

Unimolecular chain transfer (UMCT) reactions: concepts, preliminary results with silicon hydrides, and future potential

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Most radical reactions are conducted by chain methods that have bimolecular chain transfer steps. It is proposed that unimolecular chain transfer (UMCT) reactions should have advantages for conducting difficult radical transformations. The concepts of the UMCT method are illustrated with allyltributylstannane, and the first examples of UMCT reactions of silicon hydrides are introduced. Examples of bimolecular reactions conducted with silicon hydride UMCT reagents are provided, and the potential of the UMCT method is discussed.

Introduction

Over the last decade, radical reactions have been embraced as useful tools for constructing all sorts of organic molecules, and a number of books and reviews extol the virtues of radical reactions in synthesis.¹ Work in the field is partitioned between radical cyclizations (intramolecular reactions) and radical additions (bimolecular reactions). A survey of the use of radical reactions in complex molecule synthesis² shows that radical cyclizations are far more popular than radical additions. This is undoubtedly because radical cyclizations are more general than radical additions. We contend that bimolecular radical addition reactions have considerable untapped synthetic potential, and that they are currently limited by the methods that are used to conduct them. In this Keynote Article, we introduce a strategy to expand the scope and practicality of bimolecular radical addition reactions termed *Unimolecular Chain Transfer*, abbreviated UMCT.³

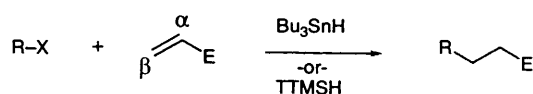
The reductive addition of radicals to electron-poor alkenes, often called the Giese reaction, is probably the most popular type of bimolecular radical addition reaction.^{1,4} The accepted mechanism and some of the features of this reaction are summarized in eqn. (1). The mechanism of the Giese reaction

illustrates a recurring selectivity problem that arises whenever bimolecular radical reactions are allowed to compete. In eqn. (1), there is a competition for each intermediate radical between the metal hydride and the electron-poor alkene. The partitioning between hydrogen transfer and addition at each stage (steps 2 *versus* 3, and 4 *versus* 5) depends upon the relative rates of the two reactions, which in turn depends upon the respective rate constants and the concentrations of the reagents. Other reagents such as tris(trimethylsilyl)silane have been introduced as alternatives to tin hydrides,⁵ and these reagents have important advantages; however, the basic selectivity problem imposed by the two competing bimolecular radical reactions (hydrogen transfer and addition) is not eliminated by these modified reagents.

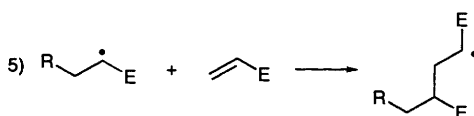
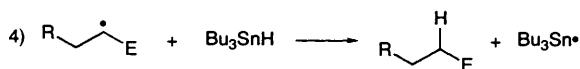
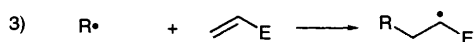
Thanks to an extensive body of work on rate constants⁶ and substituent effects,¹ it is now well understood how to choose reaction partners and experimental conditions such that maximum yields of the 1:1 adduct are formed. The problem from the synthetic perspective is that the partners and the conditions that work well are of limited usefulness. While the radical precursor R-X can be varied widely, the acceptor is generally limited to a few types of mono- or 1,1-di-substituted alkene. Furthermore, with few exceptions, one of the components (usually the acceptor) is used in significant excess. Thus, while the general features of bimolecular radical reactions (mildness of reaction conditions, tolerance of functionality, selectivity and so on) appear to be ideal for use in crucial synthetic steps that bring two large, complex segments of a molecule together, radical additions have rarely been used for such purposes.

Problems with competing bimolecular reactions pervade synthetic radical chemistry, but they are by no means unique to this area of synthesis. A popular and powerful approach to solving such rate and selectivity problems of ionic and pericyclic reactions is to render a reaction intramolecular. Provided that a favourable ring size is involved, dramatic rate accelerations are often observed. These accelerations provide at least two significant advantages: (1) reactions that do not work (or work poorly) in a bimolecular mode can work well intramolecularly, and (2) the rate acceleration provided by intramolecularity solves selectivity problems with competing bimolecular reactions.

The benefits of intramolecularity have not been lost on synthetic radical chemists; single and multiple radical cyclizations have made a major mark on synthesis.^{1,2} These radical cyclizations are frequently conducted by chain methods with reagents like tributyltin hydride, and the chain transfer step is recognized as a crucial component of the chain. The chain transfer step with tin hydride is usually considered to be the hydrogen transfer reaction [steps 2 and 4 in eqn. (1)]. The

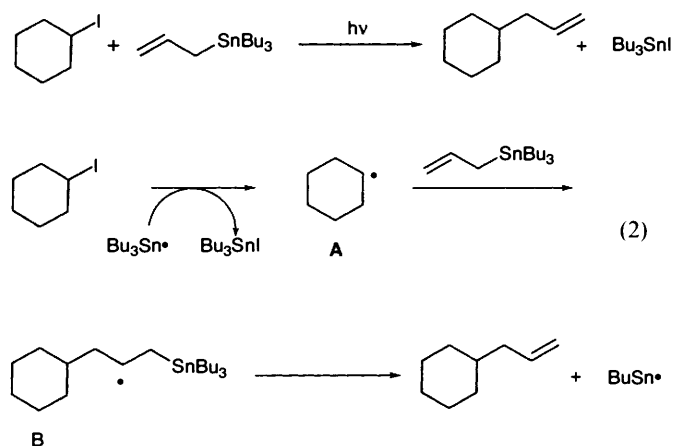


- R must be nucleophilic radical
- excess acceptor common
- low concentrations common
- C β substituents not well tolerated

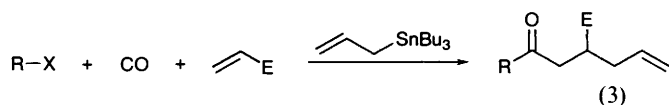


standard *modus operandi* is to couple unimolecular radical reactions (cyclizations) with bimolecular chain transfer reactions. The logical reversal of this *modus operandi* has not been generally recognized. We contend that intermolecular radical reactions (additions) will benefit significantly from being coupled with unimolecular chain transfer (UMCT) reactions.

Indeed there already exists an important class of radical reactions that proceeds by way of UMCT: reactions with allylstannanes and related reagents.⁷ The accepted mechanism for allylation of cyclohexyl iodide with allyltributylstannane is shown in eqn. (2). It has been said for some time that allyl-



stannanes are 'special' reagents.¹ For example, allyltributylstannane has about the same reactivity towards cyclohexyl radical as methyl crotonate,⁸ yet the preparative addition of cyclohexyl iodide to allylstannane occurs in better yield under more practical conditions. Further, many of the most difficult and sophisticated sequences of radical reactions involve allylstannanes⁹ or conceptually related reagents like vinylstannanes and allyl sulfides. The 'four-component' condensation of Ryu and co-workers^{9a} shown in eqn. (3) provides a



nice example of the power of allylstannanes to mediate complex transformations.

The features of allylstannanes naturally pose the question 'what is so special about allylstannanes?' The common response to this question is that 'they react slowly with radicals, thereby giving the radicals a significant lifetime in which to react'. This is true,⁸ and the ability of allylstannanes to conduct slow radical reactions is a powerful feature. Yet this is not the correct answer.¹⁰ The correct answer, 'selectivity', was clearly stated by Keck:¹¹ radicals **A** and **B** [eqn. (2)] in the chain are both secondary alkyl radicals and must be differentiated. With tin hydride differentiation is difficult because tin hydride reacts with all alkyl radicals at similar rates. However, radicals **A** and **B** are differentiated because **B** is a β-stannyl radical, and it has a very short lifetime with respect to β-elimination of a tributylstannyl radical. In contrast, **A** has a relatively long lifetime. The extension of this selectivity concept to sequential reactions was made by Feldman and us.¹² However, we all couched our discussions of the power of this class of reactions in terms of β-fragmentation mechanisms. That the chain transfer reaction is a β-fragmentation is incidental.

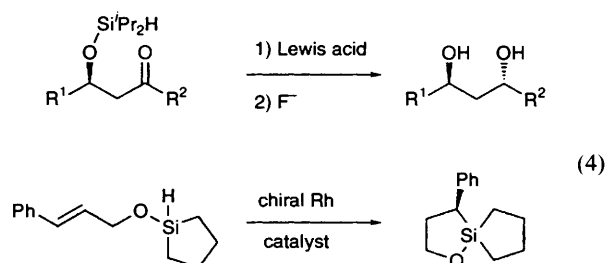
The answer to the question 'what is so special about allylstannanes?' is more fundamental: *the key chain transfer reaction*

(β-fragmentation) is a rapid, unimolecular reaction. Selectivity among one or more radicals with similar competing reactions can readily be established by giving one radical a rapid, unimolecular chain transfer option that the other radicals do not have. The selectivity features that make allylstannanes 'special' can be conferred upon any other class of radical chain transfer reaction by making it unimolecular.

Because the most popular methods to conduct radical chain reactions are based on bimolecular hydrogen transfer from reagents like tin hydrides, tris(trimethylsilyl)silicon hydride (TTMSH) and related reagents,¹³ we have decided to develop an analogous class of unimolecular chain transfer reagents. This class of reagents will have all the advantages of allylstannanes, but will be useful for conducting a more diverse array of reactions. At the outset of our work, we could find no examples of intramolecular radical hydrogen transfer reactions of silicon,¹⁴ germanium or tin hydrides. However, intramolecular hydrogen transfer reactions of C-H bonds are well known,¹⁵ and it seems probable that related intramolecular reactions of Si-H, Ge-H and Sn-H bonds should be faster than those of related C-H bonds. The logical starting point for this work is silicon hydrides.¹⁶ With a few exceptions¹⁷ (like TTMSH), most silicon hydrides will not propagate bimolecular radical chain reductions because the hydrogen transfer step is too slow.¹⁸

However, halogen abstraction reactions of silyl radicals are very fast,¹⁹ so even a modest rate increase from rendering the hydrogen transfer reaction intramolecular should then result in a viable chain.

