aryl ethers has been long known, the much more efficient cleavage of alkyl aryl ethers with iodotrimethylsilane was only examined in the mid 70s by three independent groups, i.e., Ho and Olah,[20] Jung and Lyster[129] and Voronkov et al.[130]

$$\text{Ar-O-R} + \text{Me}_3\text{SiI} \longrightarrow \text{Ar-O-SiMe}_3 + \text{RI} \xrightarrow{\text{H}_2\text{O}} \text{ArOH}$$

The intermediate aryloxytrimethylsilanes can be isolated if desired, or hydrolyzed directly to the corresponding phenols. Methyl ethers were found to be more reactive than other alkyl, aryl ethers. *Ortho* substitution also lowered the yield of the desired dealkylated product. This method is a substantial improvement over the available methods which require harsher reaction conditions, and are in general limited to methyl aryl ethers.

Dealkylation of alkyl aryl ethers with the phenyltrimethylsilane/iodine reagent was found to be more effective than with the preformed reagent. These observations were reconfirmed by Benkeser et al.[21]

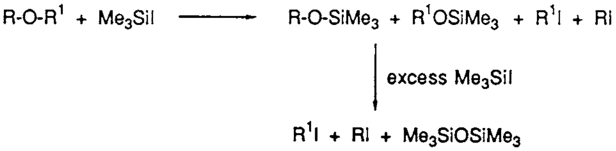
Many alkyl ethers are used as protecting groups for alcohols in organic synthesis. The most commonly used groups are benzyl, trityl, THP(tetrahydropyranyl), and *t*-butyl. These groups are removed by hydrogenolysis or by treatment with acids. A variety of highly specific protecting groups are also available. Although methyl ethers have been used extensively as protecting groups for phenols, they have not been used in aliphatic systems because of the difficulty of their removal. Aliphatic ethers including methyl ethers can be removed with boron trihalides, other Lewis acids, and *in situ* generated HI. However, most of these methods provide mixtures of products. It is in this context that Jung and Lyster[129] have studied in detail the simple and efficient dealkylation of aliphatic ethers with iodotrimethylsilane, providing the deprotected alcohols and phenols in high yield.

$$\text{R-O-R}^1 + \text{Me}_3\text{SiI} \longrightarrow \text{R-O-SiMe}_3 + \text{R}^1\text{-O-SiMe}_3 + \text{R}^1\text{I} + \text{RI}$$

Although the reaction is totally regiospecific for alkyl aryl ethers (only phenols are formed), cleavage of dialkyl ethers provided mixture of products depending upon the nature of R and R′, and the reaction conditions. In the cleavage of cyclohexyl methyl ether, higher selectivity was observed by lowering the reaction temperature. Trityl, benzyl, and *t*-butyl ethers react at a much faster rate than other alkyl ethers, thus permitting their selective cleavage. Dialkyl ethers react much faster than alkyl aryl ethers, allowing the cleavage of dialkyl ethers in the presence of alkyl aryl ethers. Alkyl methyl ethers react faster than methyl esters, so that the ethers can be cleaved cleanly in the presence of the methyl esters. The reactions are cleaner in the presence of propene as an acid scavenger.

Klemer et al.[131] have cleaved carbohydrate triphenylmethyl and benzyl ethers to their trimethylsilyl ethers by iodotrimethylsilane. The silyl ethers were hydrolyzed to provide free sugars. From multiple benzylated glycosides these authors[131] were able to selectively remove a primary benzyl group.

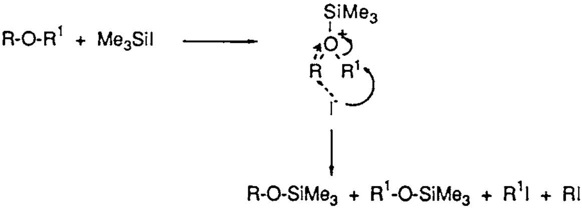
When the dialkyl ethers were treated with excess iodotrimethylsilane, the corresponding alkyl iodides were obtained in high yield thus providing a convenient synthesis of alkyl iodides directly from the corresponding ethers.



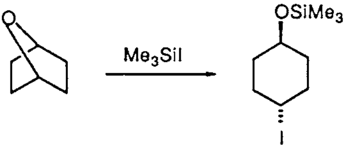
$$\begin{tikzcd}
\text{R-O-R}^1 + \text{Me}_3\text{SiI} \arrow[r] & \text{R-O-SiMe}_3 + \text{R}^1\text{OSiMe}_3 + \text{R}^1\text{I} + \text{RI} \arrow[d, "\text{excess Me}_3\text{SiI}"] \\
& \text{R}^1\text{I} + \text{RI} + \text{Me}_3\text{SiOSiMe}_3
\end{tikzcd}$$

Ethers can also be cleaved with chlorotrimethylsilane/sodium iodide in acetonitrile as shown by Olah et al.[23] and Morita et al.[24] The reaction of ethers with chlorotrimethylsilane/sodium iodide proceeds faster than with iodotrimethylsilane itself. Detty[12] has demonstrated the usefulness of phenylselenotrimethylsilane/iodine for the dealkylation of ethers. Hexamethyldisilane/iodine[30–32] and allyltrimethylsilane/iodine[14] can also be used for efficient cleavage of ethers.

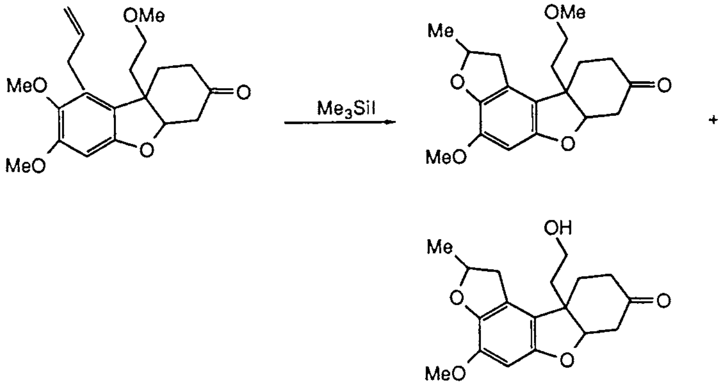
The cleavage of ethers with iodotrimethylsilane and its *in situ* analogs occurs via a polar mechanism. There is initial interaction of the electron-deficient silicon with a nonbonded electron pair on oxygen resulting in the formation of a trimethylsilyl oxonium ion followed by nucleophilic displacement by iodide on carbon. These results are consistent with the observed catalysis by iodide ion.[23]



The literature abounds with examples of the cleavage of alkyl ethers with iodotrimethylsilane. 7-Oxabicyclo-[2.2.1]heptane undergoes clean cleavage with iodotrimethylsilane to give *trans*-1-trimethylsiloxy-4-iodocyclohexane.[132]

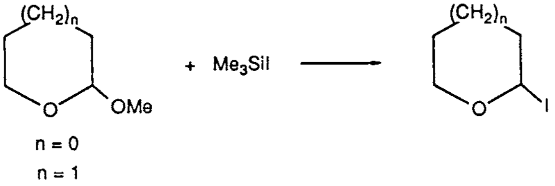


Although methyl alkyl ethers are cleaved faster than methyl aryl ethers, an unusually fast methyl aryl ether cleavage has been recently observed in the case of a complex catechol derivative.[133]

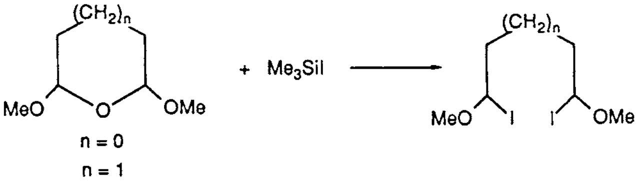


Such regiospecific cleavage of the more sterically hindered O-methyl group in 3-substituted catechol dimethyl ethers has been earlier observed. Once the O-allylphenol derivative is formed, the cyclization to yield the observed product is catalyzed by adventitious hydrogen iodide. Similar observations[133] were made with other derivatives.

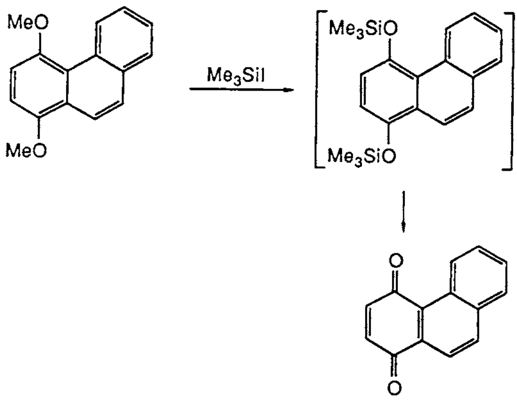
A variety of iodo sugars have been prepared by treating digitoxose with iodotrimethylsilane.[134] An unexpected site selectivity has been observed by Chan and Lee[135] in the case of methoxy-substituted tetrahydrofurans and pyrans. 2-Methoxytetrahydrofuran and 2-methoxytetrahydropyran give the corresponding 2-iodo derivatives rather cleanly.



On the other hand, the corresponding 2,5-dimethoxytetrahydrofuran and 2,6-dimethoxytetrahydropyran gave ring-opened products. Similar observations were made with bromotrimethylsilane wherein bromo derivatives were obtained.

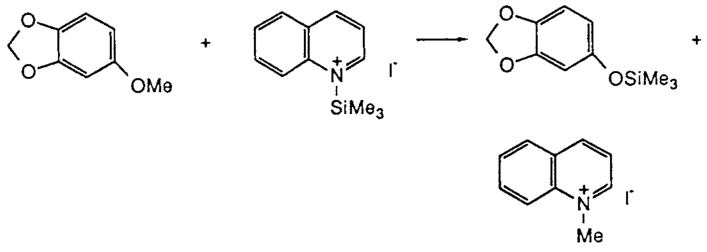


Iodotrimethylsilane has also been successfully used for the demethylation of 1,4-dimethoxyphenanthrene by Rosen and Weber.[136]



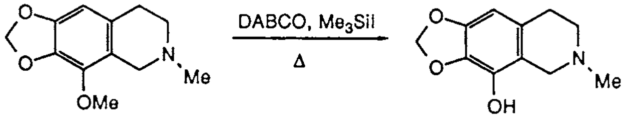
1,4-Phenanthraquinone was isolated due to the *in situ* oxidation of the hydroquinone intermediate. It is interesting to note that conventional demethylating agents like LiI/collidine and sodium ethanethiolate in dimethylformamide failed to provide any demethylated product.

Although there are methods available for the selective cleavage of methylenedioxy groups in polyoxygenated alkaloids,[137] no general method was available for the selective demethylation of a methyl ether in the presence of a methylenedioxy group. Such a transformation was achieved with iodotrimethylsilane, but only when the usual solvents were replaced by quinoline.[138]

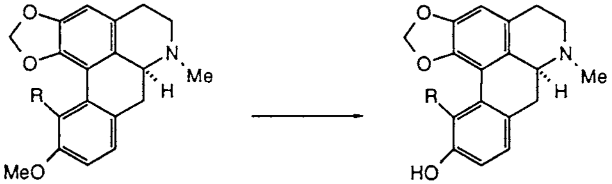


Sesamol methyl ether was thus demethylated with the concomitant formation of N-methylquinolinium iodide. The methyl iodide formed in the reaction reacts with quinoline to form the quaternary ammonium salt. 2,3-Methylenedioxyphenol was obtained in a similar manner from the corresponding methyl ether.

The active reagent for these dealkylations is most probably the N-trimethylsilylquinolinium iodide. When this reaction system was tried for demethylation of alkaloid hydrocotarnoline, a complex mixture of products was obtained due to side reactions with simultaneously produced methyl iodide. However, replacement of quinoline by the stronger base, i.e., 1,4-diazabicyclooctane (DABCO), resulted in a clean reaction.[139]

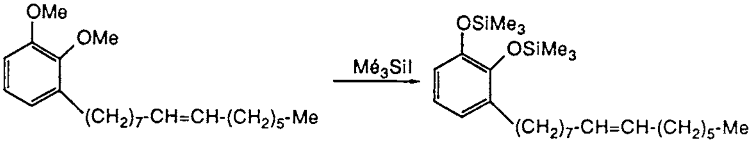


Similarly, S-(+)-mecambroline was obtained from S-(+)-laurelin in 54% yield.



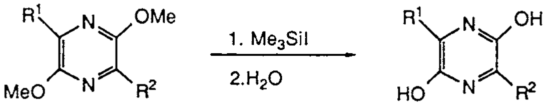
This methodology is very useful in the conversion of abundantly available polyoxygenated alkaloids into less oxygenated congeners for chemical correlation and for biological evaluation.

The demethylation of aryl methyl ethers with iodotrimethylsilane in the absence of any base has been applied to the synthesis of urushiol derivatives,[140] which are the vesicant principles of poison ivy and related plants.

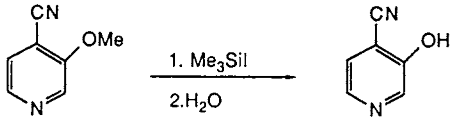


Vickery et al.[141] have compared iodotrimethylsilane and boron tribromide for the demethylation of certain catechol ethers. They found that in this application, Me3SiI is less reactive than BBr3. Iodotrimethylsilane was found to be more effective than boron tribromide for the cleavage of less accessible methoxy groups. Such facile arylmethyl ether cleavage has been discussed earlier.[133]

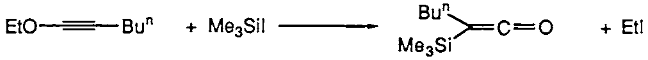
Francis and Reeves[142] reported facile lignin removal from cellulose pulp using iodotrimethylsilane and related reagents. The key step appears to be the demethylation of the methoxy group on the aryl ring. Reaction of 2,5-dimethoxypyrazines with iodotrimethylsilane followed by hydrolysis gives moderate yields of 2,5-dihydroxypyrazines.[143]



3-Methoxy-4-cyanopyridine also undergoes facile demethylation in the presence of iodotrimethylsilane.[144]

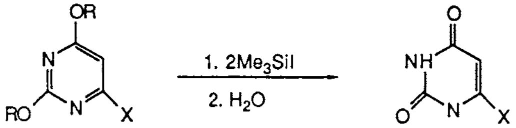


A novel application of dealkylation of ethers with iodotrimethylsilane is the synthesis of hitherto relatively inaccessible trimethylsilyl ketenes from the corresponding 1-alkoxy-1-alkynes.[32]



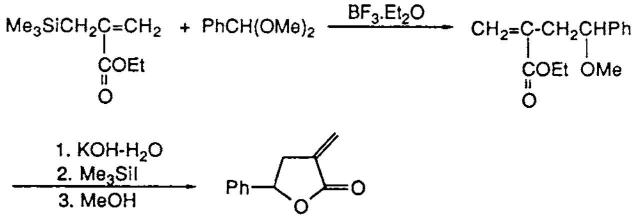
Bis(trimethylsilyl)ketene was prepared in a similar manner. The scope of this reaction has been extended to obtain a variety of substituted ketene derivatives.[145,146] Even enol methyl ethers have been cleaved with iodotrimethylsilane.[147]

6-Substituted uracils are usually prepared by acid hydrolysis of 2,4-dialkoxy-6-substituted pyrimidines, but under acidic conditions, the products usually undergo extensive decomposition. Iodotrimethylsilane has been found to be an excellent dealkylating agent for 2,4-dialkoxypyrimidines.[148]



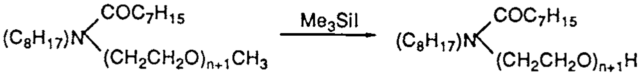
This method was particularly useful for the preparation of uracil-6-sulfonic acid ($X=SO_3H$) which undergoes loss of bisulfite under the usual acidic hydrolysis conditions.