Ionic intramolecular reactions of silicon hydrides have been studied by several groups, and a number of valuable Lewis acid and transition-metal catalysed intramolecular hydrosilylation reactions have been developed. Eqn. (4) shows two representative



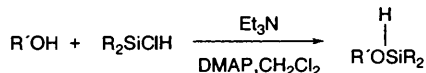
examples.²⁰ Carbon-carbon bond formation does not usually occur in such processes. Encouragingly, these intramolecular ionic and organometallic reactions are more rapid than their bimolecular analogues, and they provide the levels of regio- and stereo-control that one expects from an intramolecular reaction. Beyond that, this body of work provided a starting point for preparing some interesting types of silicon hydrides for radical reactions.

Results and discussion

To demonstrate that UMCT chains based on silicon hydrides can propagate, we first studied the isomerization reactions of a series of simple (haloalkyl)silicon hydrides. These reactions are of little or no preparative value, but they provide important information about the feasibility of the intramolecular hydrogen atom transfer step. Standard methods were used to prepare the requisite silanes, as summarized in eqn. (5). Most of the substrates are alkoxy silanes (silyl ethers), which were prepared by silylation of an alcohol with the appropriate disubstituted chlorosilane. Several carbosilanes were also prepared by silylation of appropriate organometallic reagents followed by standard transformations. The chlorosilanes are either commercially available (*t*-Bu₂SiClH, *i*-Pr₂SiClH) or readily prepared [Ph₂SiClH,^{20d} (CH₂)₄SiClH²¹].

Because the corresponding chlorosilane was commercially

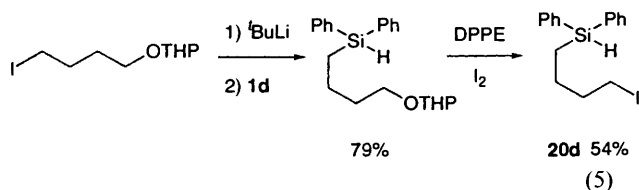
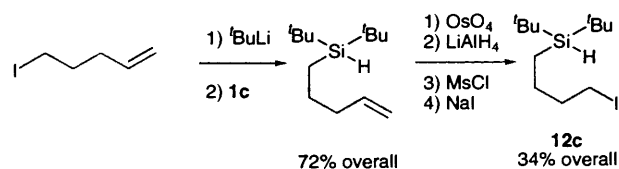
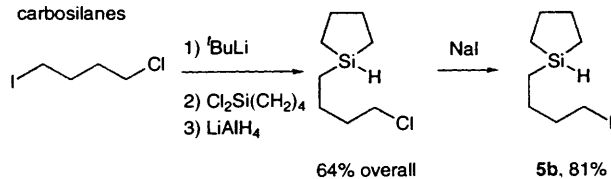
alkoxysilanes



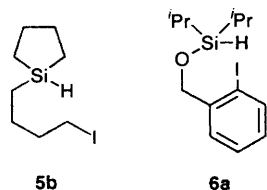
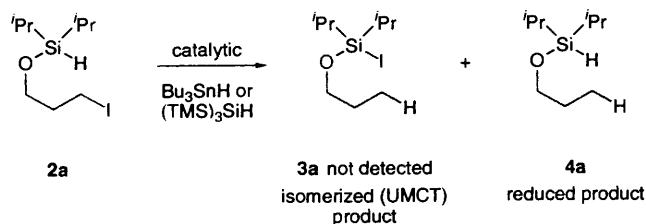
1 a-d

series a R = ^tPr
 b R = (CH₂)₄
 c R = ^tBu
 d R = Ph

carbosilanes

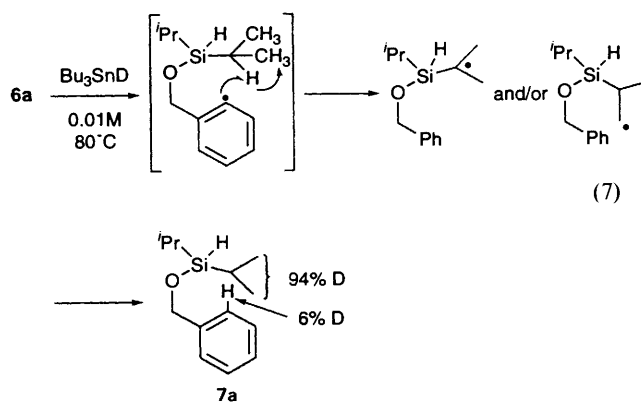


available. the (diisopropyl)silyl group was selected for initial investigation [eqn. (6)]. This proved to be a mistake. Attempts



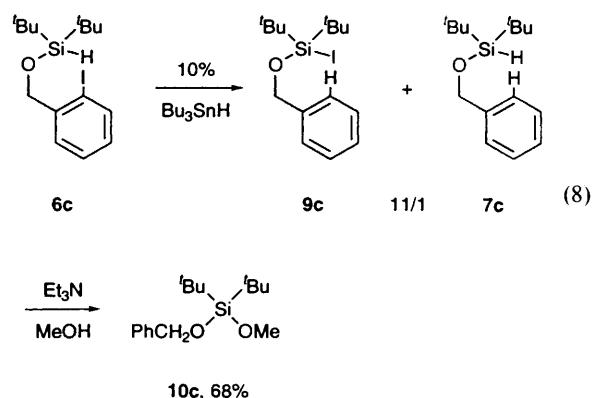
to initiate the isomerization of **2a** to **3a** were completely unsuccessful. When **2a** was treated with tributyltin hydride (or TTMSH), only the reduced product **4a** was formed, and the yield of **4a** never exceeded the amount of tin hydride that was added. This suggests that **4a** is formed by a normal tin hydride chain and that no UMCT chains are propagating. Similar negative results were obtained with the silacyclopentyl derivative **5b** and with the aryl halide **6a**.

In the case of **6a**, a deuterium-labelling experiment [eqn. (7)] provided significant information. Reduction of **6a** with 1 equiv. Bu₃SnD at 0.01 M cleanly provided **7a**. Integration of the ²H NMR spectrum of **7a** showed that 6% of the label was on the aryl ring and 94% on the isopropyl groups. Unfortunately, the ²H resonances of the isopropyl methyl and the methine hydrogens overlap, so it is not possible to specify the relative



proportion of the label in each group. Nonetheless, the results show that 1,6-hydrogen transfer from the methine and/or 1,7-hydrogen transfer from the methyl groups is faster than 1,5-hydrogen transfer from the silicon hydride. While we did not establish this for **2a** and **5b** (the *n*-alkyl methyl group resonance overlaps the relevant hydrogens in the isopropylsilyl group), it seems likely that these substrates also fail to propagate a UMCT chain for the same reason. We have observed on a number of occasions that 1,6- and even 1,7-hydrogen transfer reactions compete with 1,5-hydrogen transfer when silicon is in the connecting chain.²² In substrates **2a**, **5b** and **6a**, such hydrogen transfers are probably facilitated by the silicon substituent, which weakens both α and β C-H bonds.¹⁸

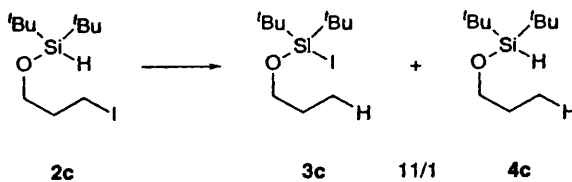
Since 1,7-hydrogen transfers are relatively uncommon, it seems probable that 1,6-hydrogen transfer from the isopropyl methine hydrogens is the culprit that spoils the UMCT. We therefore directed our attention to the di-*tert*-butyl analogue **6c** shown in eqn. (8). This has no hydrogens located for 1,6-



hydrogen transfer but it has 18 hydrogens located for 1,7-hydrogen transfer. Heating of a 0.01 M solution of **6c** in benzene containing 10 mol% tributyltin hydride (added in two portions at 1 h intervals) provided an 11 : 1 mixture (GC analysis) of the isomerized silicon iodide **9c** and the reduced silicon hydride **7c**.²³ Unlike **6c**, whose percentage conversion never exceeded the percentage of tin hydride added, **7c** was completely consumed even though only 10% tributyltin hydride was added.

Silicon iodides are very sensitive to hydrolysis, so the isolation of **9c** was not attempted. Instead, the crude reaction mixture was exposed to methanol and triethylamine, resulting in smooth conversion of the silicon iodide **9c** into the mixed silyl acetal **10c**, which was isolated in pure form after flash chromatography in 68% yield. This methanolysis was adopted as a standard procedure to characterize products and to determine isolated yields. When mixed silyl acetals like **10c** are produced, care must be taken to avoid prolonged reaction times; continued exposure of **9c** to MeOH-Et₃N results in the slow displacement of benzyl alcohol by methanol to form di-*tert*-butyldimethoxysilane.