One of the useful applications of iodotrimethylsilane in organic synthesis has been the synthesis of α-methylene-γ-butyrolactones, the key structures in a number of naturally occurring sesquiterpenes with potential cytotoxic activity.[149] Hosomi et al.[150] have shown that α-methylene-γ-butyrolactones can be obtained in very high yield in a two-step synthesis from 2-alkoxycarbonylallyltrimethylsilanes and acetals.



The crucial step involves demethylation of the methyl ether with iodotrimethylsilane followed by ring closure to the lactone.

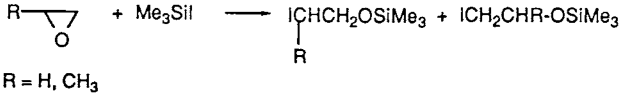
Several oxymethylated amides have been prepared[151] as wetting agents by reacting 1-alkylaziridines with ethylene oxide or monomethylated diethylene, triethylene, or tetraethylene glycol. The resulting amino ethers were acylated, and the methyl ether group cleaved using iodotrimethylsilane.



4.6. Epoxides

In analogy with the reaction of iodotrimethylsilane with ethers, it is not unexpected that epoxides will also cleave with the possibility of formation of various products depending upon the reaction conditions.

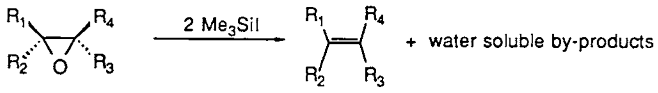
Voronkov et al.[152] reported the cleavage of ethylene oxide and propylene oxide to yield the corresponding iodoalkyl, silyl ethers.



When the reaction was performed in the presence of sodium metal, the corresponding olefins were obtained.

$$Me_3SiOCH_2CHIR + 2\,Na \longrightarrow CH_2{=}CHR + Me_3SiONa + NaI$$

Denis et al.[153] have developed a simple method for the deoxygenation of epoxides by treatment with two molar equivalents of iodotrimethylsilane.

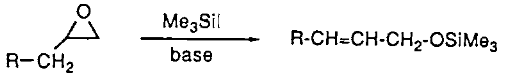


$R_1 = R_3 = CH_3(CH_2)_7$, $R_2 = R_4 = H$ Yield = 89%

$R_1 = R_4 = H$, $R_2 = R_3 = CH_3(CH_2)_7$ Yield = 83%

The reaction was found to be 100% regiospecific. The reaction has been proposed to go through the intermediate 9-iodo-10-trimethylsilyloxyoctadecane. The reactions are stereospecific (>97%) with the product olefins possessing the same stereochemistry as the starting epoxide. Iodotrimethylsilane thus provides an efficient method for the transformation of epoxides to olefins, an important step in the synthesis of all trans squalene, for the structure determination of natural products.

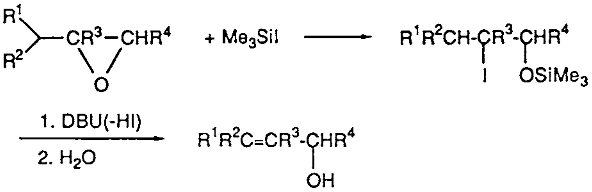
In an attempt to prepare allylic alcohols, Detty[154] studied the reaction of iodotrimethylsilane with epoxides, but found that the reaction was not clean.



Mixtures of deoxygenated and ring-opened products were obtained. The analogous reactions with trimethylsilyl trifluoromethanesulfonate[155] or with *t*-butyldimethyliodosilane[154] (prepared from the reaction of iodine with phenylseleno-*t*-butyldimethylsilane) yield the desired allyl trimethylsilyl ethers in high yield. Detty and Seidler[156] have also looked at the regiochemistry and stereochemistry of epoxide ring opening by iodotrimethylsilane and related halo derivatives. Whereas regiochemistry was independent of the attacking species, the stereochemistry of ring opening was sensitive to both the nature of the halogen and nature of hydrocarbon groups on silicon. The effect of nucleophilic catalysis on oxirane ring opening with iodotrimethylsilane, bromotrimethylsilane, and chlorotrimethylsilane to the corresponding O-protected vicinal halohydrins has been probed by Andrews et al.[157] Enhanced regioselectivity was observed in all cases.

Sakurai et al.[158] have solved this problem by carrying out the reaction with iodotrimethylsilane (generated *in situ* from hexamethyldisilane and iodine) in a stepwise manner.

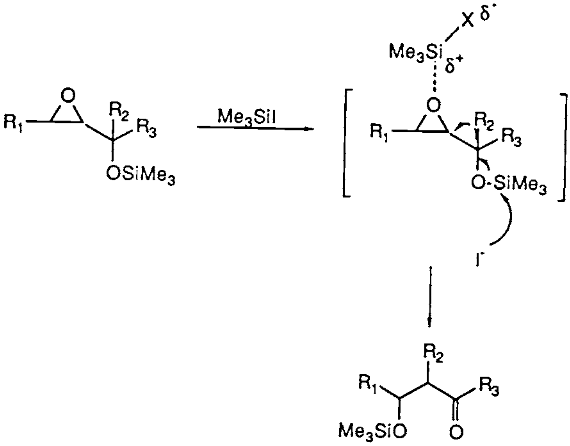
$$Me_3SiSiMe_3 + I_2 \longrightarrow 2\ Me_3SiI$$



The whole conversion is carried out in a one-pot operation. The essential reagent for the process is hexamethyldisilane which is thermally and hygroscopically stable, nontoxic, and readily available. The reactivity of iodotrimethylsilane towards epoxides was found to be higher than that of trimethylsilyl trifluoromethanesulfonate.

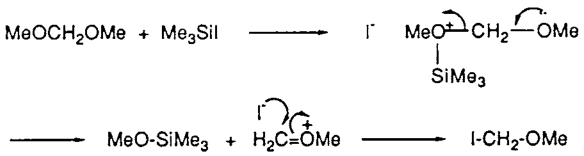
Kraus and Frazier[159] have also demonstrated the efficient preparation of allylic alcohols from the reaction of epoxides with iodotrimethylsilane followed by dehydrohalogenation with DBN. The reaction conditions were found to be compatible with esters and cyclic acetals. The mild conditions and simplicity of operation offer distinct advantages over other methods. The iodotrimethylsilane mediated procedure is complimentary to the organoselenium method of Sharpless and Lauer[160] in that trisubstituted epoxides afford secondary allylic alcohols.

Suzuki et al.[161] have observed an interesting iodotrimethylsilane-catalyzed epoxy silyl ether rearrangement. Essentially, iodotrimethylsilane functions as a Lewis acid catalyst. Indeed the reaction also proceeds with Lewis acids.



4.7. Acetals and Related Derivatives

In analogy with the reaction of ethers, the reaction of acetals with iodotrimethylsilane is expected to give α-iodoethers. These expectations have been fully realized in the reaction of dimethoxymethane(methylal).[162] Iodomethyl methyl ether was obtained in high yield.

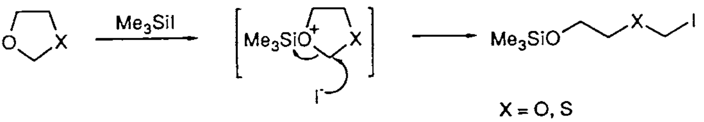


$$MeOCH_2OMe + Me_3SiI \longrightarrow I^- \; MeO^+(SiMe_3)\text{-}CH_2\text{-}OMe \longrightarrow MeO\text{-}SiMe_3 + H_2C{=}\overset{+}{O}Me \longrightarrow I\text{-}CH_2\text{-}OMe$$

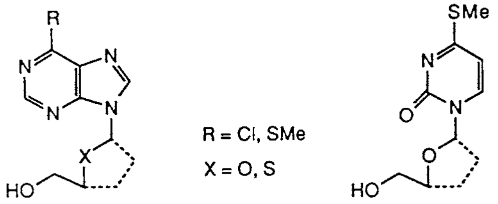
Iodomethyl methyl ether is a useful reagent for the synthesis of methoxymethyl ethers from alcohols,[163] and for iodomethylation of aromatic substrates.[164] It is preferable to chloromethyl methyl ether which is always contaminated with bis(chloromethyl)ether and is highly carcinogenic. Iodomethyl methyl ether shows enhanced reactivity compared to chloromethyl methyl ether. Olah et al.[165] have developed an iodotrimethylsilane catalyzed preparation of methoxymethyl ethers of primary and secondary alcohols with dimethoxymethane. The method also works with the allyltrimethylsilane/I2 reagent system.

$$R\text{-}OH + CH_3OCH_2OCH_3 \xrightarrow{Me_3SiI} R\text{-}OCH_2\text{-}OCH_3$$

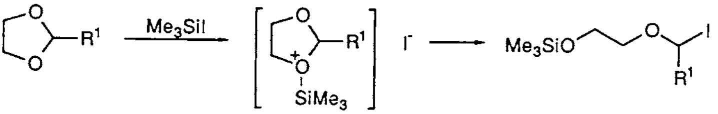
The reaction has been extended to 1,3-dioxolanes and 1,3-oxathiolanes to prepare the corresponding α-iodoethers as alkylating agents.[166]



Thus, both iodomethyl trimethylsilyloxyethyl ether (X = O) and the corresponding sulfide (X = S) react with several purine and pyrimidine bases to provide nucleoside analogues of some potent antiviral compounds.



The analogous cleavage of 2-substituted 1,3-dioxolanes provides the synthesis of acyclic sugar analogues which are lacking only C(3′) or the C(3′)–C(4′) bond.[167]

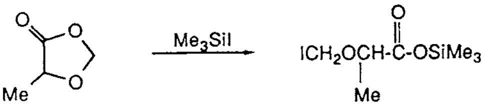


R^1 = Me, CH_2OCH_2Ph, $CH_2CH_2OCH_2Ph$

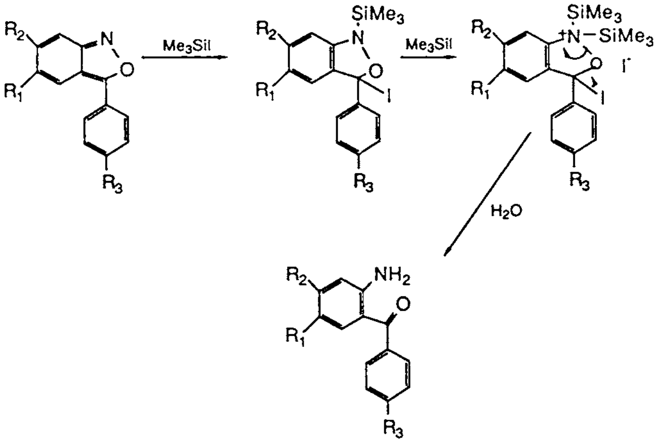
It is interesting to note that the benzyloxy group is not cleaved under the reaction conditions. These alkylating agents were used to prepare several adenine and purine derivatives.

This methodology can be used to synthesize a variety of potential antibiotic, antitumor, and antiviral agents, which would be difficult to obtain via conventional routes.

The reaction of 1,3-dioxolanes has also been extended to 4-oxa-analogues, to yield iodomethoxyacetic acid silyl ester derivatives.[168] This bifunctional ether ester has been used as a starting material in the synthesis of hemithioacetals by alkylation of thiols. The hemithioacetals are useful precursors for the synthesis of cleavable cross-linking reagents for proteins.

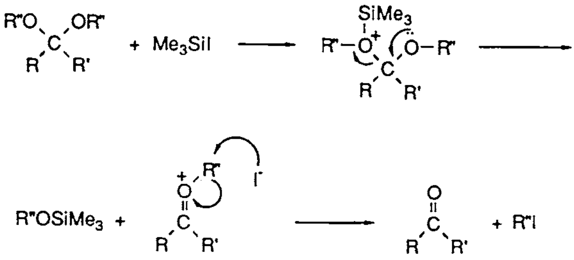


Konwar et al.[169] have cleaved 2,1-benzisoxazoles with iodotrimethylsilane to obtain 2-aminobenzophenones. The reaction also proceeds with 2,1-benzisoxazolium salts.[170]

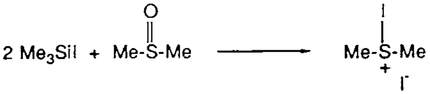


The conversion of acetals and ketals to aldehydes and ketones, respectively, is usually achieved by treatment with aqueous acid. In many instances, it would be highly desirable to achieve this transformation under strictly neutral conditions. Iodotrimethylsilane can be used to convert acetals and ketals to the corresponding carbonyl compounds in very high yield.[171] The reaction is carried out in the presence of propene to remove traces of HI, which is always present in iodotrimethylsilane.

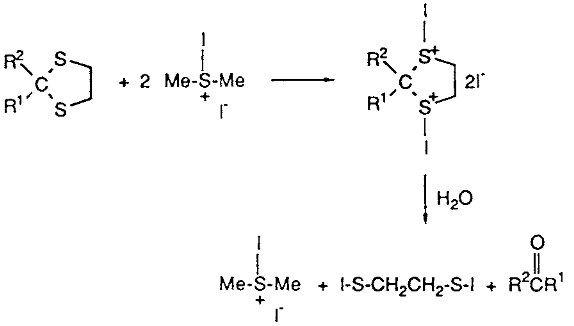
In analogy with the reaction of ethers, the mechanism can be formulated as



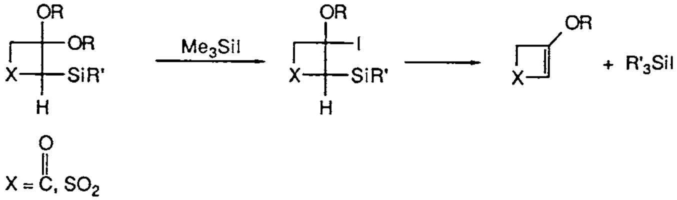
The reaction is, however, limited to dimethyl and diethyl acetals. Ethylene ketals gave complex mixtures of products. Ethylenedithioacetals could not be cleaved under the reaction conditions. This is not surprising since silicon forms a very weak bond with sulfur, but a strong bond with oxygen. However, in the presence of dimethylsulfoxide, iodotrimethylsilane cleaves thioketals rather efficiently.[172] The reaction also works with bromotrimethylsilane. The active reagent is the halodimethylsulfonium halide.