The di-*tert*-butylsilyl derivative of 3-iodopropanol **2c** was

Table 1 Isomerization of the di-*tert*-butylsilyl ether **2c**


Entry	Initiator	[2c]/mM	<i>T</i> /°C	Ratio 3c : 4c
1	5 × 5% Bu ₃ SnH	5	80	5.4:1
2	3 × 5% TTMSH	10	80	7.2:1
3	15% Bu ₃ SnH, syringe pump	5	80	9.2:1
4	10% (Bu ₃ Sn) ₂ , <i>hν</i>	100	60	3.4:1
5	10% (Bu ₃ Sn) ₂ , <i>hν</i>	30	60	8.7:1
6	10% (Bu ₃ Sn) ₂ , <i>hν</i>	10	60	16.8:1

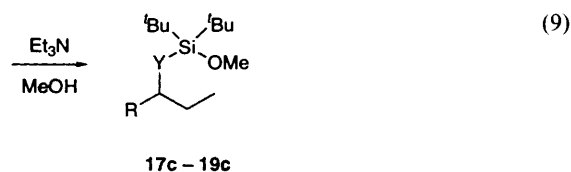
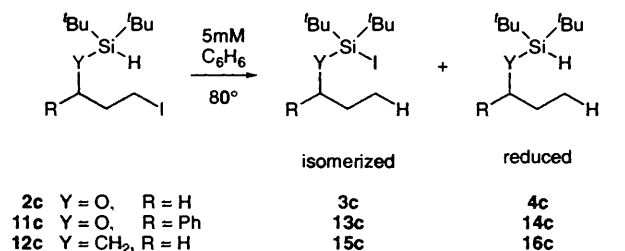
selected as a suitable substrate for surveying reaction conditions, and Table 1 collects the results of this survey. Initiation with tin hydride required the addition of five portions of 5 mol% tin hydride to consume **2c**, and the isomerized product **3c** and the reduced product **4c** were formed in a 5.4:1 ratio (entry 1). The use of tris(trimethylsilyl)silicon hydride³ (TTMSH, a poorer hydrogen donor than tin hydride) required 3 × 5% portions and provided **3c** and **4c** in a 7.2:1 ratio (entry 2), while the syringe pump addition of 15% mol Bu₃SnH provided a 9.2:1 ratio (entry 3). These results suggest that at least some of the reduced product **4c** arises from standard bimolecular hydrogen transfer reactions with the Bu₃SnH or TTMSH.

To suppress this hydrogen transfer, reactions were initiated by UV irradiation of a benzene solution of **2c** containing 10% hexabutylditin. In these experiments, the reduced product was still formed, but the ratio of **3c** to **4c** depended significantly on the reaction concentration. At lower concentrations, the reaction provided improved ratios; the best ratio, 16.8:1 was observed at 10 mM (entries 4–6). The mechanistic implications of these results are discussed below.

Preparative isomerizations of **2c**, alkoxyisilane **11c**, and carbasilane **12c** were conducted by portionwise addition of tin hydride, and the results of these experiments are shown in eqn. (9). In each case, 5% tin hydride was added hourly until GC analysis²³ indicated that the starting material was consumed. The isomerized:reduced ratio was then measured by GC prior to exposure of the mixture to MeOH–Et₃N. Flash chromatography provided the pure mixed acetals **17c–19c**; no attempt was made to isolate the minor reduced products. There is a rough correlation between the increasingly facile conversion (as reflected by the need for fewer portions of tin hydride) and the ratio of isomerized:reduced products, suggesting that the chains increase in efficiency in the order **2c** < **12c** < **11c**.

The results of a similar experiment with the diphenylsilane **20d** are summarized in eqn. (10). This substrate required addition of only two portions of tin hydride, but the reduced product **22d** was still formed in small amounts even though **20d** lacks a reactive C–H bond either α or β to the silicon. After exposure of the reaction to Et₃N–MeOH, **23d** was isolated in 84% yield. None of the experiments in eqns. (9) and (10) was attempted with ditin initiation, although based on the results in eqn. (8), small improvements in the isomerized:reduced ratio might be expected.

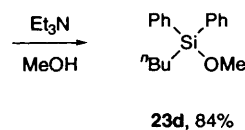
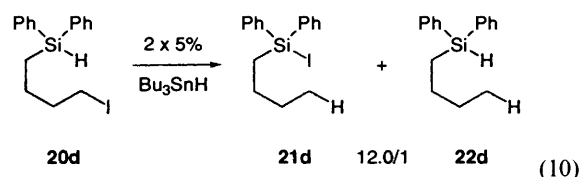
Although the origin of the minor reduced product in these experiments is not entirely clear, the observations that the major product is an isomer of the starting material and that only catalytic amounts of initiator are required clearly show that silicon hydride chains are propagating. Three types of chain can be envisioned: a standard chain where all the propagation steps are bimolecular (not shown, but analogous to a tin hydride reduction), and two chains that have one

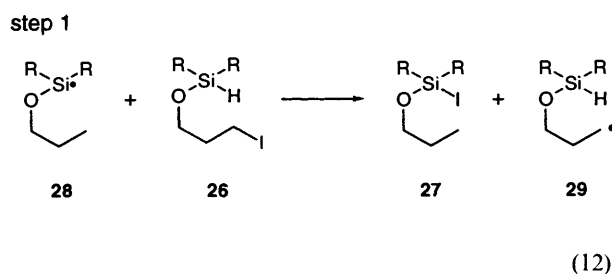
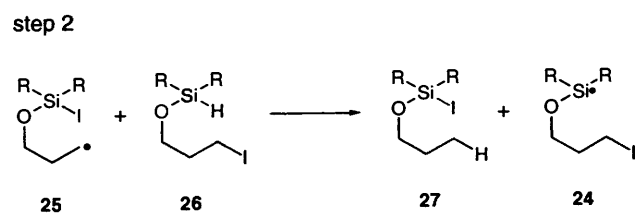
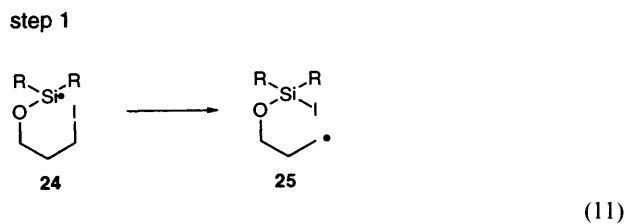


Precursor	Initiation with Bu ₃ SnH	Isomerized/reduced ratio	yield 17c–19c
2c	5 × 5%	5.4/1	47%
11c	2 × 5%	15.0/1	71%
12c	3 × 5%	9.1/1	72%

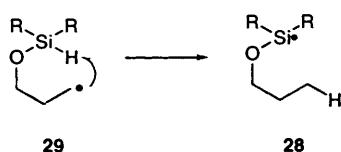
intramolecular and one bimolecular step. The latter two chains are shown in eqns. (11) and (12). These two chains have an interesting feature: they proceed from the same starting material to the same product yet there are no common radical intermediates in the propagation steps. We term these 'orthogonal chains'. The chain in eqn. (11) propagates by unimolecular halogen transfer and bimolecular hydrogen transfer, while the chain in eqn. (12) propagates by bimolecular halogen transfer and unimolecular hydrogen transfer. Defining hydrogen transfer as the 'chain transfer step' makes the reaction in eqn. (12) a 'UMCT' transformation.

The results provide strong circumstantial support that the





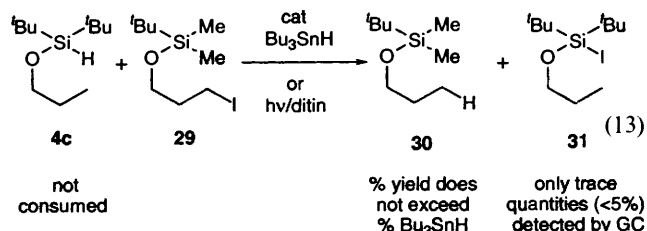
step 2 (UMCT)



UMCT chain in eqn. (12) is operating. Both the standard bimolecular chain and the chain in eqn. (11) invoke bimolecular hydrogen transfer from a silicon hydride to an alkyl radical. However, it is known that such reactions are slow,¹⁸ and for this reason chain reductions with silicon hydrides do not usually propagate. Primary alkyl radicals (neophyl, hexenyl) abstract hydrogen atoms from Et₃SiH with rate constants (at 80 °C) less than 10⁴ M⁻¹ s⁻¹.¹⁸ In the case of the neophyl radical, about 40% of the hydrogens that are transferred come from the ethyl groups.

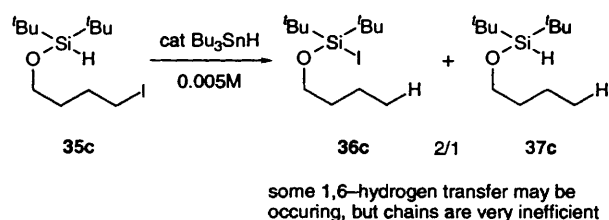
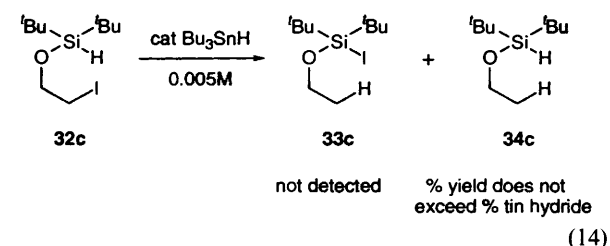
Also, the inability to propagate chains with the isopropylsilanes can only be accounted for by the UMCT chain in eqn. (12). The labelling studies suggest that 1,6- and/or 1,7-hydrogen transfers occur with these substrates to produce α - and β -silyl radicals [eqn. (7)]. Were bimolecular hydrogen transfer reactions occurring, these radicals would behave like any other carbon-centred radicals, abstracting a hydrogen atom and continuing the chain. Thus, in any mechanism involving bimolecular hydrogen transfers, the isopropylsilanes should be no different from the *tert*-butyl- or phenyl-silanes. However, within the context of the UMCT chain in eqn. (12), these 1,6- and 1,7-hydrogen transfers are chain-breaking events—the carbon radicals in eqn. (7) are not in the chain, and save for bimolecular hydrogen transfer, there is no way for them to re-enter the chain.

Control experiments summarized in eqn. (13) also support the UMCT mechanism. In the first set of experiments, the iodide and the silicon hydride were separated into two molecules, **4c** and **29**. Attempts to initiate chains with these mixtures under the conditions in Table 1 did not succeed. When catalytic amounts of tin hydride were added, the yield of the reduced product **30** never exceeded the amount of tin hydride added, and only traces of the silicon iodide **31** were detected by



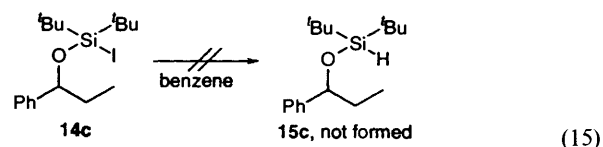
GC. These results suggest that **29** is reduced by tin hydride in a normal chain, and silicon hydride **4c** is ignored.

The isomerizations of higher and lower homologues of **2c** were also attempted [eqn. (14)]. Isomerization of substrates



32c and **35c** by bimolecular chains should be of comparable efficiency to **2c**, but UMCT mechanisms require a 1,4-hydrogen transfer for **32c** and a 1,6-hydrogen transfer for **35c**. In the event, no chains could be initiated with **32c**; however, the observation of **36c** suggested that very short chains might be operating with **35c**. These results are consistent with established trends in intramolecular hydrogen transfer reactions: 1,4-hydrogen transfer reactions are rare but 1,6-hydrogen transfer reactions are common, though they are usually slower than their 1,5-counterparts. Although the results with **35c** are marginal, we believe that in substrates designed for more rapid hydrogen transfer, it may be possible to propagate UMCT chains based on 1,6-hydrogen transfer reactions.

It is desirable to suppress as much as possible the amount of the minor reduction product, but the current experimental results do not allow a definitive conclusion as to the origin of this product. However, some clues are available. First, the results of an extensive set of control experiments summarized in eqn. (15) show that the reduced product **15c** does not arise by a



no reaction under the conditions listed below

80 °C/48 h; Bu₃SnH, 80 °C, 24 h; Bu₃SnH, AIBN, 80 °C, 24 h; UV irradiation, 60 °C, 24 h; UV irradiation, Bu₃SnSnBu₃, 60 °C, 24 h.

subsequent reaction of the isomerized product **14c**. There then remain four different possibilities: (1) hydrogen transfer from the initiating reagent Bu₃SnH, (2) bimolecular hydrogen transfer from the Si–H or β C–H bond of the silicon hydride, (3)

intramolecular 1,7-hydrogen transfer of the C–H bond β to the silicon or (4) hydrogen transfer from the medium (solvent or reagents, or disproportionation).

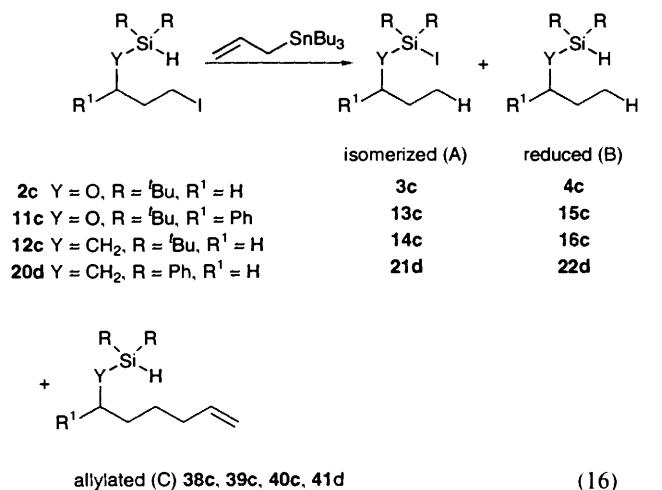
Although competing hydrogen transfer from Bu_3SnH (possibility 1) is probably occurring when this reagent is used, this cannot be the sole source of the reduction product because the reduced product is formed, albeit in smaller amounts, even when hexabutylditin is used as the initiating reagent. Possibility 4 also should not account for much of the reduction product; benzene is a poor hydrogen donor and disproportionation seems unlikely because neither the recombination product nor the other expected disproportionation products (alkenes) were observed in significant amounts. That the ratio of isomerized-to-reduced product also increases significantly as the concentration is decreased (Table 1) suggests that an inter- not an intra-molecular hydrogen transfer is the primary source of the reduced product. This rules out possibility 3 and therefore suggests that a major source of the reduced product must be bimolecular hydrogen transfer from the silicon hydride reagent (possibility 2). Further, the observation that the di-*tert*-butyl and diphenyl substrates give similar results [compare **12e**, eqn. (9) with **20c**, eqn. (10)] points a finger at the Si–H bond because the β C–H bonds in the arylsilane **20c** are not potential hydrogen atom sources. Double labelling experiments may ultimately shed more light on this point.

Crude competitive experiments allow us to make an estimate of the rate constant for 1,5-hydrogen transfer for several of the silicon hydrides. These experiments, summarized in Table 2 and eqn. (16), were conducted in the presence of allyltributylstannane. Rate constants for the reaction of allyltributylstannane are known,⁸ although not with high accuracy. However, we chose this competition reaction over the usual tin hydride method because the latter method would require isotopic labelling and there were already questions about the source of the hydrogen atoms in the products. Clearly allylated products can come only from reactions of radicals with allyltributylstannane.

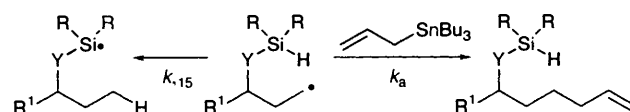
For the competitive experiments [eqn. (16)], a mixture of the appropriate iodide, allyltributylstannane (2 equiv., 1.0 M) and AIBN in benzene was heated at 80 °C, and the product ratio was analysed by GC²³ (Table 2). Combined yields were very good (>80%) and the di-*tert*-butylsilanes typically produced three types of product: isomerized **A**, reduced **B** and allylated **C**. Authentic samples of all the allylated products (**38–40c** and **41d**) were prepared by standard methods described in the Experimental section. To estimate the rate constant for 1,5-hydrogen transfer, the ratios of **A** and **C** were substituted into the standard kinetic equations. Assuming competition between allylation and intramolecular hydrogen transfer [eqn. (16)], the reduced product **B** was ignored.

With the diphenylsilane **20d**, two other products were detected in the reaction mixture: allylsilane **42**, which was identified by comparison with an authentic sample, and allylated silyl iodide **43**, which was identified by isolation of the derived methanolysis product **44** after exposure of the reaction to $\text{MeOH-Et}_3\text{N}$. The origins of these minor products are currently speculative. Allylsilane **42** may result from addition of a silyl radical to the allylstannane or from an ionic allylation of reduced product **21d**. The silicon iodide **43** may come from bimolecular hydrogen transfer of product **41d**. If these speculations are correct, then **42** should not be factored into the rate calculation, but **43** should be added to **41**. However, because the yield of **43** is so small (<5%) and because its origin is uncertain, it was not included in the rate calculation.

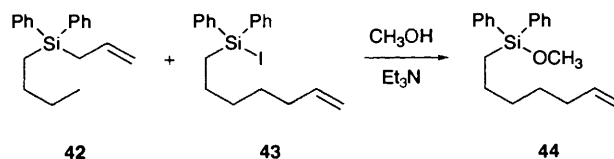
The rate constants listed should not be regarded as highly accurate for (at least) three reasons: (1) the base allylation rate constant is not known with high accuracy, (2) the quantitative methods used,²³ while reasonable, are not up to the standards often used for highly accurate rate measurements and (3) the high concentrations needed to propagate allylstannane chains



Competition



Minor products from **21d**



and ensure sufficient competition trapping rates are less than ideal for the UMCT chains because they favour the reduced product **B**. That said, we believe that the numbers in Table 2 should serve as useful estimates until better numbers are measured. Effective molarities for these reactions are crucial for bimolecular applications of UMCT reactions; however, since no bimolecular rate constants for hydrogen transfer reactions of these types of silicon hydride are known, we cannot yet calculate accurate effective molarities. Taking Chatgililoglu's rate constant for the reaction of the neophyl radical with the Si–H bond of triethylsilane as the bimolecular standard, we estimate effective molarities of ≥ 1 M for these reactions.

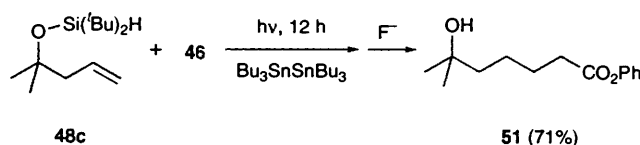
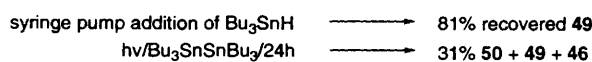
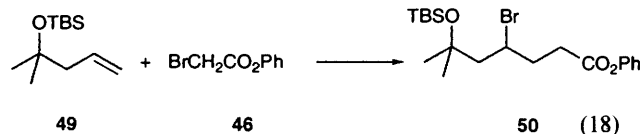
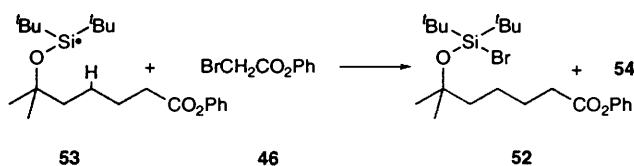
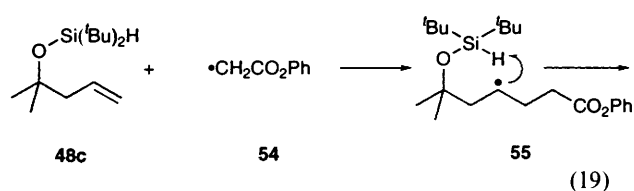
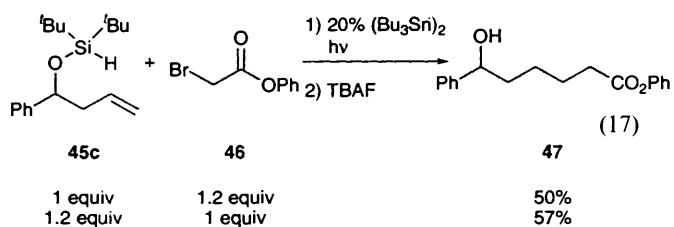
The successful isomerizations pave the way to develop bimolecular UMCT chains based on silicon hydrides. To show the viability of such chains, we selected the additions of ester-substituted radicals to terminal alkenes. Such reactions occur rapidly enough to be synthetically useful, but they are at the lower end of the rate scale. Conducting these additions by the tin hydride method is expected to be difficult since appropriate 'polar effects' are absent. The atom transfer method is a potential alternative, especially if the radical precursor is an iodide.²⁴

Initial UMCT addition reactions were conducted with alkene **45c** and phenyl bromoacetate (**46**). Irradiation of a benzene solution of these reactants in near stoichiometric amounts in the presence of 20% hexabutylditin was followed by exposure of the reaction mixture to tetrabutylammonium fluoride (TBAF) and flash chromatography. The two unoptimized experiments shown in eqn. (17) provided product **47** in about 50 and 57% yield. These yields are quite good considering that the radical addition is not an especially rapid one and that neither reagent was used in large excess.