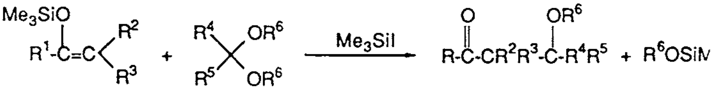
$$2\,Me_3SiI + Me\text{-}\overset{\overset{O}{\|}}{S}\text{-}Me \longrightarrow Me\text{-}\underset{+}{\overset{\overset{I}{|}}{S}}\text{-}Me\ \ I^-$$



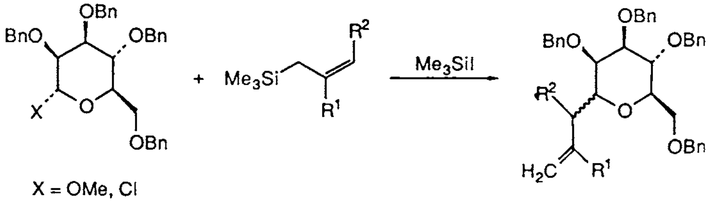
Shipov and co-workers[173] have reported that α-silylated ketals cleave in the presence of iodotrimethylsilane to give vinyl ethers.



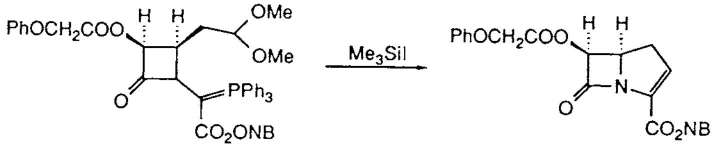
Stereoselective cross-aldol reactions of silyl enol ethers with acetals have been carried out under iodotrimethylsilane catalysis by Sakurai et al.[174]



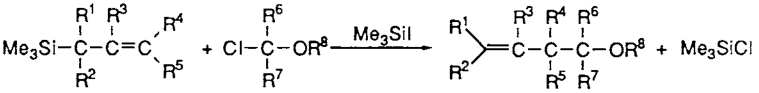
Acetals also undergo condensation with allyltrimethylsilane to provide homoallyl ethers under the influence of iodotrimethylsilane *(vide supra)*.[175] Such allylations have also been carried out with glycopyranosides.[176,177] These reactions are also catalyzed by trimethylsilyl trifluoromethanesulfonate.

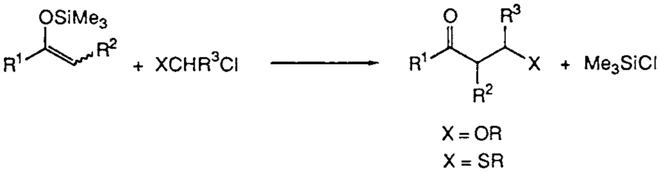


Intramolecular condensation of a phosphorane center and an acetal group has been achieved under iodotrimethylsilane catalysis.[178]



α-Chloro ethers (or α-chlorosulfides) also undergo condensation with allyltrimethylsilane[179a] as well as enol silyl ethers.[179b]



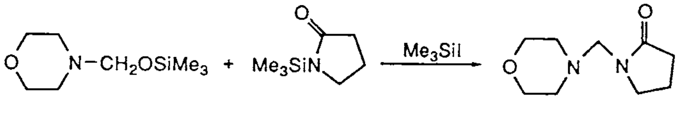


Aminomethyl ethers are cleaved by iodotrimethylsilane to give Mannich salts.[180]

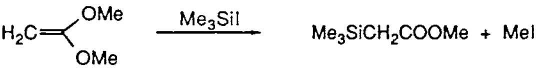
$$Me_3SiOCH_2NMe_2 + Me_3SiI \longrightarrow [CH_2{=}N^+Me_2I^-] + (Me_3Si)_2O$$

These salts readily react with enol silyl ethers to give a-aminomethyl carbonyl compounds. Such condensations can also be directly carried out by treating aminomethyl ethers with the enol silyl ether under iodotrimethylsilane catalysis.[181]

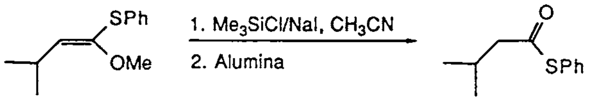
α-Aminomethyl ethers also condense with N-trimethylsilyl-2-pyrrolidone catalyzed by iodotrimethylsilane.[182]



Iodotrimethylsilane also reacts with ketene dialkyl acetals to yield (trimethylsilyl)acetic esters.[183]



Ketene O-, S- acetals are also reactive towards iodotrimethylsilane or its equivalents.[184]

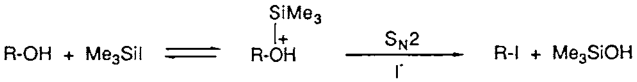


It is interesting to note that orthoformates yield formic esters on treatment with iodotrimethylsilane.

$$HC(OMe)_3 + Me_3SiI \longrightarrow HCOOMe + MeOSiMe_3 + MeI$$

4.8. Alcohols

In the preceding discussion of the reaction of ethers and acetals with iodotrimethylsilane, the reaction of intermediate silyl ethers with excess iodotrimethylsilane was shown to yield alkyl iodides.[127,185,187] These observations have been applied to the synthesis of alkyl iodides from the corresponding alcohols by reaction with iodotrimethylsilane.[188]



$$R\text{-}OH + Me_3SiI \rightleftharpoons R\text{-}\overset{\overset{SiMe_3}{|+}}{O}H \xrightarrow[I^-]{S_N2} R\text{-}I + Me_3SiOH$$

$$Me_3SiOH + Me_3SiI \longrightarrow (Me_3Si)_2O + HI$$

Silyl ethers can also be used for this purpose, as was initially demonstrated by Voronkov et al.[127,185–187] This eliminates the formation of HI in the reaction. These observations were later applied by Jung and Ornstein.[188]

$$R\text{-}O\text{-}SiMe_3 + Me_3SiI \longrightarrow RI + (Me_3Si)_2O$$

The reaction is general for primary, secondary, and tertiary alcohols. Optically pure (+)-2-octanol was converted to (-)-2-octyl iodide with 94% inversion. Thus, the silylated oxonium ion reacts with iodide via an S_N2 type mechanism.

When alcohols are reacted with chlorotrimethylsilane/sodium iodide in acetonitrile solution, the corresponding alkyl iodides are obtained in high yield.

The reaction with chlorotrimethylsilane/sodium iodide is rapid compared to that with iodotrimethylsilane. This is probably due to the use of a larger excess of the reagent. The reaction with iodotrimethylsilane can be accelerated not only by using an excess of the reagent, but also by using added sodium iodide. Alcohols can be converted to alkyl iodides with hexamethyldisilane/iodine as well.

Conversion of a hydroxy group to an iodide is an important synthetic transformation with wide applications. Many iodo-carbohydrate derivatives have been prepared using the chlorotrimethylsilane/sodium iodide system.[189] An important step in the synthesis of the fused triquinane skeleton is the conversion of a diol intermediate into a diiodide.[190]

The facile reaction of alcohols and ethers with iodotrimethylsilane to form iodoalkanes, and their subsequent dehalogenation with zinc[191] has been combined into a simple and convenient one-pot procedure for the deoxygenation of alcohols and ethers.[192]

$$R^1\text{-O-}R^2 \xrightarrow[\text{2. Zn/AcOH/MeCN}]{\text{1. Me}_3\text{SiCl/NaI/MeCN}} R^1\text{-H}$$

R^1 = Alkyl
R^2 = H, Alkyl, Me_3Si

The addition of some acetic acid in the reduction step dramatically improves the product yield. The procedure is very convenient, producing only hexamethyldisiloxane as the by-product. Although alcohols can be deoxygenated by a variety of other methods, there is no other satisfactory method available for the conversion of ethers to alkanes. The deoxygenation of ethers is very efficient with the chlorotrimethylsilane/sodium iodide/zinc reagent.

Although alcohols usually react with iodotrimethylsilane to yield alkyl iodides, the reaction can be stopped at the silyl ether stage in a interesting modification of the reagent system. Hosomi and Sakurai[193] have observed that alcohols and carboxylic acids can be protected as their O-silyl derivatives by reaction with allyltrimethylsilane in the presence of iodotrimethylsilane. Iodine can be used in place of iodotrimethylsilane, thus exploiting the *in situ* generation of iodotrimethylsilane. The silylation is possible only for primary and secondary alcohols. Tertiary alcohols undergo the more familiar reaction to yield alkyl iodides, thus retarding the catalytic cycle.

$$Me_3SiCH_2\text{-}CH{=}CH_2 + ROH \xrightarrow{I_2 \text{ or } Me_3SiI} R\text{-O-}SiMe_3 + Me\text{-}CH{=}CH_2$$

$$Me_3SiCH_2\text{-}CH{=}CH_2 + I_2 \longrightarrow Me_3SiI + CH_2{=}CH\text{-}CH_2\text{-}I$$

$$Me_3SiI + R\text{-O-H} \longrightarrow R\text{-O-}SiMe_3 + HI$$

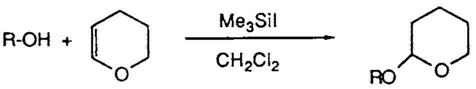
$$HI + Me_3SiCH_2\text{-}CH{=}CH_2 \longrightarrow [Me_3SiCH_2\text{-}CH^+\text{-}CH_3]I^-$$

or

$$(Me_3SiCH_2\text{-}CH^+CH_3]I^- \longrightarrow Me_3SiI + Me\text{-}CH{=}CH_2$$

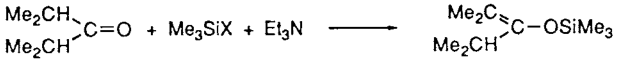
Other substituted allylsilanes can also be used for the reaction. Iodine and iodotrimethylsilane can be substituted by bromine and bromotrimethylsilane, although higher reaction temperatures are required. This procedure is reminiscent of the silylation of –OH and –SH groups by allyltrimethylsilane in the presence of *p*-toluenesulfonic acid or trifluoromethanesulfonic acid as catalysts.

Olah et al.[194] have employed iodotrimethylsilane catalysis for the preparation of tetrahydropyranyl derivatives of primary and secondary alcohols with dihydropyran.



4.9. Carbonyl Compounds

Because of the lability of the silicon–iodine bond, iodotrimethylsilane can be used for O-silylation of carbonyl compounds. Hergott and Simchen[195] compared various silylating agents for the synthesis of the enol silyl ether from diisopropylketone.



$$\begin{matrix}Me_2CH\\ Me_2CH\end{matrix}\!\!>C=O + Me_3SiX + Et_3N \longrightarrow \begin{matrix}Me_2C\\ Me_2CH\end{matrix}\!\!>C-OSiMe_3$$

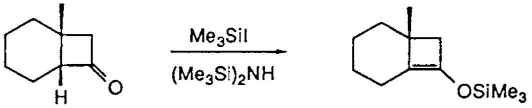
The order of reactivity for different silylating agents was found to be as follows:

$$X = I > CF_3SO_3 > Br > CF_3CH_2SO_3 >> Me_3SiOSO_3 > CH_3SO_3 > Cl$$

Iodotrimethylsilane was found to be the most reactive reagent among a variety of reagents including trimethylsilyl trifluoromethanesulfonate. Trimethylsilyl enol ethers are important intermediates in organic synthesis. They are used for the preparation of α-functionalized carbonyl compounds by reaction with electrophiles, for the preparation of α,β-unsaturated compounds, and above all for directed aldol condensations. There are many reagents available for the synthesis of kinetic enolates, but the generation of thermodynamically equilibrated mixture of enol silyl ethers from unsymmetrical ketones often requires harsh conditions or inconvenient procedures.

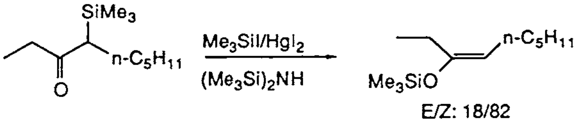
Miller and McKean[196] have discovered that iodotrimethylsilane in conjunction with hexamethyldisilazane can be used to prepare enol silyl ethers in high yield at room temperature. These exceedingly mild conditions lead to thermodynamically equilibrated products and is applicable to ketones, aldehydes, and enones. Esters were not affected under the reaction conditions.

Cohen et al.[197] have prepared the enol silyl ether of annulated cyclobutanone.

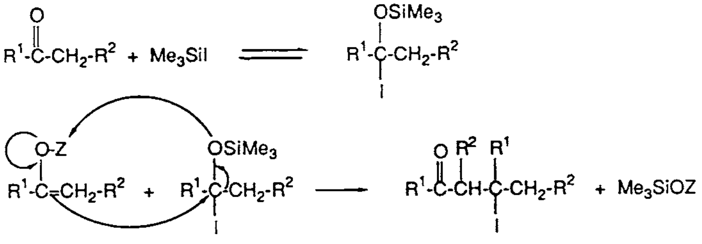


The same procedure has been employed[198] in one of the steps in the enantioselective synthesis of *trans*-octahydro-1,6-dioxoinden-4-yl propionic acid from (R)-2,3-O-isopropylidene glyceraldehyde. α-Chloroketones in the presence of iodotrimethylsilane and a base provides chlorotrimethylsilyl enol ethers.[199] In the absence of base the reaction takes a different course *(vide supra)*.

α-Trimethylsilyl ketones undergo facile isomerization to enol silyl ethers catalyzed by iodotrimethylsilane/HgI_2/$(Me_3Si)_2NH$.[200]

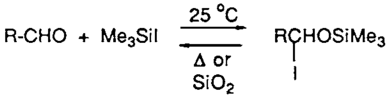


Schmidt and Russ[201] discovered that treatment of ketones containing an α-CH_2 or -CH_3 group with chlorotrimethylsilane/sodium iodide in acetonitrile results in condensation to yield β-haloketones. The reactions have been postulated to proceed via the 1-iodo-1-trimethylsilyloxy adducts formed by 1,2-addition of iodotrimethylsilane to the carbonyl group.



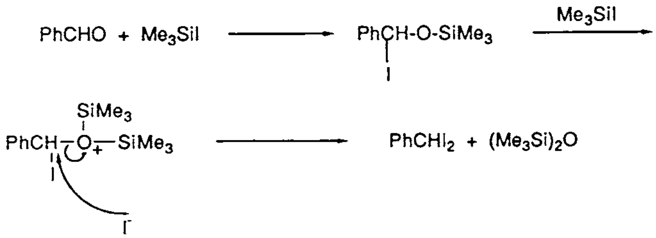
Z = H, SiMe$_3$

The formation of such halosilyloxy adducts from aldehydes and iodotrimethylsilane was demonstrated by Jung et al.[202]

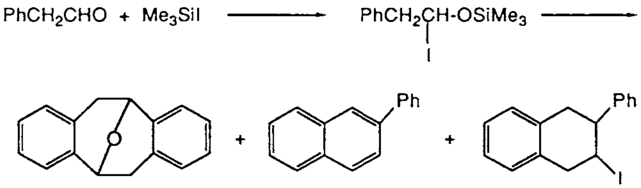


$$\text{R-CHO} + \text{Me}_3\text{SiI} \underset{\Delta \text{ or } \text{SiO}_2}{\overset{25\ ^\circ\text{C}}{\rightleftharpoons}} \text{RCH(I)OSiMe}_3$$

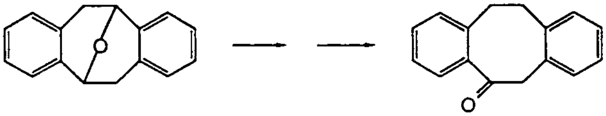
When benzaldehyde was treated with iodotrimethylsilane, α,α-diiodotoluene was obtained via the intermediate iodoether.