More detailed comparisons were conducted with alkene **48c** and its 'non-UMCT' control **49** [eqn. (18)]. Standard syringe

Table 2 Competition experiments with allyltributylstannane

Precursor	Products (% yields)				Estimated $k_{1,5}$ $M^{-1} s^{-1}$
	A	B	C	Others	
2c	3c (19)	4c (12)	38c (50)	—	4×10^3
11c	13c (44)	15c (5)	39c (43)	—	1×10^4
12c	14c (38)	16c (7)	40c (44)	—	1×10^4
20d	21d (49)	22d (8)	41d (22)	42 (5) 43 (<5)	2×10^4



pump addition of tin hydride to a refluxing benzene solution of **46** and **49**, followed by work-up and purification, resulted in the recovery of unchanged **49** in 81% yield. Apparently, addition of the radical derived from **46** to **49** could not compete with direct reduction even under conditions designed to minimize the rate of reduction. Photolysis of a mixture of **46** and **49** under standard atom transfer conditions resulted in a slow, inefficient conversion into bromide **50**. The reaction was stopped after 1 day at 60 °C, at which point large amounts of unchanged **49** and **46** still remained. Flash chromatography provided **50** in 31% yield. In this reaction, both the radical addition and the bromine transfer are at the low end of the useful rate spectrum, so it is difficult to propagate a chain.

In contrast, the UMCT reaction of **48c** and **46** was more efficient and higher yielding [eqn. (18)]. Irradiation of a solution of 1 equiv. each of these reagents and for 12 h at 25 °C (benzene, 5% ditin) resulted in complete consumption of **48c**. Direct desilylation and purification by flash chromatography provided **51** in 71% yield. During the course of the reaction, we could not detect any bromide analogous to **50**, so we believe that this reaction proceeds directly by a UMCT addition mechanism rather than indirectly by bromine transfer addition followed by UMCT reduction.

The proposed UMCT addition mechanism for the formation of **52** is shown in eqn. (19). Abstraction of bromine by the silyl radical **53** generates the initial radical **54**. Because the bimolecular reduction of radical **54** by the silicon hydride is slow, this radical has a relatively long lifetime despite the high silicon hydride concentration. The radical addition step provides radical **55**, which now suffers the intramolecular hydrogen transfer reaction. In effect, initial radical **54** and adduct radical **55** are differentiated because one has a rapid intramolecular chain transfer reaction and the other does not.

Future prospects

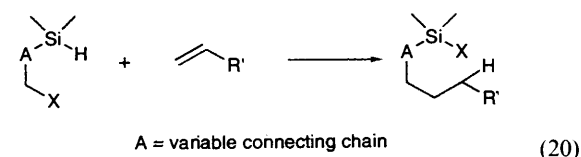
Selectivity is always a problem in radical reactions because all the radicals in a given chain are present simultaneously in the reaction medium. The use of unimolecular chain transfer reactions to impart selectivity on the reactions of organic radicals is a general method whose potential has not been generally recognized. One radical can be differentiated from all the others in the medium by giving it a rapid, unimolecular chain transfer option. This option does not have to be a fragmentation reaction (as with allylstannanes), but can be any type of chain transfer step.

UMCT reactions based on silicon hydrides are not a panacea for conducting bimolecular radical reactions, nor, for that matter, is any type of UMCT reaction. Bimolecular reactions with second-order rate constants below about 10^2 or $10^3 M^{-1} s^{-1}$ cannot be conducted in solution by any method. However, just like the reactions of allylstannanes, the UMCT reactions of silicon hydrides will both extend the types of reaction that can be conducted (especially in the moderate rate constant range of 10^3 to $10^5 M^{-1} s^{-1}$) and allow more practical reaction conditions. In short, more diverse types of bimolecular radical reaction will become possible. The conduction of relatively slow radical cyclization reactions should also be facilitated.

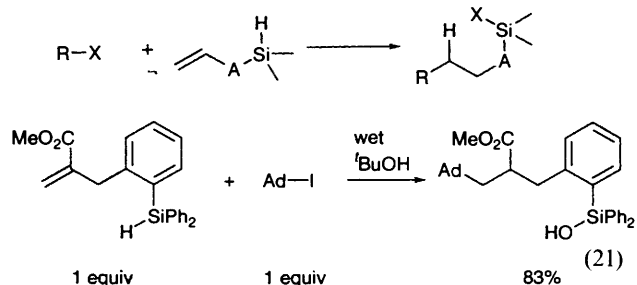
There are many potential applications of UMCT reactions of silicon hydrides for formation of carbon–carbon bonds in bimolecular radical addition reactions. We envision the development of two new classes of reagents based on whether the silicon hydride is located in the radical precursor or the radical acceptor. These are summarized in eqn. (20). Attention must still be paid to appropriate pairing of precursors and acceptors, so these classes might be further sub-divided by traditional polar and enthalpic effects. While there are as yet no examples of reagents with the silicon hydride in the radical precursor, the reagents in eqns. (17) and (18) are examples of radical acceptors designed for reactions with electrophilic (or enthalpic) radicals. We have also developed the first silicon hydride reagent designed as a nucleophilic radical acceptor. An example of a reaction with this reagent is shown in eqn. (21), and the details of these types of reaction are being communicated separately.²⁵

UMCT reagents based on silicon hydrides should also be of great value in planning tandem radical reactions. The ability to control the timing of the chain transfer step in complex radical

UMCT-based Precursor



UMCT-based Acceptor



sequences is crucial, and it is not a coincidence that many of the most sophisticated radical sequences are conducted with allylstannanes and related reagents.⁹ The introduction of UMCT silicon hydride reagents should expand the scope of existing classes of tandem reactions and permit the introduction of new classes.

Although the ability to control the timing of the chain transfer step is probably the most important feature of UMCT-based silicon hydride reagents, other uses can also be envisioned, especially in the area of stereocontrol. Intramolecular hydrogen transfer steps should often occur with high, predictable levels of stereoselectivity to both sp^2 and sp^3 radicals controlled by the connectivity between the radical and the silicon hydride. Stereoselectivities in inter- and intramolecular hydrogen transfer reactions may often be complementary.

Practical aspects of the UMCT silicon hydride reagents also merit attention. Although the reagents should provide alternatives for reactions now conducted by tin hydride, they lack the often-cited liabilities of tin (toxicity, difficulties in purification). Silyl radicals also have a different reactivity profile from tin radicals, (for example, they add much more readily to multiple bonds), so these reagents cannot be thought of as simple intramolecular analogues of Bu_3SnH . Analogies to TTMSH may be better, but there may still be differences. On the downside, there are now good catalytic procedures for using Bu_3SnH and TTMSH, but catalytic applications of UMCT reagents are not readily envisioned. Further, the silicon must be connected by a bond to one of the reactants and later removed by another step. In return for these extra steps, one gains all the practical advantages of the UMCT method, and reagents can be designed such that the residual silyl group serves a useful purpose. For example, *O*-silyl groups can be converted into mixed silyl acetals (as we did in the isolation procedure), and thereby continue to serve as alcohol protecting groups. *C*-Silyl groups are poised for Tamao oxidation, and there other ways that the diverse synthetic features of silicon can be tapped.

Ultimately, the scope of this method will be determined by the rate and selectivity of the intramolecular hydrogen transfer reaction, about which little is currently known. Synthetic applications will be greatly facilitated by studies of substituent effects on the rates of both intra- and inter-molecular hydrogen transfer reactions of silicon hydrides. Accurate measurements of absolute rate constants would be especially welcome. The rate constants for the 1,5-hydrogen transfer reactions of the current family of silicon hydrides may be a little too low. Further alteration of the substituents on silicon or the investigation of germanium or tin groups is clearly warranted.

However, high bimolecular rate constants for hydrogen transfer must be avoided because the standard premature trapping problem will ensue and selectivity will be compromised. Ideal reagents will have a relatively low rate constant for bimolecular hydrogen transfer (10^3 to 10^4 $M^{-1} s^{-1}$) and a high effective molarity.

Finally, the possibility of 'orthogonal chains' will occur repeatedly in UMCT reactions. While we do not yet see any obvious synthetic applications for orthogonal chains, we believe that the phenomenon itself is interesting. For example, can one design a precursor that has two efficient orthogonal chains? If so, then simply by changing the initiator, it may be possible to change the pathway by which the products are formed. Since the starting materials and products are the same, how can this change be detected? Is it possible to design precursors that will give different products from the same precursor simply by changing the initiator?

Experimental

Pent-4-enyldi-*tert*-butylsilane

t-BuLi in pentane (1.7 M, 9.23 ml, 15.7 mmol) was added dropwise to a solution of 5-iodopent-1-ene (1.47 ml, 7.4 mmol) in pentane-ether (3:2, 30 ml) at -78 °C. After 2 h at -78 °C, di-*tert*-butylchlorosilane (1.96 ml, 9.6 mmol) was added. The reaction mixture was allowed to warm to 23 °C over 2 h. After 48 h, the mixture was treated with aqueous ammonium chloride and extracted with ether. The ether layers were washed with water and then brine, and dried over magnesium sulfate. The solvent was evaporated off and the residue was purified by flash chromatography (hexane-EtOAc = 60:1) to give the silane (1.14 g, 72%); δ_H 5.80 (m, 1 H), 4.98 (m, 2 H), 3.31 (t, $J = 2.5$ Hz, 1 H), 2.11 (m, 2 H), 1.56 (m, 2 H), 1.01 (s, 18 H) and 0.63 (m, 2 H); δ_C 138.9, 114.7, 37.7, 28.8, 26.3, 18.9, 8.6; ν_{max}/cm^{-1} 2922, 2079, 1610, 1514, 1498 and 817.