The second step is analogous to the reaction of silyl ethers with iodotrimethylsilane. The α,α-diiodotoluene is extremely sensitive to decomposition during the workup procedure. When phenylacetaldehyde was treated with iodotrimethylsilane, a mixture of products was obtained.



The ether was converted in two steps into dibenzocyclooctadienone, an important starting material for the synthesis of some biologically active compounds.

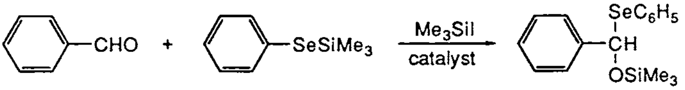


Jung and Lewis[203] have reacted the intermediate α-iodoalkyltrimethylsilyl ethers formed from aldehydes and trimethylsilyl iodide with organocuprates to obtain secondary alcohols.

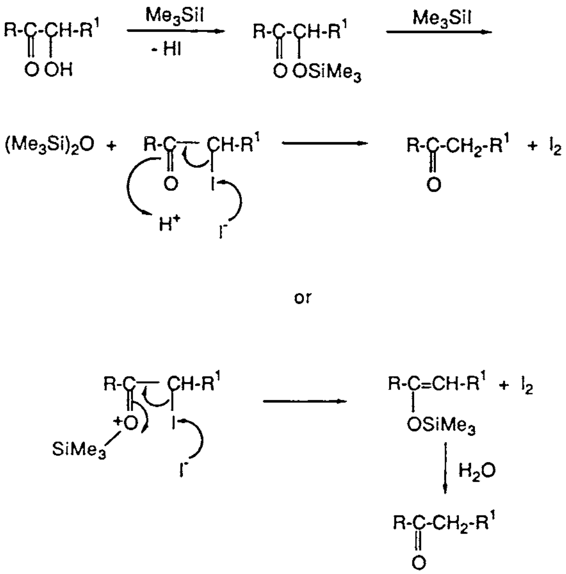
Voronkov et al.[204] have shown that iodotrimethylsilane reacts with formaldehyde to give di(iodomethyl)ether.

$$2/n\ (CH_2O)_n + 2\ Me_3SiI \longrightarrow ICH_2OCH_2I + (Me_3Si)_2O$$

Detty[12] has observed the Me3SiI-catalyzed 1,2 and 1,4 additions of phenylselenotrimethylsilane to various carbonyl compounds in analogy with the formation of 1-iodo-1-silyloxyalkanes with iodotrimethylsilane itself, e.g.,

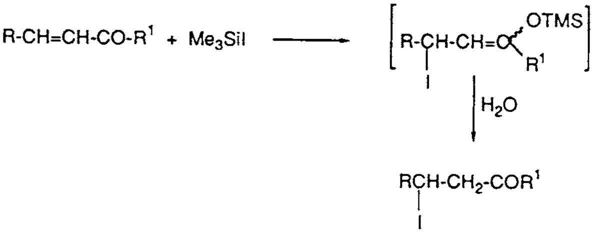


α-Hydroxyketones are deoxygenated by iodotrimethylsilane in a very facile reaction thus providing an easy synthesis of deoxybenzoins.[205] The reaction can be visualized to proceed via the formation of α-iodoketones, in analogy with the reaction of alcohols with iodotrimethylsilane to yield alkyl iodides.



The intermediacy of α-haloketones in the reduction of α-hydroxyketones was demonstrated by treating α-haloketones with chlorotrimethylsilane/sodium iodide in acetonitrile, when the corresponding dehalogenated ketones were obtained in very high yield.[206]

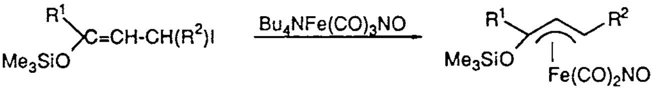
When α,β-unsaturated ketones are treated with iodotrimethylsilane, 1,4-adducts (Michael addition) are formed in high yield.[207a] Larson and Klesse[207b] have utilized this reaction elegantly to prepare β-iodo ketals by reacting the intermediate β-iodo enol silyl ethers with diols.



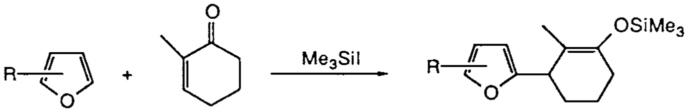
The adducts react with water to yield β-iodoketones, which are synthetically very useful. The β-iodoketones could be transformed further into other compounds by nucleophilic displacement of the iodide.

$$\underset{\text{I}}{\text{RCH}}\text{-CH}_2\text{-COR}^1 + \text{Nu}^- \longrightarrow \underset{\text{Nu}}{\text{RCH}}\text{-CH}_2\text{-COR}^1 + \text{I}^-$$

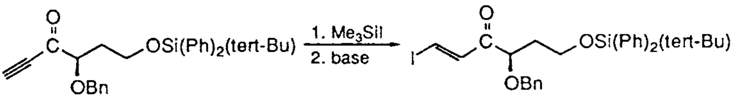
Ito et al.[208] have employed the Michael adducts of α,β-unsaturated ketones with iodotrimethylsilane to prepare 1-trimethylsiloxyallylic iron complexes which act as β-acylcarbanion equivalents.



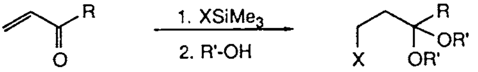
Such iodoenol silyl ether intermediates have also been alkylated with the anions of dimethoxyphenyl carboxylic acids produced by Birch reduction.[209a] Iodoenol silyl ethers can also undergo condensations with furans. Thus enones are condensed with furans under iodotrimethylsilane treatment.[209b,c]



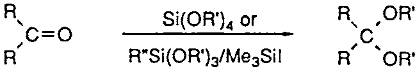
Acetylenic ketones also react with iodotrimethylsilane to yield *trans*-β-iodovinyl ketones.[210] The procedure has been used to prepare key intermediate in the synthesis of the marine natural product palytoxin.[211]



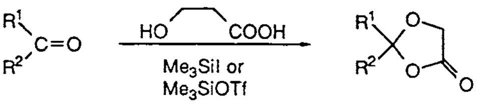
Gil[212] has reported a modification to the addition of iodotrimethylsilane and related halides to α,β-unsaturated ketones. When the reaction is performed in the presence of alcohols, the corresponding β-iodo(halo)acetals are obtained in one pot.



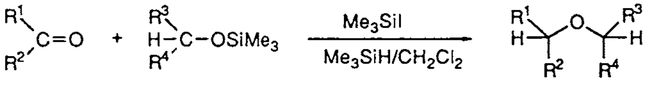
Sakurai et al.[175] and Sakurai[213] has reported that tetraalkoxysilanes and trialkoxysilanes react with carbonyl compounds under iodotrimethylsilane catalysis to provide the corresponding acetals in good yields.

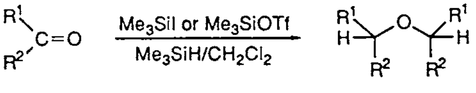


Pearson and Cheng[214] have developed a simple procedure to condense carbonyl compounds with glycolic acids catalyzed by iodotrimethylsilane (or the triflate) to obtain 1,3-dioxolan-4-ones. The stereochemistry and regiochemistry of the reaction has also been investigated.



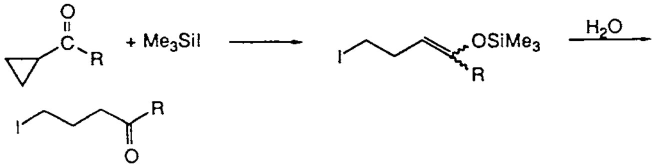
Sassaman and co-workers[215] have developed a general method for ether synthesis by the reductive coupling of carbonyl compounds with trimethylsilane catalyzed by iodotrimethylsilane. Iodotrimethylsilane was found to be a superior catalyst than trimethylsilyl triflate for unsymmetrical ether synthesis using alkoxysilanes.





Such studies have also been pursued by Aizpurua et al.[216] Recently, Sassaman et al.[217] have extended the procedure for intramolecular reductive carbonyl coupling.

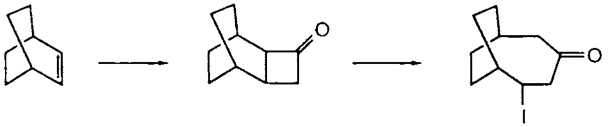
α-Cyclopropyl substituted ketones react similar to enones giving γ-iodoketones by cleavage of the cyclopropyl ring.[218–220]



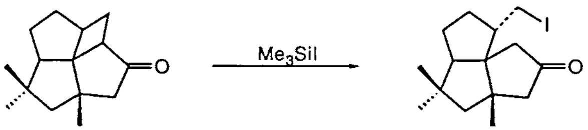
The ring opening proceeds under very mild conditions and the γ-iodoketones are obtained in high yield upon aqueous workup.

The reaction usually proceeds with high regioselectivity resulting in cleavage of the cyclopropane bond with the best overlap with the π-orbitals of the carbonyl group. The intermediate silyl ethers can be isolated when the reaction is performed in the presence of a hindered base and the hydrolytic workup is avoided. The electrophilic ring opening of cyclopropyl ketones has applications in the synthesis of natural products. The yields and regioselectivity obtained by cleavage of cyclopropyl ketones with iodotrimethylsilane, under mild and neutral conditions, are a significant improvement over the usual acidic reagents employed for this reaction.[219] The method has been further improved using *in situ* iodotrimethylsilane equivalents.[220] Under these conditions, even cyclopropyl cyanide as well as cyclopropane carboxylic acid are cleaved to the corresponding γ-iododerivatives.

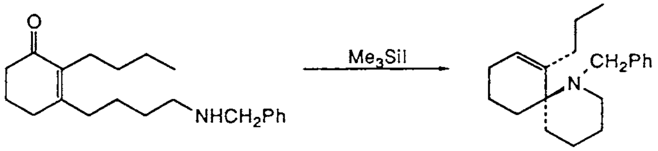
When sterically strained cyclobutanones are treated with iodotrimethylsilane in the presence of ZnI_2 or $Hg–H_2O$, the cyclobutyl ring is cleaved, resulting in the formation of β-iodoketones in high yield.[221] The reaction shows high regioselectivity. Because of the easy synthesis of cyclobutanones from olefins and ketones via [2 + 2]cycloaddition, this sequence of reactions represents a cyclic homologation of a cyclic olefin to a β-functionalized cyclic ketone, e.g.,

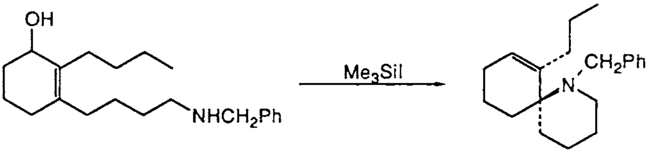


Even δ-iodoketones have been obtained by the cleavage of α-cyclobutyl ketone. Such a cleavage has been recently employed in the total synthesis of (±)-silphinene.[222]

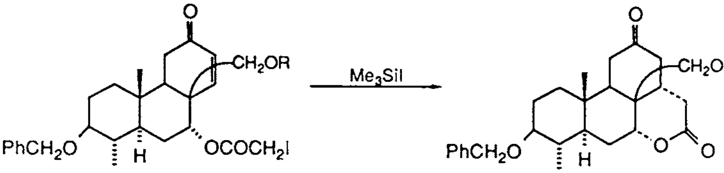


Iodotrimethylsilane has been used as a Lewis acid type catalyst for the intramolecular cyclization of an enone amine as well as S_N2' spirocyclization of an allylic alcohol amine. These are the key reactions in the two new syntheses of perhydrohistrionicotoxin.[223]

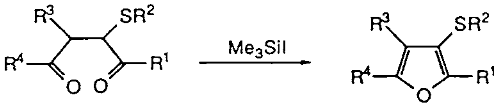




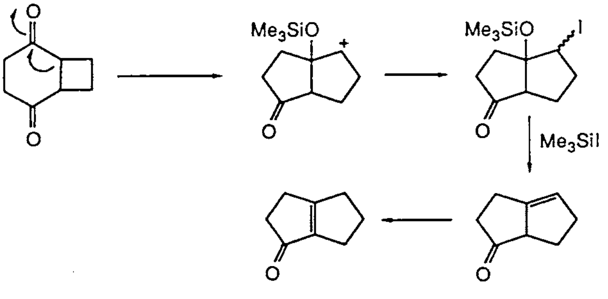
An unusual lactonization procedure induced by iodotrimethylsilane has been employed in the synthesis of quassinoid precursors.[224]



1,4-Diketones also react with iodotrimethylsilane. Duhamel and Chauvin[225] have carried out cyclization of α-thiosubstituted 1,4-diketones to 3-thiosubstituted furans catalyzed by iodotrimethylsilane and related reagents.



A clean reductive rearrangement of bicyclo[4.2.0]octan-2,5-dione with iodotrimethylsilane gave bicyclo[3.3.0]oct-1(5)-ene-2-one.[226] The reaction mechanism was depicted as the following.



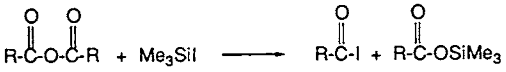
Acyl halides also react with iodotrimethylsilane or hexamethyldisilane/iodine to yield the corresponding acyl iodides via a halogen-exchange reaction.[227] This method provides easy access to unstable acyl iodides in high yield with only chlorotrimethylsilane as the by-product, which can be removed from the reaction mixture under reduced pressure.

$$RCOCl + Me_3SiI \longrightarrow RCOI + Me_3SiCl$$

It was previously mentioned[64] that in the case of tertiary alkanoyl halides, decarbonylation takes place at high temperature to yield the corresponding *t*-alkyl iodides.

$$R_3C\text{-}COI \xrightarrow{-CO} R_3C\text{-}I$$

The reaction of anhydrides with iodotrimethylsilane is limited to straight-chain primary alkylcarboxylic acid derivatives.[64]



$$R\text{-}\overset{O}{\overset{\|}{C}}\text{-}O\text{-}\overset{O}{\overset{\|}{C}}\text{-}R + Me_3SiI \longrightarrow R\text{-}\overset{O}{\overset{\|}{C}}\text{-}I + R\text{-}\overset{O}{\overset{\|}{C}}\text{-}OSiMe_3$$

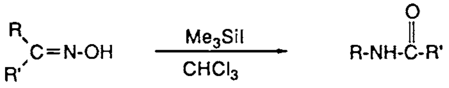
$R = CH_3, CH_3\text{-}CH_2, CH_3\text{-}CH_2\text{-}CH_2$

No reaction was observed with chloroformates, ROCOCl.

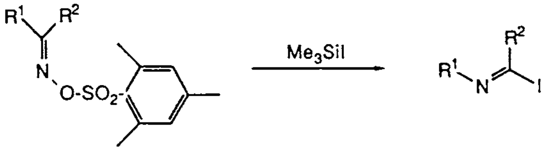
4.10. Oximes and Derivatives

Aldoximes have been dehydrated on treatment with iodotrimethylsilane to provide nitriles.[228] The yield of the reaction dramatically improved upon addition of hexamethyldilsilazane. Ketoximes underwent Beckmann rearrangement with iodotrimethylsilane.[223]

$$R\text{-}CH{=}NOH \xrightarrow[(Me_3Si)_2NH/CHCl_3]{Me_3SiI} R\text{-}C{\equiv}N$$



Oxime sulfonates when treated with iodotrimethylsilane also undergo Beckmann rearrangement to give the corresponding imidoyl iodides.[229]

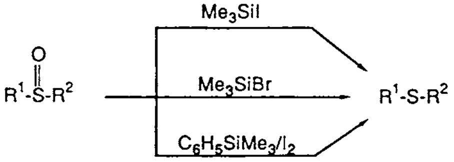


4.11. Sulfoxides and Sulfonyl Compounds

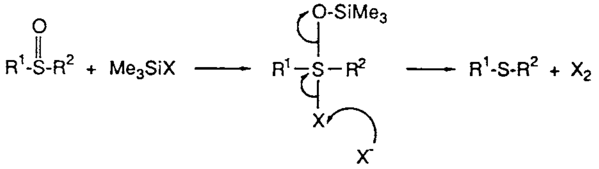
Deoxygenation of sulfoxides to sulfides is an important synthetic transformation in organic chemistry. A variety of methods are available for the synthesis of sulfides from sulfoxides.[230] Because of the high affinity of silicon for oxygen, hexachlorodisilane has proved to be an effective reagent.[231]

$$R^1\text{-}\overset{O}{\overset{\|}{S}}\text{-}R^2 + Cl_3Si\text{-}SiCl_3 \longrightarrow R^1\text{-}S\text{-}R^2 + Cl_3Si\text{-}OSiCl_3$$

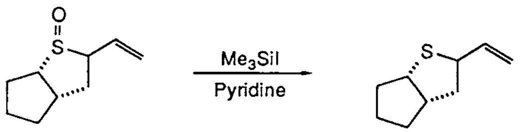
Sulfoxides are deoxygenated under mild conditions by iodotrimethylsilane, bromotrimethylsilane, and phenyltrimethylsilane/iodine to the corresponding sulfides in high yield.[232]

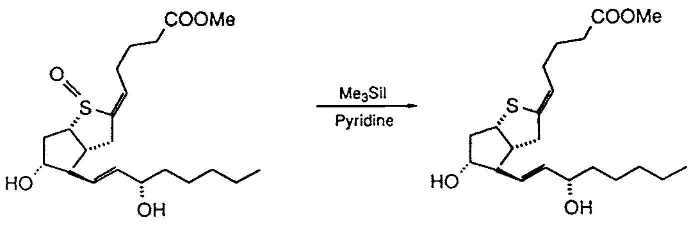


Iodotrimethylsilane reacted much more vigorously than bromotrimethylsilane. Deoxygenations with phenyltrimethylsilane/iodine were carried out at 120°C. The reaction mechanism probably involves the formation of a tetracoordinate intermediate, followed by nucleophilic attack by the halide ion to give the desired sulfide.



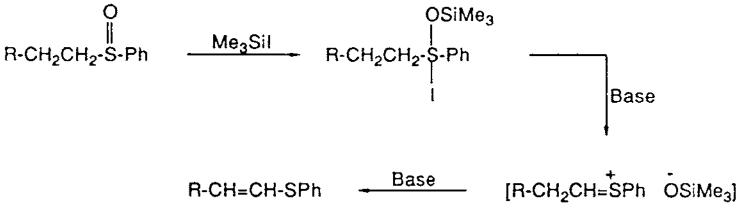
In some cases, halogenated by-products were obtained probably by the 1,2-elimination followed by reaction with halogen. When chlorotrimethylsilane/sodium iodide is used for deoxygenation of sulfoxides, the reaction proceeds faster as the amount of iodide is increased.[233] These results support the second step of the mechanism proposed above. Iodide catalysis has also been observed with other deoxygenation agents. The hexamethyldisilane/iodine reagent has also been used for the synthesis of sulfides from sulfoxides. The mild nature of the reaction conditions for deoxygenation of sulfoxides with iodotrimethylsilane and its *in situ* equivalents has been exploited by Nicolaou et al.[234] in the synthesis of biologically important thiaprostacyclins.



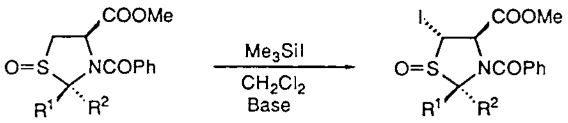


The reduction is highly selective with the alcohol and ester functions remaining intact during the course of the reaction.

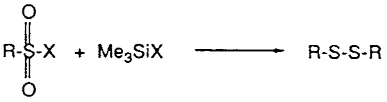
Treatment of sulfoxides with iodotrimethylsilane in the presence of sterically hindered *tert*-amines results in facile eliminative deoxygenation to yield the corresponding vinyl sulfides[235] (the Pummerer reaction).



The Pummerer reaction of optically active thiazolidine S-oxides using iodotrimethylsilane led to the formation of α-iodosulfides as the major product.[236]

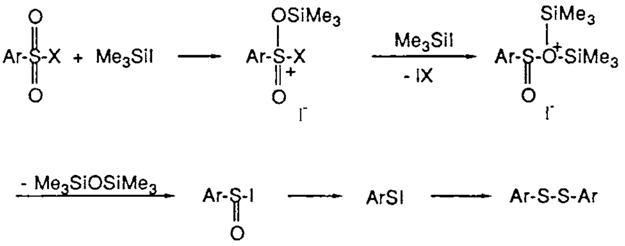


Sulfones do not react with iodotrimethylsilane, presumably due to the lower nucleophilicity of the sulfone oxygen compared to the sulfoxide oxygen. On the other hand, sulfonyl halides react very readily with iodotrimethylsilane and its *in situ* equivalents to yield the corresponding disulfides in excellent yield.[237]

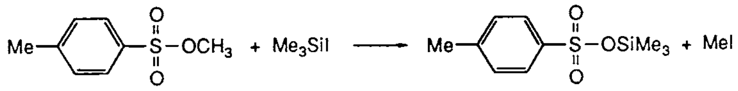


$$R\text{-}S(=O)_2\text{-}X + Me_3SiX \longrightarrow R\text{-}S\text{-}S\text{-}R$$

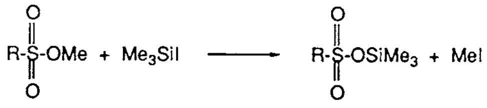
Arylsulfonyl and aralkylsulfonyl chlorides and bromides react rapidly with iodotrimethylsilane at room temperature, whereas alkylsulfonyl halides are reduced at 81 °C. The following mechanism has been proposed.



The reductive dimerization is also applicable to sulfinic acids, sulfinic acid salts, sulfinyl chlorides, and sulfenyl chlorides. Sulfonyl fluorides, sulfonic acids and their salts, and esters are not reduced under the reaction conditions. It should be noted, however, that methyl *p*-toluenesulfonate was dealkylated very efficiently by iodotrimethylsilane.



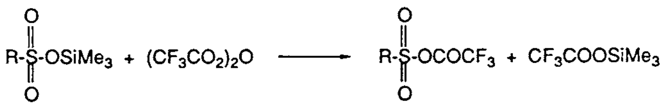
Shipov and Baukov[238] have used this reaction for the synthesis of various trimethylsilyl sulfonates.



$$R\text{-}S(=O)_2\text{-}OMe + Me_3SiI \longrightarrow R\text{-}S(=O)_2\text{-}OSiMe_3 + MeI$$

R = methyl, n-butyl, phenyl, etc

The trimethylsilyl sulfonates can be used for the synthesis of mixed anhydrides.



$$R\text{-}S(=O)_2\text{-}OSiMe_3 + (CF_3CO_2)_2O \longrightarrow R\text{-}S(=O)_2\text{-}OCOCF_3 + CF_3COOSiMe_3$$

Reduction of thiosulfonic S-esters, however, gave the corresponding disulfides.[239] Unsymmetrical esters gave a mixture of three disulfides indicating initial S–S cleavage of the ester.

$$R\text{-}SO_2\text{-}S\text{-}R \xrightarrow{Me_3SiI} R\text{-}S\text{-}S\text{-}R$$

The detailed mechanistic aspects of the reduction of sulfonyl halides and derivatives with iodotrimethylsilane has been recently discussed by Kielbasinski et al.[240]

4.12. Amines

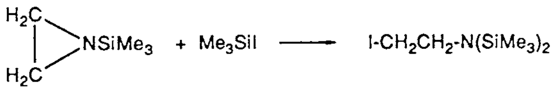
Iodotrimethylsilane forms adducts with amines. Adducts with quinoline and diazabicyclooctane have been used for the demethylation of methyl ethers. The formation of an initial adduct with the dimethylamino group has also been proposed during the synthesis of α-methylene-γ-butyrolactones. The reaction of lithium or sodium bis(trimethylsilyl)amide with iodotrimethylsilane has been used to prepare tris(trimethylsilyl)amine.[241]

$$(Me_3Si)_2NM + Me_3SiI \longrightarrow (Me_3Si)_3N + MI$$

M = Li, Na

The reaction is carried out at room temperature, thus offering a distinct advantage over the corresponding reaction with chlorotrimethylsilane, which requires 8–10 h in refluxing benzene.

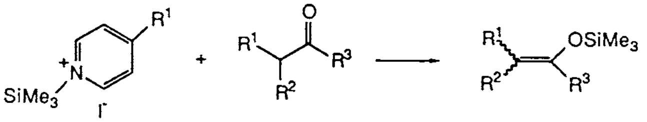
When N-trimethylsilylaziridine is treated with iodotrimethylsilane, N-β-iodoethyl-N,N-bis(trimethylsilyl)amine is formed spontaneously in 94% yield.[242]



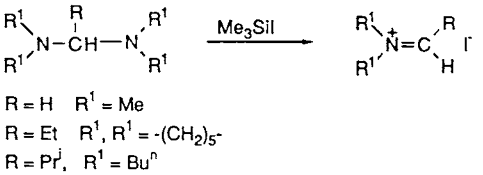
The product can be used for the introduction of aminoethyl groups into organic and organosilicon compounds. The ring opening of aziridines is reminiscent of the ring opening of epoxides with iodotrimethylsilane.

Bassindale et al.[27,243,244] have studied the interaction of various amine bases with iodotrimethylsilane. The intermediate N-silylated onium salts were characterized by NMR spectroscopy.

Anders et al.[245] have used N-trimethylsilylpyridinium salts to efficiently silylate carbonyl compounds and carboxylic acids.



The reaction of iodotrimethylsilane with 1,1-diaminoalkanes has important synthetic applications. Reaction with N,N-tetraalkyldiaminoalkanes yields the corresponding Mannich salts in very high yields.[246]



N,N-Dimethyl(methylene) immonium iodide ($R=H$, $R^1=CH_3$) has found extensive use in organic synthesis by Schreiber et al.[247] and other groups.[248] These Mannich salts react with many nucleophiles such as Grignard reagents, vinyllithium reagents, thiophenoxides, and many stabilized carbanions to yield synthetically useful intermediates.

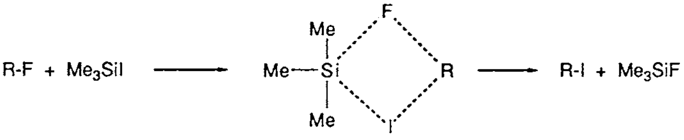
4.13. Alkyl Halides

As discussed so far, all of the reactions of iodotrimethylsilane have involved bonding of silicon to an oxygen or nitrogen atom. Iodotrimethylsilane is also capable of effecting halogen exchange in benzyl chloride and bromide.[249]

$$Me_3SiI + C_6H_5CH_2Cl \longrightarrow Me_3SiCl + C_6H_5CH_2I$$

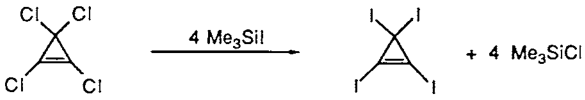
The reaction was carried out at 50°C in the presence of 5 mol % tetra-*n*-butylammonium chloride. In the absence of the catalyst, no reaction takes place even after an extended period of time. The corresponding reaction with benzyl bromide is reversible to a certain extent, so that a mixture of benzyl iodide and bromide (92 : 8) is produced under equilibrium conditions. The corresponding fluoro compounds also undergo facile halogen exchange with iodotrimethylsilane.[250]

The reaction of iodotrimethylsilane with alkyl fluorides has been studied by Olah et al.,[251] and is faster than with chlorides and bromides. Benzylic, secondary, and tertiary alkyl fluorides provide the corresponding iodoalkanes in very high yields.



The halogen-exchange reaction probably proceeds via an intermediate pentacoordinated silicon species. The fluoride–iodide halogen exchange can also be accomplished with chlorotrimethylsilane/sodium iodide or hexamethyldisilane/iodine. The reaction with primary fluoroalkanes is sluggish and generally leads to a mixture of iodoalkanes. Tertiary alkyl chlorides can also be converted to the corresponding iodides. The easy synthesis of fluoroalkanes from alkenes, alcohols, and other precursors with HF or with HF/pyridine reagent[252] make the present method an attractive route to iodoalkanes through the corresponding fluoroalkanes.

Weiss et al.[253] were able to convert tetrachlorocyclopropene to the tetraiodo derivative with iodotrimethylsilane.