4-Hydroxybutyldi-*tert*-butylsilane

Sodium periodate (2.88 g, 13.5 mmol) was added portionwise to a solution of the above silane (1.43 g, 6.7 mmol) in THF-water (30 ml, 3:1 by volume) containing catalytic amount of OsO_4 at 0 °C. After stirring at 23 °C for an additional 1 h (monitored by TLC), the reaction mixture was quenched with water (10 ml). The aqueous layer was extracted with ether. The combined ether layers were washed with water and brine, and dried over magnesium sulfate. The solvent was evaporated off and the residue was redissolved in ether (100 ml). Lithium aluminum hydride (0.26 g, 6.7 mmol) was added to the above solution at 0 °C. The reaction mixture was stirred for 1 h. The excess lithium aluminum hydride was destroyed by addition of water (40 ml). The aqueous layer was extracted with ether. The combined organic layer was filtered through a pad of Celite and dried over magnesium sulfate. The solvent was evaporated off and the residue was purified by flash chromatography (hexane-EtOAc = 5:1) to give the alcohol (0.52 g, 41%); δ_H 3.65 (t, $J = 6.7$ Hz, 2 H), 3.31 (t, $J = 2.5$ Hz, 1 H), 1.60 (m, 4 H), 1.00 (s, 18 H) and 0.67 (m, 2 H); δ_C 62.7, 36.7, 28.9, 23.1, 18.9 and 8.9.

4-Iodobutyldi-*tert*-butylsilane (12c)

Compound 12c was prepared with 4-hydroxybutyldi-*tert*-butylsilane (0.81 g, 4.3 mmol), $MsCl$ (0.67 ml, 8.6 mmol), Et_3N (1.8 ml, 9.0 mmol) and NaI (1.29 g, 8.6 mmol). Purification by flash chromatography (pure hexanes) afforded 12c (1.15 g, 82%); δ_H 3.31 (t, $J = 2.5$ Hz, 1 H), 3.20 (t, $J = 7$ Hz, 2 H), 1.85 (m, 2 H), 1.58 (m, 2 H), 1.01 (s, 18 H) and 0.62 (m, 2 H); δ_C 31.1, 28.9, 27.7, 18.9, 7.9 and 6.9; m/z 269, 227, 185, 171, 99, 85 and 73 [HRMS calc. for $C_8H_{18}SiI$ ($M - C_4H_9$) 269.0243. Found 269.0247].

2-Iodo-1-diisopropylsilyloxymethylbenzene (6a)

Diisopropylsilane (0.59 ml, 3.4 mmol) was added dropwise to a

solution of 2-iodobenzyl alcohol (0.67 g, 2.9 mmol), Et₃N (0.8 ml, 5.9 mmol) and a catalytic amount of DMAP in THF (15 ml) at 23 °C. After being stirred at 23 °C for 12 h, the reaction was quenched with water and extracted with ether. The ether layers were washed with brine, dried with magnesium sulfate, filtered and concentrated. The resulting oil was purified by flash chromatography (hexane–EtOAc = 60:1) to give **6a** (0.94 g, 93%); δ_{H} 7.85–6.91 (m, 5 H), 4.79 (s, 2 H), 4.32 (s, 1 H) and 1.12 (m, 14 H); δ_{C} 142.6, 138.8, 128.7, 128.2, 127.5, 96.0, 71.6, 17.6, 17.4 and 12.5; m/z 305, 217, 135, 109, 91, 81, 69 and 55 [HRMS calc. for C₁₀H₁₄OSi (*M* – C₃H₇) 304.9847. Found 304.9839].

Deuterium labelling experiment of **6a**

Compound **6a** (0.14 g, 0.2 mmol, 0.01 M), tributyltin deuteride (0.25 ml, 0.3 mmol) and AIBN (13.4 mg, 0.04 mmol) were heated at 80 °C for 8 h. The crude mixture was treated with DBU–I₂. The ether solution was concentrated and the residue was subjected to ²H NMR analysis to determine the sites of deuteration without further purification.

1-(4-Chlorobutyl)silacyclopentane

t-BuLi in pentane (1.7 M, 29.2 ml, 49.6 mmol) was added dropwise to a solution of 1-chloro-4-iodobutane (5.17 g, 23.6 mmol) in pentane–ether (3:2, 50 ml) at –78 °C. After 2 h at –78 °C, cyclopentylchlorosilane (6.2 ml, 47.2 mmol) was added. The reaction mixture was allowed to warm to 23 °C over 2 h. After being stirred at 23 °C for 4 h, the mixture was cooled to 0 °C and lithium aluminium hydride (0.66 g, 17.7 mmol) was added. After 1 h, the mixture was treated with aqueous ammonium chloride and extracted with ether. The ether layers were washed with water and brine, and dried over magnesium sulfate. The solvent was evaporated off and the residue was purified by flash chromatography (pure hexanes) to give the silane (3.15 g, 75%); δ_{H} 3.97 (m, 1 H), 3.55 (t, *J* = 7 Hz, 2 H), 1.85 (m, 2 H), 1.53 (m, 6 H) and 0.68 (m, 6 H); δ_{C} 44.7, 35.8, 27.3, 22.2 and 11.7.

1-(4-Iodobutyl)silacyclopentane **5b**

Sodium iodide (7.43 g, 49.5 mmol) was added to a solution of the above silane (2.19 g, 12.3 mmol) in acetone at 23 °C. The mixture was refluxed for 12 h, after which the acetone was evaporated off and the reaction mixture was diluted with water. The aqueous layer was extracted with ether. The ether layers were washed with a 10% solution of Na₂S₂O₃, dried with magnesium sulfate, filtered and concentrated. The resulting oil was purified by flash chromatography (pure hexanes) to give **5b** (2.67 g, 81%); δ_{H} 3.97 (m, 1 H), 3.20 (t, *J* = 7 Hz, 2 H), 1.86 (m, 2 H), 1.57 (m, 6 H) and 0.70 (m, 6 H); δ_{C} 36.5, 27.3, 25.8, 11.3, 8.9 and 6.8; m/z 267, 211, 183, 155, 141, 127, 99, 85 and 57 [HRMS calc. for C₈H₁₇SiI 268.0144. Found 268.0136].

2-Iodo-1-di-*tert*-butylsilyloxymethylbenzene (**6c**)

Compound **6c** was prepared following the procedure for **6a** by using 2-iodobenzyl alcohol (1.69 g, 7.2 mmol), di-*tert*-butylchlorosilane (1.6 ml, 0.79 mmol) and triethylamine (2.0 ml, 14.4 mmol). Purification by flash chromatography (hexane–EtOAc = 60:1) afforded **6c** (2.54, 93%); δ_{H} 7.83 (d, *J* = 1 Hz, 1 H), 7.80 (d, *J* = 1 Hz, 1 H), 7.42 (t, *J* = 1 Hz, 1 H), 6.99 (t, *J* = 1 Hz, 1 H), 4.80 (s, 2 H), 4.20 (s, 2 H) and 1.08 (s, 18 H); δ_{C} 142.7, 138.8, 128.6, 128.2, 127.5, 95.9, 73.1, 27.4 and 20.4; $\nu_{\text{max}}/\text{cm}^{-1}$ 3090, 2930, 2856, 2089, 1635, 1506, 1440, 1373, 1203, 1115, 1091, 937, 825 and 744; m/z 375, 335, 319, 291, 217, 135, 90, 74 and 59 [HRMS calc. for C₁₁H₁₆OSi (*M* – C₄H₉) 319.0015. Found 319.003].

UMCT reaction of **6c**

Bu₃SnH (0.03 ml, 0.09 mmol), and catalytic amount of AIBN (added in two portions at 1 h intervals) were added to a solution of **6c** in refluxing benzene. The reaction was monitored by GC. The UMCT reaction of **6c** provided the silyl iodide **9c** and the

reduced product **7c** in a ratio of 11:1 (GC). After **6c** was consumed (3 h), the mixture was cooled to 23 °C and Et₃N (1 ml) and methanol (1 ml) were added (added in several portions). When the silyl iodide was consumed (monitored by GC), the benzene was evaporated off and the residue was purified by flash chromatography (hexane–EtOAc = 8:1) to provide **10c** (0.19 g, 68%). The structure of reduced product **7c** was proved by comparison with an authentic sample.

Benzyl (methoxydi-*tert*-butyl)silyl ether (10c**)**. δ_{H} 7.40 (m, 5 H), 5.01 (s, 1 H), 3.66 (s, 3 H) and 1.09 (s, 18 H); δ_{C} 141.4, 128.3, 126.9, 125.8, 65.6, 52.4, 28.0 and 21.4; $\nu_{\text{max}}/\text{cm}^{-1}$ 3028, 2936, 2858, 1630, 1573, 1496, 1375, 1363, 1207, 1188, 1099, 937, 827 and 727; m/z 223, 191, 181, 151, 91, 65 and 59 [HRMS calc. for C₁₂H₁₉O₂Si (*M* – C₄H₉), 223.1154. Found 223.1144].

Di-*tert*-butylsilyloxymethylbenzene (7c**)**. δ_{H} 7.42 (m, 5 H), 4.95 (s, 2 H) and 4.20 (s, 2 H); δ_{C} 141.1, 128.3, 127.1, 126.4, 68.9, 27.4 and 20.3; $\nu_{\text{max}}/\text{cm}^{-1}$ 3032, 2963, 2856, 2085, 1650, 1560, 1496, 1375, 1209, 1097, 1068, 1010, 937, 825 and 729; m/z 250, 193, 165, 91, 65, 57 [HRMS calc. for C₁₁H₁₇OSi (*M* – C₄H₉OSi) 193.1049. Found 193.1032].