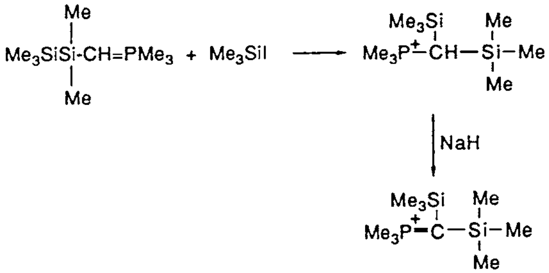
Similar halogen exchange (fluorine to iodine) has been studied at the bridgehead position of bicyclo[2.2.2]octane skeleton with iodotrimethylsilane.[254]

Phenyl selenyl chloride is also cleanly converted into phenyl selenyl iodide on treatment with iodotrimethylsilane.[255]

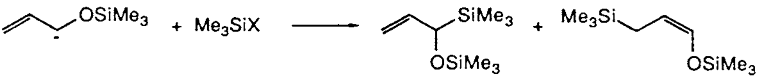
$$C_6H_5Se\text{-}Cl + Me_3SiI \longrightarrow C_6H_5Se\text{-}I + Me_3SiCl$$

4.14. Carbanions

Iodotrimethylsilane has been used for the C-silylation of phosphonium ylids for the synthesis of silyl substituted derivatives.[256]

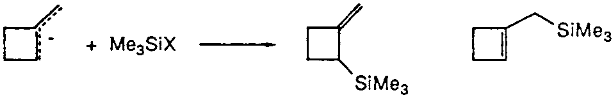


Iodotrimethylsilane has been used for the silylation of ambident carbanions to achieve different regioselectivity from that obtained with chlorotrimethylsilane and other silylating agents, e.g.,[257]



X = F	35%	65%
X = Cl	50%	50%
X = Br	75%	25%
X = I	85%	15%

The regioselectivity as seen changes depending upon the nature of the leaving group on silicon. Differing regioselectivity has also been observed in the silylation of the allylic carbanion derived from methylenecyclobutane.[258]

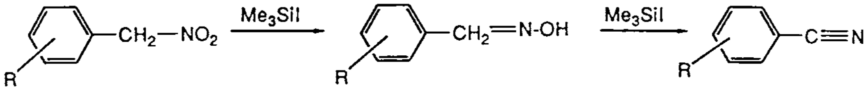


X = Cl, 25 °	50%	50%
X = Cl, -78 °	60%	40%
X = Br, 25 °	25%	75%
X = I, 0 °	25%	75%

These products have been converted to trimethylsilylisoprene, which is a useful terpene synthon.

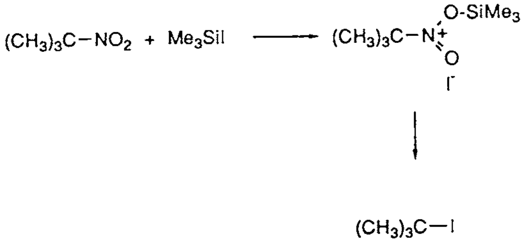
4.15. Nitro and Nitroso Compounds

Primary nitro compounds react with iodotrimethylsilane via initial deoxygenation followed by dehydration.[259]



R = o-Me, m-Me, p-Me, p-MeO

When the nitro group is attached to a tertiary alkyl center, immediate cleavage of the carbon–nitrogen bond is observed, resulting in the formation of *t*-alkyl iodide. The fate of the nitro group is not known, although a large amount of hexamethyldisiloxane is formed. *t*-Alkyl nitrosoalkanes react in a similar fashion.



$$(CH_3)_3C{-}NO_2 + Me_3SiI \longrightarrow (CH_3)_3C{-}\overset{+}{N}(O{-}SiMe_3)(O)\ I^- \longrightarrow (CH_3)_3C{-}I$$

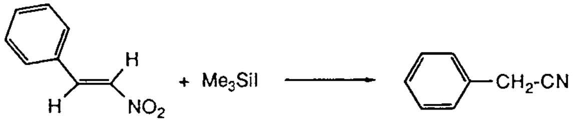
$$(CH_3)_3C{-}NO + Me_3SiI \longrightarrow (CH_3)_3C{-}I$$

Secondary alkyl nitro compounds undergo selective deoxygenation to the corresponding oxime silyl ethers. No further reaction (reduction or Beckman rearrangement) is observed under the reaction conditions.

$$RR^1C(H)NO_2 + Me_3SiI \longrightarrow RR^1C{=}N{-}O{-}SiMe_3$$

$R, R^1 = CH_3, CH_3;\ CH_3, C_2H_5;\ -(CH_2)_4;\ -(CH_2)_5$

Finally, when nitrostyrene was treated with iodotrimethylsilane, phenylacetonitrile was obtained in excellent yield.



4.16. Miscellaneous Reactions

A number of miscellaneous reactions induced by iodotrimethylsilane were reported. Some representative cases are the following.

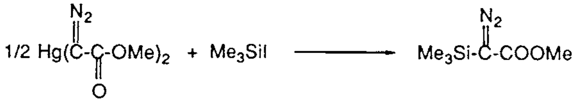
Iodotrimethylsilane catalyzes the addition of trialkyl silanes to acetylenes.[260,261]

$$Et_3SiH + HC{\equiv}CR \xrightarrow{Me_3SiI} Et_3SiC{\equiv}CR + H_2$$

Alkyl nitrites undergo cleavage with iodotrimethylsilane.[262]

$$R\text{-}ONO + Me_3SiI \longrightarrow NOI + ROSiMe_3$$

Mercury-bis(diazomethylcarbonyl) compounds react with iodotrimethylsilane to give the corresponding trimethylsilyl-bis(diazomethylcarbonyl) compounds.[263]



$$1/2\ \mathrm{Hg}(\overset{N_2}{\overset{\|}{C}}\text{-}\underset{O}{\underset{\|}{C}}\text{-OMe})_2 + Me_3SiI \longrightarrow Me_3Si\text{-}\overset{N_2}{\overset{\|}{C}}\text{-COOMe}$$

Acetylenic stannanes undergo reaction with iodotrimethylsilane to give trimethylsilylated acetylenes.[263–265]

$$Me_3SnC{\equiv}C\text{-}R + Me_3SiI \longrightarrow Me_3SiC{\equiv}C\text{-}R + Me_3SnI$$

Iodotrimethylsilane has also been used as a reagent in organometallic chemistry. However, these reactions are outside the scope of this review.

5. CONCLUSIONS AND OUTLOOK

In barely over a decade and a half since its first reported use, iodotrimethylsilane has established itself as an extremely versatile and widely used reagent for a variety of synthetic transformations. The present review amply demonstrates the already established scope and utility of reactions initiated by iodotrimethylsilane. As an effective hard–soft reagent, it allows reactions to be carried out under acid-free, neutral conditions. The relatively weak Si–I bond as well as the high affinity of silicon for oxygen, halogen, etc., contribute to the driving force for the reactions with iodotrimethylsilane. The development of *in situ* iodotrimethylsilane equivalents provides further significant advantages.

There is little doubt that the use of iodotrimethylsilane and its convenient *in situ* analogues will continue to expand. They represent one of the most significant applications of the use of organosilicon reagents in synthesis.

6. REFERENCES

1. Colvin, E. W. *"Silicon in Organic Synthesis"*, R. E. Krieger Publishing Co.: Malabar, Florida, 1985; Chapter 18.
2. Weber, W. P. *"Silicon Reagents for Organic Synthesis"*, Springer-Verlag; Berlin, 1983; Chapters 2, 3, and 4.
3. Simons, G.; Zandler, M. E.; and Talaty, E. R. *J. Am. Chem. Soc.* **1976**, *98*, 7869.
4. (a) Ebsworth, E. A. V. In *"Organometallic Compounds of the Group IV Elements"*, MacDiarmid, A. G., Ed., Marcel Dekker: New York, 1968; Vol. 1, Part 1. (b) Cottrell, T. L. *"The Strengths of Chemical Bonds"*, Butterworths: London, 1958; Chapter.
5. (a) Prakash, G. K. S.; Krishnamurti, R.; and Olah, G. A. *J. Am. Chem. Soc.* **1989**, *111*, 393. (b) Prakash, G. K. S., Keyaniyan, S.; Aniszfeld, R.; Heiliger, L.; Olah, G. A.; Stevens, R. C.; Choi, H-K.; and Bau, R. *J. Am. Chem. Soc.* **1987**, *109*, 5123.
6. (a) Olah, G. A.; and Narang, S. C. *Tetrahedron* **1982**, *38*, 2225. (b) Banerjee, A. K. *J. Sci. Ind. Res. (India)* **1981**, *41*, 699. (c) Hosomi, A. *Yuki Gosei Kagaku Kyokaishi* **1982**, *40*, 545; *Chem. Abstr.* **1981**, *97*, 163036*h*. (d) Ohnishi, S.; and Yamamoto, Y. *Annu. Rep. Tohuku Coll. Phar.* **1981**, *28*, 1; *Chem. Abstr.* **1981**, *97*, 161839*y*.
7. Voronoko, M. G.; and Khudobin, Yu I. *Izv. Akad. Nauk. SSSR, Ser. Khim.* **1956**, *713*.

8. Pray, B. O.; Sommer, L. H.; Goldberg, G. M.; Kerr, G. T.; DiGorgio, P. A.; and Whitmore, F. C. *J. Am. Chem. Soc.* **1948,** *70,* 433.
9. Jung, M. E.; and Lyster, M. A. *Organic Syntheses* **1980,** *59,* 35.
10. Kruerke, U. *Chem. Ber.* **1962,** *95,* 174.
11. Lissel, M.; and Drechsler, K. *Synthesis* **1983,** *459.*
12. Detty, M. R. *Tetrahedron Lett.* **1979,** 4189.
13. Kovaleva, T. V. *Zh. Obshch. Khim.* **1981,** *51,* 2641.
14. Birkofer, L.; and Kramer, E. *Chem. Ber.* **1967,** *100,* 2776.
15. Jung, M. E.; and Blumenkopf, T. A. *Tetrahedron Lett.* **1978,** 3657.
16. Haubold, W.; Gemmler, A.; and Kraatz, U. *Z. Naturforsch.* **1978,** *33b,* 140.
17. (a) Abel, E. W.; Armitage, D. A.; and Bush, R. P. *J. Chem. Soc.* **1964,** 2455. (b) Abel, E. W.; and Willey, G. R. *Ibid.* **1964,** 1528.
18. Andrianov, K. A.; Astachin, V. V.; and Kockin, D. A. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1962,** 1852.
19. Pinchuk, A. M.; Gorbatenko, Ah. K.; and Feshchenko, N. G. *Zh. Obshch. Khim.* **1973,** *43,* 1855.
20. Ho, T. L.; and Olah, G. A. *Synthesis* **1977,** 417.
21. Benkeser et al. proposed the following equilibrium in this reagent system: $Me_3SiI + I_2 \rightleftharpoons Me_3SiI_3$. Benkeser, R. A.; Mozden, E. C.; and Muth, C. L. *J. Org. Chem.* **1979,** *44,* 2185.
22. Schmidt, A. H.; and Russ, M. *Chem.-Ztg.* **1978,** *102,* 26; Schmidt, A. H.; and Russ, M. *Ibid.* **1978,** *102,* 65.
23. Olah, G. A.; Narang, S. C.; Gupta, B. G. B.; and Malhotra, R. *Synthesis* **1979,** 61.
24. Morita, T.; Okamoto, Y.; and Sakurai, H. *Tetrahedron Lett.* **1978,** 2523.
25. Morita, T.; Okamoto, Y.; and Sakurai, H. *J. Chem. Soc. Chem. Commun.* **1978,** 874.
26. Machida, Y.; Nomoto, S.; and Saito, I. *Synth. Commun.* **1979,** *9,* 97.
27. Bassindale, A. R.; and Stoat, T. *J. Organomet. Chem.* **1982,** *238*(41).
28. Kumada, M.; Shiiman, K.; Yamaguchi, M. *Kogyo Kagaku Zasshi* **1954,** *57,* 230.
29. Olah, G. A.; Narang, S. C.; Gupta, B. G. B.; and Malhotra, R. *J. Org. Chem.* **1979,** *44,* 1247.
30. Olah, G. A.; Narang, S. C.; Gupta, B. G. B.; and Malhotra, R. *Angew. Chem.* **1979,** *91,* 648; *Angew. Chem. Int. Ed. Engl.* **1979,** *18,* 612.
31. Seitz, D. E.; and Ferreira, L. *Synth. Commun.* **1979,** *9,* 931.
32. Sakurai, H.; Shirahata, A.; Sasaki, K.; and Hosomi, A. *Synthesis* **1979,** 740.
33. Buerser, H. *Spectrochim. Acta, Part A* **1968,** *24,* 2015.
34. van den Berghe, E. V.; and van der Kelen, G. P. *J. Organomet. Chem.* **1973,** *59,* 175.
35. Engelhardt, G.; Radeglia, R.; Jancke, H.; Lippmma, E.; and Magi, M. *Org. Mag. Res.* **1973,** *5,* 561.
36. Harris, R. K.; and Kimber, B. J. *J. Mag. Res.* **1975,** *17,* 174.
37. For a review of these methods, See McOmie, J. F. W., Ed.; "Protective Groups in Organic Chemistry," Plenum Press: New York, 1973.
38. Elsinger, F.; Schreiber, J.; and Eschenomoser, A. *Helv. Chim. Acta* **1960,** *43,* 113.
39. Ho, T. L.; and Wong, C. M. *Synth. Commun.* **1975,** *5,* 305.
40. Kornblum, N.; and Scott, A. *J. Am. Chem. Soc.* **1974,** *96,* 590.
41. Ho, T. L.; and Olah, G. A. *Angew. Chem.* **1976,** *88,* 847; *Angew. Chem. Int. Ed. Engl.* **1976,** *15,* 774.
42. Jung, M. E.; and Lyster, M. A. *J. Am. Chem. Soc.* **1977,** *99,* 968.
43. Nudelman, A.; Braun, F.; Karoly, E.; and Erickson, R. C. *J. Org. Chem.* **1978,** *43,* 3788.
44. Bryan, D. B.; Hall, R. F.; Holden, K. G.; Huffman, W. F.; and Gleason, J. G. *J. Am. Chem. Soc.* **1977,** *99,* 2353.
45. Yamaguchi, H.; Hideo, K.; Yoshiaki, O.; and Kyotaka, S. Japanese Patent 61/161263, 1986; *Chem. Abstr.* **1987,** *106,* 32853*d.*
46. Voronkov, M. G.; Dolmaa, G.; Putilova, G. G.; and Dubinskaya, E. I. *Zh. Obshch. Khim.* **1985,** *55,* 2297.
47. Ho, T. L.; and Olah, G. A. *Proc. Natl. Acad. Sci. U.S.A.* **1978,** *75,* 4.

48. Hiyama, T.; Saimoto, H.; Nishio, K.; Shinoda, M.; Yamamoto, H.; and Nozaki, H. *Tetrahedron Lett.* **1979**, 2043.
49. Greico, P. A. *Synthesis* **1975**, 67.
50. Hudrlik, P. F.; Rundnik, L. R.; and Horzeniowski, S. H. *J. Am. Chem. Soc.* **1973**, *95*, 6848.
51. (a) Brown, S. P.; and Bal, B. S. *Tetrahedron Lett.* **1981**, *22*, 4891. (b) Walley, D. R.; and Belletire, J. L. *Synth. Commun.* **1984**, *14*, 401.
52. Sekiguchi, A.; Kabe, Y.; and Ando, W. *Tetrahedron Lett.* **1979**, 871.
53. Ho, T. L. *Synth. Commun.* **1979**, *9*, 233.
54. Krapcho, A. P.; Jahngen, Jr., E. G. E.; and Lovey, A. J. *Tetrahedron Lett.* **1974**, 1091; and references therein.
55. (a) Tocik, Z.; Earl, R. A.; and Beranek, J. *Nucl. Acids Res.* **1980**, *8*, 4755. (b) Tocik, Z.; and Beranek, J. *Nucl. Acids Res.* **1981**, *9*, 37.
56. Bonojouklian, R.; and Philips, M. L. *Tetrahedron Lett.* **1981**, 3915.
57. Lattrell, R.; Duerckheimer, W.; Kirrstetter, R.; and Seibert, G. German Patent DE 3539901, 1987; *Chem. Abstr.* **1987**, *107*, 5844*q*.
58. Skotnicki, J. S.; and Commons, T. J. U.S. Patent 4692517, 1987; *Chem. Abstr.* **1987**, *107*, 197942*r*.
59. Lang, M. European Patent Appl. EP 246187, 1987; *Chem. Abstr.* **1988**, *108*, 112069*j*.
60. Skotnicki, J. S.; and Strike, D. P. U.S. Patent 4728733, 1988; *Chem. Abstr.* **1988**, *109*, 37684*w*.
61. Yamauchi, H.; Komatsu, T.; Sugiyama, I.; and Nomoto, S. Japanese Patent JP 6259284, 1987; *Chem. Abstr.* **1987**, *107*, 134131*e*.
62. Morin, Jr., J. M.; and Leonard, N. J. European Patent Applied EP 186463, 1986; *Chem. Abstr.* **1985**, *105*, 152828*a*.
63. Olah, G. A.; Narang, S. C.; Salem, G. F.; and Gupta, B. G. B. *Synthesis* **1981**, *142*.
64. Olah, G. A.; Malhotra, R.; and Narang, S. C.; unpublished work.
65. Berth, G.; Fechner, K.; Kaufman, K. D.; Michael, G.; and Tomaschewski, G. *Z. Chem.* **1971**, *11*, 102.
66. Burlachenko, G. S.; Baukove, Yu. I.; Dzherayan, T. G.; and Lutsenko, I. F. *Zh. Obshch. Khim.* **1975**, *45*, 81.
67. Reissig, H-U.; and Bohm, I. *Tetrahedron Lett.* **1983**, *24*, 715.
68. Voronkov, M. G.; Komarov, V. G.; Albanov, A. I.; Kositsina, E. I.; and Dubinskaya, E. I. *Izv. Akad. Nauk SSSR Ser. Khim.* **1978**, *7*, 1692.
69. Kricheldorf, H. R. *Angew Chem.* **1979**, *91*, 749; *Angew. Chem. Int. Ed. Engl.* **1979**, *18*, 689.
70. (a) Deslongchamps, P.; and Guay, D. *Can. J. Chem.* **1985**, *63*, 2757. (b) Yamamoto, Y.; Ohnishi, S.; and Azuma, Y. *Chem. Pharm. Bull.* **1982**, *30*, 3505.
71. (a) Kramarova, E. P.; Shipov, A. G.; Artamkina, O. B.; and Baukov, Yu. I. *Zh. Obshch. Khim.* **1984**, *54*, 1921. (b) Woodbury, R. P.; and Rathkey, M. W. *J. Org. Chem.* **1978**, *43*, 881. (c) Trost, B. M.; and Kunz, R. A. *J. Org. Chem.* **1974**, *39*, 2475.
72. Shipov, A. G.; and Baukov, Yu. I. *Zh. Obshch. Khim.* **1984**, *54*, 1842.
73. Ben-Ishai, D.; and Berger, A. *J. Org. Chem.* **1952**, *17*, 1564.
74. Hartung, W. H.; and Simonoff, R. *Organic Reactions* **1953**, *7*, 273.
75. Barltrop, J. A.; and Schofield, P. *Tetrahedron Lett.* **1962**, 697.
76. Jung, M. E.; and Lyster, M. A. *J. Chem. Soc. Chem. Commun.* **1978**, 315.
77. Altenbach, V. H-J.; Blech, B.; Marco, J. A.; and Vogel, E. *Angew. Chem.* **1982**, *94*, 789.
78. Kurita, J.; Enkaku, M.; and Tsuchiya, T. *Heterocycles* **1983**, *20*, 2173.
79. Lott, R. S.; Chauhan, V. S.; and Stammer, C. H. *J. Chem. Soc. Chem. Commun.* 1979, 495.
80. Kundu, N. G. *Synth. Commun.* **1981**, *11*, 787.
81. Corey, J. Y.; and West, R. *J. Am. Chem. Soc.* **1963**, *85*, 4034.
82. Beattie, I. R.; Gilson, T.; Webster, M.; and McQuillan, G. P. *J. Chem. Soc.* **1964**, 238.
83. Beattie, I. R.; and Parrett, F. W. *J. Chem. Soc.*, Part A, **1966**, 1784.
84. Romanenko, V. D.; Tovstenko, V. I.; and Markovskii, L. N. *Zh. Obshch. Khim.* **1979**, *49*, 1907.
85. Chojnowski, J.; Cypryk, M.; and Michalski, J. *J. Organomet. Chem.* **1978**, *161*, C31.
86. Corriu, R.; Leard, M.; and Masse, J. *Bull. Cos. Chim. Fr.* **1968**, 2555.

87. Corriu, R.; and Henner, M. *J. Organomet. Chem.* **1974**, *74*, 1.
88. Corriu, R.; Dabosi, G.; and Royo, G. *J. Organomet. Chem.* **1977**, *129*, 299.
89. Livantsov, M. V.; Proskurnina, M. V.; Prischenko, A. A.; and Lutsenko, I. F. *Zh. Obshch. Khim.* **1984**, *54*, 2504.
90. Romanenko, V. D.; Tovstenko, V. I.; and Markovski, L. N. *Synthesis* **1980**, 823.
91. (a) Kabachnik, M. M.; Prishchenko, A. A.; Novikova, Z. S.; and Lutsenko, I. F. *Zh. Obshch. Khim.* **1979**, *49*, 1446; and references therein. (b) Schubert, D. M.; and Norman, A. D. *Inorg. Chem.* **1985**, *24*, 1107.
92. Issleib, K.; and Mitscherling, B. *Z. Naturforsch. B* **1960**, *15*, 267.
93. Tattershale, B. W. *J. Chem. Soc., Dalton Trans.* **1987**, 1515.
94. Denis, J. N.; and Krief, A. *J. Chem. Soc. Chem. Commun.* **1980**, 544; and references therein.
95. Olah, G. A.; Gupta, B. G. B.; and Narang, S. C. *J. Org. Chem.* **1978**, *43*, 4503.
96. Gomelya, N.; and Feshchenko, N. G. *Zh. Obshch. Khim.* **1987**, *57*, 1206.
97. Marchenko, A. P.; Koidan, G. N.; and Pinchuk, A. M. *Zh. Obshch. Khim.* **1983**, *53*, 670.
98. Miroshnicbenko, V. V.; Marchenko, A. P.; Kudryavtsov, A. A.; and Pinchuk, A. M. *Zh. Obshch. Khim.* **1982**, *52*, 2517.
99. Cypryk, M.; Chojnowski, J.; and Michalski, J. *Tetrahedron* **1985**, *41*, 2471.
100. Bunton, C. A. *Acct. Chem. Res.* **1970**, *3*, 257.
101. Amarnath, V.; and Broom, A. D. *Chem. Res.* **1977**, *77*, 183.
102. Weimann, G.; and Khorana, H. G. *J. Am. Chem. Soc.* **1962**, *84*, 4329.
103. Eckstein, F. *Angew. Chem.* **1966**, *78*, 682; *Angew. Chem. Int. Ed. Engl.* **1966**, *5*, 671.
104. Kosolapoff, G. M. *"Organophosphorous Compounds"*; Wiley, New York, 1950.
105. Voronkov, M. G.; and Zgonnik, V. N. *Zh. Obshch. Khim.* **1957**, *27*, 1483.
106. Schwarz, R.; and Schoeller, K. *Chem. Ber.* **1958**, *91*, 2103.
107. Rabinowitz, R. *J. Org. Chem.* **1963**, *28*, 2975.
108. Rundinskas, J.; Hullar, T. L.; and Salvador, R. N. *J. Org. Chem.* **1977**, *42*, 2771.
109. McKenna, C. E.; Higa, M. T.; Cheung, N. H.; and McKenna, M. C. *Tetrahedron Lett.* 1977, 155.
110. Zygmunt, J.; Kafarski, P.; and Mastalerz, P. *Synthesis* **1978**, 609.
111. Blackburn, G. M.; and Ingleson, D. *J. Chem. Soc. Chem. Commun.* **1978**, 870; Blackburn, G. M.; and Ingleson, D. *J. Chem. Soc., Perkin Trans. 1* **1980**, 1150.
112. Murdock, K. C. European Patent Applied, EP 264901, 1988; *Chem. Abstr.* **1988**, *109*, 54777*w*.
113. Noding, S. A. U.S. Patent 4689123, 1987; *Chem. Abstr.* **1988**, *108*, 13082*b*.
114. McKenna, C. E.; and Schmidhauser, J. *J. Chem. Soc. Chem. Commun.* **1979**, 739.
115. Takeuchi, Y.; Demachi, Y.; and Yoshii, E. *Tetrahedron Lett.* **1979**, 1231.
116. Chojnowski, J.; Cypryk, M.; and Michalski, J. *Synthesis* **1978**, 777.
117. Borecka, B.; Chojnowski, J.; Cypryk, M.; Michalski, J.; and Zielinska, J. *J. Organomet. Chem.* **1979**, *171*, 17.
118. Predvoditelev, D. A.; Smirnova, L. I.; and Nifantev, E. E. *Zh. Org. Khim.* **1979**, *15*, 2223.
119. Frazer, N. J.; Gerrard, W.; and Singh, A. P. *J. Chem. Soc.* **1961**, 4680.
120. Schmidbaur, H.; and Seeber, R. *Chem. Ber.* **1974**, *107*, 1731.
121. Dabkowski, W.; Michalski, J.; and Skrzypczynski, Z. *Chem. Ber.* **1985**, *118*, 1809.
122. Chojnowski, J.; Cypryk, M.; Michalski, J.; and Wozniak, L. *ACS Symp. Ser.* 1981, *171* (Phosphorous Chem.), 521.
123. Chojnowski, J.; Cypryk, M.; and Michalski, J. *J. Organomet. Chem.* **1981**, *215*, 355.
124. Al'fonsov, V. A.; Nizamov, I. S.; Batyeva, E. S.; and Pudovik, A. N. *Zh. Obshch. Khim.* **1983**, *53*, 1713.
125. Al'fonsov, V. A.; Nizamov, I. S.; Batyeva, E. S.; and Pudovik, A. N. *Zh. Obshch. Khim.* **1984**, *54*, 535.
126. Voronkov, M. G.; Puzanova, V. E.; Pavlov, S. F.; and Dubinskaya, E. I. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1975**, 448.
127. Voronkov, M. G.; Komarov, B. G.; Albanov, A. I.; Korotaeva, U. M.; and Dubinskaya, E. I. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1978**, 1415.

128. Voronkov, M. G.; Dubinskaya, E. I.; Kormarov, V. G.; and Pavlov, S. F. *Zh. Obshch. Khim.* **1976**, *46*, 1908.
129. Jung, M. E.; and Lyster, M. A. *J. Org. Chem.* **1977**, *42*, 3761.
130. Voronkov, M. G.; Dubinskaya, E. I.; Pavlov, S. F.; and Gorokhova, V. G. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1976**, 2355.
131. Klemer, A.; Bieber, M.; and Wilbers, H. *Leibigs Ann. Chem.* **1983**, 1416.
132. Ricci, A.; Taddei, M.; and Seconi, G. *J. Organomet. Chem.* **1986**, *306*, 23.
133. Ajao, J. F.; Bird, C. W.; and Brown, A. L. *Chem. Ind. (London)* **1985**, 34.
134. Thiem, J.; and Köpper, S. *J. Carbohydrate Chem.* **1983**, *2*, 75.
135. Chan, T. H.; and Lee, S. D. *Tetrahedron Lett.* **1983**, *24*, 1225.
136. Rosen, B. I.; and Weber, W. P. *J. Org. Chem.* **1977**, *42*, 3463.
137. Tietel, S.; and O'Brien, J. P. *J. Org. Chem.* **1976**, *41*, 1657; Spath, E.; and Quietensky, J. *Chem. Ber.* **1929**, *60*, 1882.
138. Minamikawa, J.; and Brossi, A. *Tetrahedron Lett.* **1978**, 3085.
139. Minamikawa, J.; and Brossi, A. *Can. J. Chem.* **1979**, *57*, 1720.
140. Halim, H.; Locksley, H. D.; and Memon, J. J. *J. Chem. Soc., Perkin Trans. 1* 1980, 2331.
141. Vickery, E. H.; Pahler, L. F.; and Eisenbraun, E. J. *J. Org. Chem.* **1979**, *44*, 4444.
142. Francis, R. C.; and Reeves, W. D. German Patent DE 3526695, 1986; *Chem. Abstr.* **1986**, *104*, 170412*u*.
143. Sato, N.; and Kato, Y. *Heterocycl. Chem.* **1986**, *23*, 1677.
144. Schlieper, C. A.; and Wemple, J. *Nucleosides and Nucleotides* **1984**, *3*, 369.
145. Kalganov, B. E.; Efimova, I. V.; Kazankova, M. A.; and Lutsenko, I. F. *Zh. Obshch. Khim.* **1985**, *55*, 708.
146. Efirmova, I. V.; Kazankova, M. A.; and Lutsenko, I. F. *Zh. Obshch. Khim.* **1985**, *55*, 1647.
147. Kinoshita, H.; Hori, I.; Oishi, T.; and Ban, Y. *Chem. Lett.* **1984**, 1517.
148. Silverman, R. B.; Radak, R. E.; and Hacker, N. P. *J. Org. Chem.* **1979**, *44*, 4970.
149. Kupchan, S. M. *Trans. N. Y. Acad. Sci.* **1970**, *32*, 85.
150. Hosomi, A.; Hashimoto, H.; and Sakurai, H. *Tetrahedron Lett.* **1980**, 951.
151. Sonnet, P. E.; Piotrowski, E.; Wise, W. B.; and Micich, T. J. *J. Am. Oil Chem. Soc.* **1986**, *63*, 1579.
152. Voronkov, M. G.; Komarov, V. G.; Albanov, A. I.; and Dubinskaya, E. I. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1978**, 2623.
153. Denis, J. N.; Magnane, R. M.; van Eenoo, M.; and Krief, A. *Nouv. J. Chim.* **1979**, *3*, 705.
154. Detty, M. R. *J. Org. Chem.* **1980**, *45*, 924.
155. Murata, S.; Suzuki, M.; and Noyori, R. *J. Am. Chem. Soc.* **1979**, *101*, 2739.
156. Detty, M. R.; and Seidler, M. D. *Tetrahedron Lett.* **1982**, *23*, 2543.
157. Andrews, G. C.; Crawford, T. C.; and Contillo, Jr., L. G. *Tetrahedron Lett.* **1981**, *22*, 3803.
158. Sakurai, H.; Sasaki, K.; and Hosomi, A. *Tetrahedron Lett,* **1980**, 2329.
159. Kraus, H. A.; and Frazier, K. *J. Org. Chem.* **1980**, *45*, 2579.
160. Sharpless, K. B.; and Lauer, R. F. *J. Am. Chem. Soc.* **1973**, *95*, 2697.
161. Suzuki, K.; Miyazawa, M.; and Tsuchihashi, G-I. *Tetrahedron Lett.* **1987**, *28*, 3515.
162. Jung, M. E.; Mazurek, M. A.; and Lim, R. M. *Synthesis* **1978**, 588.
163. Narang, S. C.; and Olah, G. A.; unpublished results.
164. Ergozhin, E. E.; Rafikov, S. R.; and Mukhitdinova, B. A. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1969**, *19*, 49.
165. Olah, G. A.; Husain, A.; and Narang, S. C. *Synthesis* **1983**, 896.
166. Keyser, G. E.; Bryant, J. D.; and Barrio, J. R. *Tetrahedron Lett.* **1979**, 3263.
167. Bryant, J. D.; Keyser, G. E.; and Barrio, J. R. *J. Org. Chem.* **1979**, *44*, 3733.
168. Muchmore, D. C.; and Dahlquist, F. W. *Biochem. Biophys. Res. Commun.* **1979**, *86*, 599.
169. Konwar, D.; Boruah, R. C.; Sandhu, J. S.; and Baruah, J. N. *Synth. Commun.* **1984**, *14*, 1053.
170. Konwar, D.; Boruah, R. C.; and Sandhu, J. S. *Ind. J. Chem.* **1984**, *23B*, 975.
171. Jung, M. E.; Andrus, W. A.; and Ornstein, P. L. *Tetrahedron Lett.* **1977**, 4175.
172. Olah, G. A.; Narang, S. C.; and Mehrotra, A. K. *Synthesis* **1982**, 965.