1-Iodo-3-di-*tert*-butylsilyloxypropane (**2c**)

Compound **2c** was prepared following the procedure for **6a** by using 3-bromopropan-1-ol (2 ml, 22.1 mmol), di-*tert*-butylchlorosilane (5.8 ml, 28.4 mmol) and triethylamine (6.2 ml, 44.2 mmol). Purification by flash chromatography (hexane–EtOAc = 60:1) afforded the bromide (6.09, 98%). Sodium iodide (2.83 g, 18.9 mmol) was added to a solution of this bromide (1.33 g, 4.7 mmol) in acetone at 23 °C. The mixture was stirred at 23 °C for 1 h, after which the acetone was evaporated off and the reaction mixture was diluted with water. The aqueous layer was extracted with ether. The ether layers were washed with 10% solution of Na₂S₂O₃, dried with magnesium sulfate, filtered and concentrated. The resulting oil was purified by flash chromatography (hexane–EtOAc = 60:1) to give **2c** (1.28 g, 82.5 mmol) as a colourless oil: δ_{H} 4.00 (s, 1 H), 3.81 (t, *J* = 6 Hz, 2 H), 3.31 (t, *J* = 7 Hz, 2 H), 2.05 (m, 2 H) and 1.00 (s, 18 H); δ_{C} 66.3, 36.2, 27.3, 20.2 and 3.6; $\nu_{\text{max}}/\text{cm}^{-1}$ 2930, 2856, 2087, 1387, 1364, 1099 and 825; m/z 327, 271, 229, 185, 171, 87, 73 and 57 [HRMS calc. for C₇H₁₆OSi (*M* – C₄H₉) 271.0015. Found 271.0056].

1-Di-*tert*-butylsilyloxypropane (4c**)**. δ_{H} 3.98 (s, 1 H), 3.70 (t, *J* = 7 Hz, 2 H), 1.57 (m, 2 H), 1.00 (s, 18 H) and 0.92 (t, *J* = 7 Hz, 3 H); δ_{C} 68.9, 27.3, 25.9, 20.2 and 10.4; $\nu_{\text{max}}/\text{cm}^{-1}$ 2933, 2851, 2085 and 1368; m/z 202, 145, 117, 103, 87, 75 and 61; [HRMS calc. for C₇H₁₇OSi (*M* – C₄H₉) 145.1048. Found 145.1038].

Propyl (methoxydi-*tert*-butyl)silyl ether (17c**)**. δ_{H} 3.80 (t, *J* = 7.1 Hz, 2 H), 3.65 (s, 3 H), 1.59 (m, 2 H), 1.02 (s, 18 H) and 0.95 (t, *J* = 7.4 Hz, 3 H); δ_{C} 65.6, 52.1, 27.9, 26.1, 21.2 and 10.4.

Butyl-di-*tert*-butylsilane (16c**)**. δ_{H} 3.33 (t, *J* = 2.5 Hz, 1 H), 1.48 (m, 4 H), 1.02 (s, 18 H), 0.91 (t, *J* = 7.1 Hz, 3 H) and 0.64 (m, 2 H); δ_{C} 29.3, 28.9, 26.8, 18.9, 13.9 and 8.9.

Butyl-di-*tert*-butylsilyl methyl ether (19c**)**. δ_{H} 3.61 (s, 3 H), 1.49 (m, 4 H), 1.01 (s, 18 H), 0.90 (t, *J* = 7.1 Hz, 3 H) and 0.64 (m, 2 H); δ_{C} 52.7, 28.4, 27.4, 26.8, 21.5, 13.8 and 10.4; m/z 173, 131, 117, 97, 83, 75 and 57 [HRMS calc. for C₉H₂₁OSi (*M* – C₄H₉) 173.1362. Found 173.1359].

[3-Iodo-1-(di-*tert*-butylsilyloxy)propyl]benzene (**11c**)

Compound **11c** was prepared following the procedure for **6a** by using 3-iodo-1-phenylpropan-1-ol (1.51 g, 7.0 mmol), di-*tert*-butylchlorosilane (1.56 ml, 8.5 mmol), triethylamine (1.96 ml, 14 mmol) and sodium iodide (2.29 g, 15.3 mmol). Purification by flash chromatography (hexane–EtOAc = 80:1) afforded **11c** (2.39 g, 81%); δ_{H} 7.28 (m, 5 H), 4.87 (t, *J* = 6.0 Hz, 1 H), 4.04 (s, 1 H), 3.23 (m, 1 H), 3.00 (m, 1 H), 2.32 (m, 2 H), 1.06 (s, 9 H) and 0.86 (s, 9 H); δ_{C} 142.8, 128.3, 127.6, 126.4, 77.7, 44.2, 27.6, 27.2, 20.1 and 2.0; m/z 347, 319, 149, 117, 91, 75 and 61 [HRMS calc. for C₁₃H₂₀SiI (*M* – C₄H₉) 347.0328. Found 347.0305].

(1-Di-*tert*-butylsilyloxypropyl)benzene (14c). δ_{H} 7.35 (m, 5 H), 4.75 (t, $J = 6$ Hz, 2 H), 4.08 (s, 1 H), 1.87 (m, 2 H), 1.12 (s, 9 H) and 0.86 (t, $J = 7$ Hz, 3 H); δ_{C} 144.3, 127.9, 126.9, 126.5, 79.3, 32.9, 27.6, 27.3, 20.2 and 20.1; $\nu_{\text{max}}/\text{cm}^{-1}$ 3021, 2930, 2856, 2083, 1643, 1612, 1572, 1493, 1361, 1057, 1008, 920, 848, 825 and 748; m/z 278, 249, 221, 179, 103, 91, 75 and 61 [HRMS calc. for $\text{C}_{13}\text{H}_{21}\text{OSi}$ ($M - \text{C}_4\text{H}_9$) 221.1362. Found 221.1314].

Methoxy-di-*tert*-butylsilyl 1-phenylpropyl ether (18c). δ_{H} 7.40 (m, 5 H), 5.02 (m, 2 H), 3.57 (s, 3 H), 1.90 (m, 2 H), 1.16 (s, 9 H) and 0.87 (t, $J = 7$ Hz, 3 H); δ_{C} 144.8, 127.9, 126.9, 76.5, 52.4, 33.4, 28.2, 28.0, 21.4, 21.3 and 9.1; $\nu_{\text{max}}/\text{cm}^{-1}$ 3028, 2936, 2858, 1651, 1630, 1537, 1493, 1387, 1365, 1190, 1107, 1061, 937, 920, 898, 827 and 748; m/z 279, 251, 160, 133, 117, 91, 75 and 59 [HRMS calc. for $\text{C}_{14}\text{H}_{23}\text{O}_2\text{Si}$ ($M - \text{C}_4\text{H}_9$) 251.1467. Found 251.1490].

1-(Tetrahydropyranloxy)butyldiphenylsilane

Pent-4-enyl-di-*tert*-butylsilane was prepared by using the iodide (0.86 g, 3.0 mmol), diphenylchlorosilane (0.73 ml, 6.3 mmol) and *t*-BuLi (1.7 M, 3.74 ml, 6.36 mmol). Purification by flash chromatography (hexane–EtOAc = 15:1) afforded the silane (0.89 g, 87%): δ_{H} 7.12 (m, 4 H), 7.39 (m, 6 H), 4.89 (t, $J = 4$ Hz, 1 H), 4.56 (m, 1 H), 3.79 (m, 2 H), 3.51 (m, 2 H), 1.61 (m, 10 H) and 1.18 (m, 2 H); δ_{C} 135.2, 134.5, 129.9, 98.8, 67.0, 62.3, 35.0, 30.8, 25.5, 21.1, 19.6 and 11.9; $\nu_{\text{max}}/\text{cm}^{-1}$ 3067, 3013, 2936, 2851, 2118, 1645, 1587, 1352, 1261, 1199, 1116, 1076, 1030, 985, 935, 902, 870, 810 and 733; m/z 283, 263, 254, 221, 183, 85, 75, 55 and 49 [HRMS calc. for $\text{C}_{15}\text{H}_{23}\text{O}_2\text{Si}$ ($M - \text{C}_6\text{H}_5$) 263.1467. Found 263.1451].

4-Iodobutyldiphenylsilane (20d)

A solution of I_2 (0.99 g, 3.9 mmol) in CH_2Cl_2 (5 ml) was added with stirring to a solution of 1,2-bis(diphenylphosphino)ethane (DPPE) (1.56 g, 3.9 mmol) in CH_2Cl_2 (25 ml) at 0 °C under argon atmosphere. The mixture was stirred at 0 °C for 30 min, after which a solution of the above THP ether (1.06 g, 3.1 mmol) in CH_2Cl_2 (5 ml) was added and the reaction was allowed to warm to 23 °C. Stirring was continued for 2 h, when ether (70 ml) was added followed by pentane (140 ml) to precipitate the undesired by-products. The mixture was filtered through a thin pad of silica gel and the solids were washed with ether–pentane (1:2, 2 × 25 ml) and the combined filtrate was concentrated. The residue was purified by flash chromatography (pure hexanes) to provide **20d** (0.62 g, 54%): δ_{H} 7.64 (m, 4 H), 7.42 (m, 6 H), 4.95 (t, $J = 4$ Hz, 1 H), 3.21 (t, $J = 7$ Hz, 2 H), 1.95 (m, 2 H), 1.64 (m, 2 H) and 1.22 (m, 2 H); δ_{C} 135.1, 134.1, 129.7, 128.1, 36.6, 25.4, 11.1 and 6.4; $\nu_{\text{max}}/\text{cm}^{-1}$ 3030, 2922, 2851, 2116, 1635, 1576, 1506, 1259, 1196, 1111 and 800; m/z 365, 289, 274, 259, 233, 183, 161 and 105 (HRMS calc. for $\text{C}_{16}\text{H}_{19}\text{I}\text{Si}$ 363.0301. Found 363.0313).