173. Shipov, A. G.; Livantsova, L. I.; Zaitseva, G. S.; Baukov, Yu. I.; and Lutsenko, I. F. *Zh. Obshch. Khim.* **1982**, *52*, 713.
174. Sakurai, H.; Sasaki, K.; and Hosomi, A. *Bull. Chem. Soc. Jpn.* **1983**, *56*, 3195.
175. Sakurai, H.; Sasaki, K.; Hayashi, J.; and Hosomi, A. *J. Org. Chem.* **1984**, *49*, 2808.
176. Hosomi, A.; Sakata, Y.; and Sakurai, H. *Tetrahedron Lett.* **1984**, *25*, 2383.
177. Hosomi, A.; Sakata, Y.; and Sakurai, H.; *Carbohydr. Res.* **1987**, *171*, 223.
178. Kametani, T.; Huang, S-P.; Chu, S-D.; and Honda, T. *Heterocycles* **1983**, *20*, 505.
179. (a) Sakurai, H.; Sakata, Y.; and Hosomi, A. *Chem. Lett.* **1983**, 409. (b) Hosomi, A.; Sakata, Y.; and Hosomi, A. *Chem. Lett.* **1983**, 405.
180. Kozyukov, V. P.; Kozyukov, Vik P.; and Mironov, V. F. *Zh. Obshch. Khim.* **1985**, 467.
181. Hosomi, A.; Iijima, S.; and Sakurai, H.; *Tetrahedron Lett.* **1982**, *23*, 547.
182. Orlova, N. A.; Belavin, I. Yu.; Sergeev, V. N.; Shipov, A. G.; and Baukov, Yu. I. *Zh. Obshch. Khim.* **1984**, *54*, 717.
183. Shipov, A. G.; Zaitseva, G. S.; and Baukov, Yu. I. *Zh. Obshch. Khim.* **1984**, *54*, 2156.
184. Hackett, S.; and Livinghouse, T. *J. Org. Chem.* **1986**, *51*, 879.
185. Voronkov, M. G.; Pavlov, S. F.; and Dubinskaya, E. I. *Dokl. Akad. Nauk SSSR* **1976**, *227*, 607.
186. Voronkov, M. G.; Pavlov, S. F.; and Dubinskaya, E. I. *Izu. Akad. Nauk SSSR, Ser. Khim.* **1975**, 657.
187. Voronkov, M. G.; Dubinskaya, E. I.; and Chuikova, N. A. *Zh. Obshch. Khim.* **1977**, *47*, 2395.
188. Jung, M. E.; and Ornstein, P. L. *Tetrahedron Lett.* **1977**, 2659.
189. Klemer, A.; and Bieber, M. *Liebigs Ann. Chem.* **1984**, 1052.
190. Knudsen, M. J.; and Schore, N. E. *J. Org. Chem.* **1984**, *49*, 5025.
191. Mehta, G.; and Kapoor, S. K. *J. Organomet. Chem.* **1974**, *66*, C33.
192. Morita, T.; Okamoto, Y.; and Sakurai, H. *Synthesis* **1981**, 32.
193. Hosomi, A.; and Sakurai, H.; *Chem. Lett.* **1981**, 85.
194. Olah, G. A.; Husain, A.; and Singh, B. P. *Synthesis* **1985**, 703.
195. Hergott, H. H.; and Simchen, G. *Liebigs Ann. Chem.* **1980**, 1718.
196. Miller, R. D.; and McKean, D. R. *Synthesis* **1979**, 730.
197. Cohen, T.; Yu, L-C.; and Daniewski, W. M. *J. Org. Chem.* **1985**, *50*, 4596.
198. Suzuki, T.; Sato, E.; Unno, K.; and Kametani, T. *J. Chem. Soc., Perkin Trans. 1* **1986**, 2263.
199. Miller, R. D.; and McKean, D. R. *Synth. Commun.* **1982**, *12*, 319.
200. Matsuda, I.; Sato, S.; Hattori, M.; and Izumi, Y. *Tetrahedron Lett.* **1985**, *26*, 3215.
201. Schmidt, A. H.; and Russ, M. *Chem.-Ztg.* **1979**, *103*, 285; Schmidt, A. H.; and Russ, M. *Chem.-Ztg.* **1979**, *103*, 183.
202. Jung, M. E.; Mossman, A. B.; and Lyster, M. A. *J. Org. Chem.* **1978**, *43*, 3698.
203. Jung, M. E.; and Lewis, P. K. *Synth. Commun.* **1983**, *13*, 213.
204. Voronkov, M. G.; Komarov, V. G.; and Dubinskaya, E. I. *Zh. Org. Khim.* **1986**, *22*, 1777.
205. Ho, T. L. *Synth. Commun.* **1979**, *9*, 665.
206. Olah, G. A.; Arvanaghi, M.; and Vankar, Y. D. *J. Org. Chem.* **1980**, *45*, 3531.
207. (a) Miller, R. D.; and McKean, D. R. *Tetrahedron Lett.* **1979**, 2305. (b) Larson, G. L.; and Klesse, R. *J. Org. Chem.* **1985**, *50*, 3627.
208. Ito, K.; Nakanishi, S.; and Otsuji, Y. *Chem. Lett.* **1987**, 2103.
209. (a) Hamilton, R. J.; Mander, L. N.; and Sethi, S. P. *Tetrahedron* **1986**, *42*, 2881. (b) Kraus, G. A.; and Gottschalk, P. *Tetrahedron Lett.* **1983**, *24*, 2727. (c) Kraus, G. A.; and Gottschalk, P. *J. Org. Chem.* **1984**, *49*, 1153.
210. Taniguchi, M.; Kobayashi, S.; Nakagawa, M.; Hino, T.; and Kishi, Y. *Tetrahedron Lett.* **1986**, 4763.
211. Cheon, S. H.; Christ, W. J.; Hawkins, L. D.; Jin, H.; Kishi, Y.; and Taniguchi, M. *Tetrahedron Lett.* **1986**, 4759.
212. Gil, G. *Tetrahedron Lett.* **1984**, 3805.
213. Sakurai, H. Japanese Patent 8248930, 1982; *Chem. Abstr.* **1982**, *97*, 38668*q*.
214. Pearson, W. H.; and Cheng, M. C. *J. Org. Chem.* **1987**, *52*, 1353.

215. Sassaman, M. B.; Kotian, K. D.; Prakash, G. K. S.; and Olah, G. A. *J. Org. Chem.* **1987**, *52*, 4314.
216. Aizpurua, J. M.; Lecea, B.; and Palomo, C. *Can. J. Chem.* **1986**, *64*, 2342.
217. Sassaman, M. B.; Prakash, G. K. S.; and Olah, G. A. *Tetrahedron* **1988**, *44*, 3771.
218. Miller, R. D.; and McKean, D. R. *J. Org. Chem.* **1981**, *46*, 2412.
219. Giacomini, E.; Loreto, M. A.; Pellacani, L.; Tardella, P. A. *J. Org. Chem.* **1980**, *45*, 519.
220. Dieter, R. K.; and Pounds, S. *J. Org. Chem.* **1982**, *47*, 3174.
221. Miller, R. D.; and McKean, D. R. *Tetrahedron Lett.* **1980**, 2639.
222. Crimmins, M. T.; and Mascarella, S. W. *J. Am. Chem. Soc.* **1986**, *108*, 3435.
223. Godleski, S. A.; Heacock, D. J. *J. Org. Chem.* **1982**, *47*, 4820.
224. Voyle, M.; Dulap, N. K.; and Watt, D. S. *J. Org. Chem.* **1983**, *48*, 3242.
225. Duhamel, L.; and Chauvin, J. *Chem. Lett.* **1985**, 693.
226. Sasaki, K.; Kushida, M.; Iyoda, M.; and Oda, M. *Tetrahedron Lett.* **1982**, 2117.
227. Schmidt, A. H.; Russ, M.; and Grosse, D. *Synthesis* **1981**, 216.
228. Jung, M. E.; and Long-Mei, Z. *Tetrahedron Lett.* **1983**, 4533.
229. Ishida, Y.; Sasatani, S.; Maruoka, K.; and Yamamoto, H. *Tetrahedron Lett.* **1983**, 3255.
230. Drabowicz, J.; Numata, T.; and Oae, S. *Org. Prep. Proc. Int.* **1977**, *9*, 63.
231. Naumann, K.; Zon, G.; and Mislow, K. *J. Am. Chem. Soc.* **1969**, *91*, 7012.
232. Olah, G. A.; Gupta, B. G. B.; and Narang, S. C. *Synthesis* **1977**, 583.
233. Olah, G. A.; Narang, S. C.; Gupta, B. G. B.; and Malhotra, R. *Synthesis* **1979**, 61.
234. Nicolaou, K. C.; Barnette, W. E.; and Magolda, R. L. *J. Am. Chem. Soc.* **1978**, *100*, 2567.
235. Miller, R. D.; and McKean, D. R. *Tetrahedron Lett.* **1983**, *24*, 2619.
236. Tokitoh, N.; Igarashi, Y.; and Ando, W. *Tetrahedron Lett.* **1987**, *28*, 5903.
237. Olah, G. A.; Narang, S. C.; Field, L. D.; and Salem, G. F. *J. Org. Chem.* **1980**, *45*, 4792.
238. Shipov, A. G.; and Baukov, Yu. I. *Zh. Obshch. Khim.* **1979**, *49*, 1915.
239. Palumbo, G.; Parrilli, M.; Neri, O.; Ferreri, C.; and Caputo, R. *Tetrahedron Lett.* **1982**, *23*, 2391.
240. Kielbasinski, P.; Drabowicz, J.; and Mikolajczyk, M. *J. Org. Chem.* **1982**, *47*, 4806.
241. Murray, M.; Schirawski, G.; and Wannagat, U. *J. Chem. Soc., Dalton Trans.* **1972**, *11*.
242. Piper, F.; and Ruhlmann, K. *J. Organomet. Chem.* **1976**, *121*, 149.
243. Bassindale, A. R.; and Stout, T. *Tetrahedron Lett.* **1985**, *26*, 3403.
244. Bassindale, A. R.; Lau, J.C-Y.; Stout, T.; and Taylor, P. G. *J. Chem. Soc. Perkin Trans. 2* **1986**, 227.
245. Anders, E.; Stankowiak, A.; and Riemer, R. *Synthesis* **1987**, 931.
246. Bryson, T. A.; Bonitz, G. H.; Reichel, C. J.; and Dardis, R. E. *J. Org. Chem.* **1980**, *45*, 524.
247. Schreiber, J.; Maag, H.; Hashimoto, H.; and Eschenmoser, A. *Angew. Chem.* **1971**, *83*, 355; *Angew. Chem. Int. Ed. Engl.* **1971**, *10*, 330.
248. Danishefsky, S.; Schuda, P. F.; Kitahara, T.; and Etheredge, S. J. *J. Am. Chem. Soc.* **1977**, *99*, 6066.
249. Freidrich, E. C.; Abma, C. B.; and Vartanian, P. F. *J. Organomet. Chem.* **1980**, *187*, 203.
250. Freidrich, E. C.; DeLucca, G. *J. Organomet. Chem.* **1982**, *226*, 143.
251. Olah, G. A.; Narang, S. C.; and Field, L. D. *J. Org. Chem.* **1981**, *46*, 3727.
252. Olah, G. A.; Welch, J. T.; Vankar, Y. D.; Nojima, M.; Krekes, I.; and Olah, J. A. *J. Org. Chem.* **1979**, *44*, 3872.
253. Weiss, V. R.; Miess, G-E.; Haller, A.; and Reinhardt, W. *Angew. Chem.* **1986**, *98*, 102.
254. Adcock, W.; and Kok, G. B. *J. Org. Chem.* **1985**, *50*, 1079.
255. Tomada, S.; Takeuchi, Y.; and Nomura, Y. *Synthesis* **1985**, 212.
256. Schmidbaur, H.; and Vornberger, W. *Chem. Ber.* **1962**, *105*, 3173.
257. Lau, P. W. K.; and Chan, T. H. *J. Organomet. Chem.* **1979**, *179*, C24.
258. Wilson, S. R.; Phillips, L. R.; and Natalie, Jr., K. J. *J. Am. Chem. Soc.* **1979**, *101*, 3340.
259. Olah, G. A.; Narang, S. C.; Field, L. D.; and Fung, A. *J. Org. Chem.* **1983**, *48*, 2766.
260. Voronkov, M. G.; Pukhnarevich, V. B.; Ushakova, N. I.; Tsykhanskaya, I. I.; Albaxov, A. I.; and Vitkovskii, V. Yu. *Zh. Obshch. Khim.* **1985**, *55*, 94.

261. Voronkov, M. G.; Ushakova, N. I.; Tsykhanskaya, I. I.; and Pukhnarevich, V. B. *J. Organomet. Chem.* **1984**, *264*, 39.
262. Weiß, R.; and Wagner, K. G. *Chem. Ber.* **1984**, *117*, 1973.
263. Bethäuser, W.; Weber, B.; Heydt, H.; and Regitz, M. *Chem. Ber.* **1985**, *118*, 1315.
264. Bogoradovskii, E. T.; Zavgorodnii, V. S.; Moshinskaya, A. V.; and Petrov, A. A. *Zh. Obshch. Khim.* **1981**, *51*, 2144.
265. Bogoradovskii, E. T.; Zavgorodnii, V. S.; Polozov, B. V.; and Petrov, A. A. *Zh. Obshch. Khim.* **1982**, *52*, 455.