Butyldiphenylsilane (22d). δ_{H} 7.65 (m, 4 H), 7.45 (m, 6 H), 4.95 (t, $J = 3.6$ Hz, 1 H), 1.52 (m, 4 H), 1.26 (m, 2 H) and 0.97 (t, $J = 7.1$ Hz, 3 H); δ_{C} 135.2, 134.7, 129.6, 128.0, 26.7, 26.3, 13.8 and 11.9.

Butyl(methoxy)diphenylsilane (23d). δ_{H} 7.66 (m, 4 H), 7.44 (m, 6 H), 3.60 (s, 3 H), 1.44 (m, 4 H), 1.23 (m, 2 H) and 0.93 (t, $J = 7$ Hz, 3 H); δ_{C} 134.9, 134.7, 129.9, 127.9, 51.4, 26.5, 25.2, 13.8 and 13.3; $\nu_{\text{max}}/\text{cm}^{-1}$ 3069, 2957, 2856, 1642, 1589, 1552, 1508, 1427, 1377, 1300, 1261, 1188, 1160, 1086, 997, 870, 787 and 735; m/z 269, 213, 192, 183, 137, 105, 91, 75 and 59 [HRMS calc. for $\text{C}_{13}\text{H}_{13}\text{SiO}$ ($M - \text{C}_4\text{H}_9$) 213.0735. Found 213.0727].

Hex-5-enyl di-*tert*-butylsilyl ether (38c). δ_{H} 5.82 (m, 1 H), 4.98 (m, 2 H), 3.98 (s, 1 H), 3.75 (t, $J = 6$ Hz, 2 H), 2.07 (s, 2 H), 1.58 (m, 4 H), 1.00 (s, 18 H); δ_{C} 138.9, 114.5, 67.0, 33.6, 32.2, 27.4, 25.2 and 20.2; $\nu_{\text{max}}/\text{cm}^{-1}$ 3019, 2928, 2855, 2081, 1097 and 823; m/z 241, 199, 185, 143, 75, 61 and 55 [HRMS calc. for $\text{C}_{10}\text{H}_{21}\text{OSi}$ ($M - \text{C}_4\text{H}_9$) 185.1361. Found 185.1349].

Hept-6-enyl(di-*tert*-butyl)silane (40c). δ 3.65 (t, $J = 6.2$ Hz, 2 H), 3.31 (t, $J = 2.6$ Hz, 1 H), 1.62–1.55 (m, 5 H), 1.01 (s, 18 H) and 0.65 (m, 2 H).

(1-Di-*tert*-butylsilyloxyhex-5-enyl)benzene (39c). δ_{H} 7.29 (m, 5 H), 5.74 (m, 1 H), 4.90 (m, 2 H), 4.76 (t, $J = 6$ Hz, 1 H), 4.02 (s, 1 H), 2.03 (m, 2 H), 1.77 (m, 2 H), 1.38 (m, 2 H), 1.06 (s, 9 H) and 0.86 (s, 9 H); δ_{C} 144.5, 138.8, 128.0, 127.0, 126.4, 114.5, 77.9, 39.7, 33.8, 27.6, 27.3, 24.4 and 20.1; $\nu_{\text{max}}/\text{cm}^{-1}$ 3067, 3030, 2963, 2856, 2085, 1641, 1493, 1469, 1387, 1363, 1088, 1010, 937, 910, 825 and 754; m/z 318, 303, 261, 249, 219, 165, 137, 117, 91, 75 and 61 (HRMS calc. for $\text{C}_{16}\text{H}_{25}\text{OSi}$ 261.1674. Found 261.1696).

Allyl(butyl)diphenylsilane (42)

Allylmagnesium bromide (6.46 ml, 6.5 mmol) was added to a solution of diphenylsilane (1 ml, 5.4 mmol) in THF (20 ml) at 23 °C under argon. After being refluxed for 12 h, the reaction mixture was cooled to 0 °C and *n*-BuLi (1.6 M, 3.7 ml, 5.9 mmol) was added. After being stirred at 23 °C for 4 h, the mixture was treated with aqueous ammonium chloride and extracted with ether. The ether layers were washed with water and brine, and dried over magnesium sulfate. The solvent was evaporated off and the residue was purified by flash chromatography (hexane–EtOAc = 60:1) to give **42** (1.36 g, 90%): δ_{H} 7.59 (m, 4 H), 7.43 (m, 6 H), 5.85 (m, 1 H), 4.95 (m, 3 H), 2.17 (d, $J = 7$ Hz, 2 H), 1.44 (m, 4 H), 1.19 (m, 4 H) and 0.93 (t, $J = 7$ Hz, 3 H); δ_{C} 135.8, 134.9, 134.2, 129.3, 127.8, 114.3, 26.7, 25.8, 20.6, 13.8 and 11.9; m/z 280, 239, 183, 145, 119, 105, 91, 79 and 53 (HRMS calc. for $\text{C}_{16}\text{H}_{19}\text{Si}$ 239.1256. Found 239.1249).

Hept-6-enyl(diphenyl)silane (41d)

A solution of dilithium tetrachlorocuprate (13.5 ml, 1.2 mmol) was added dropwise to a solution of 1-chloro-4-iodobutane (5.38 g, 24.5 mmol) and allylmagnesium bromide (27 ml, 26.9 mmol) at 0 °C under argon. After being stirred at 0 °C for 3 h, the mixture was treated with aqueous ammonium chloride and extracted with ether. The ether layers were washed with water and brine, and dried over magnesium sulfate. The solvent was evaporated off and the residue was purified by flash chromatography (pure hexanes) to give the iodide (3.98 g, 72%).

Compound **41d** was prepared following the procedure for **12c** by using diphenyl(chloro)silane (1.63 ml, 8.3 mmol), *t*-BuLi (1.7 M, 8.1 ml, 13.7 mmol) and the above iodide (1.55 g, 6.9 mmol). Purification by flash chromatography (pure hexanes) afforded **41d** (1.56 g, 81%): δ_{H} 7.64 (m, 4 H), 7.46 (m, 6 H), 5.86 (m, 1 H), 5.01 (m, 2 H), 4.94 (2 H), 4.94 (t, $J = 4$ Hz, 1 H), 2.07 (m, 2 H), 1.54 (m, 6 H) and 1.21 (m, 2 H); δ_{C} 139.1, 135.1, 134.6, 129.5, 128.0, 114.3, 33.7, 32.7, 28.2, 24.3 and 12.2; $\nu_{\text{max}}/\text{cm}^{-1}$ 3067, 3003, 2116, 1639, 1587, 1485, 1427, 1261, 1161, 1115, 995, 908, 808 and 731.

(1-Di-*tert*-butylsilyloxybut-3-enyl)benzene (45c)

Allylmagnesium bromide (49 ml, 63.9 mmol) was added dropwise to a solution of benzaldehyde (5 ml, 49.1 mmol) in ether (100 ml) at 0 °C. After being stirred at 23 °C for 6 h, the reaction was quenched with aqueous ammonium chloride and extracted with ether. The ether layers were washed with brine, dried with magnesium sulfate, filtered and concentrated. Purification by flash chromatography (hexane–EtOAc = 5:1) afforded the alcohol (5.94 g, 82%). The resulting alcohol was protected following the procedure for **35** by using the alcohol (1.75 g, 11.8 mmol), di-*tert*-butyl(chloro)silane (2.86 ml, 14.2 mmol), triethylamine (2.46 ml, 17.7 mmol) and DMAP (cat.). Purification by flash chromatography (hexane–EtOAc = 60:1) afforded **45c** (3.05 g, 89%): δ_{H} 7.31 (m, 5 H), 5.74 (m, 1 H), 5.03 (m, 2 H), 4.84 (t, $J = 6.2$ Hz, 1 H), 4.08 (s, 1 H), 2.59 (m, 2 H), 1.09 (s, 9 H) and 0.89 (s, 9 H); δ_{C} 143.9, 134.6, 128.0, 127.2, 126.5, 117.3, 77.9, 44.8, 27.6, 27.3 and 20.2; m/z 289, 273, 249, 233, 191, 165, 149, 131, 91 and 75 [HRMS calc. for $\text{C}_{14}\text{H}_{21}\text{SiO}$ ($M - \text{C}_4\text{H}_9$) 233.1361. Found 233.1352].

Phenyl 6-hydroxy-6-phenylhexanoate (47). δ_{H} 7.36 (m, 8 H), 7.09 (m, 2 H), 4.75 (m, 1 H), 2.60 (t, $J = 7.3$ Hz, 2 H), 1.82 (m, 5

H) and 1.51 (m, 2 H); δ_C 172.2, 150.7, 144.7, 129.4, 128.6, 127.7, 125.9, 125.8, 121.6, 74.4, 38.7, 34.3, 25.3 and 24.8; m/z 190, 173, 145, 130, 107, 91, 79 and 55 [HRMS calc. for $C_{12}H_5O_2$ ($M - C_6H_5O$) 191.1072. Found 191.1077].

4-Di-*tert*-butylsilyloxy-4-methylpent-1-ene (48c)

Compound **48c** was prepared by using the corresponding alcohol (2.46 g, 24.6 mmol), di-*tert*-butyl(chloro)silane (7.46 ml, 36.9 mmol), imidazole (2.51 g, 36.9 mmol), sodium iodide (3.69 g, 24.6 mmol) and DMAP (cat.). Purification by flash chromatography (pure hexanes) afforded **48c** (2.44 g, 41%): δ_H 5.86 (m, 1 H), 5.03 (m, 2 H), 4.18 (s, 1 H), 2.27 (d, $J = 7.2$ Hz, 2 H), 1.25 (s, 6 H) and 0.99 (s, 18 H); δ_C 135.5, 117.1, 73.8, 49.8, 29.9, 27.8 and 19.7; m/z 227, 201, 185, 143, 115, 99, 85, 75 and 61 [HRMS calc. for $C_{10}H_{21}SiO$ ($M - C_4H_9$) 185.1361. Found 185.1357].

Bimolecular radical addition reaction of 48c

Bis(tributyltin) (0.04 ml, 0.08 mmol) was added to a solution of **48c** (0.38 g, 1.6 mmol) and the bromide **46** (0.41 g, 1.9 mmol) in benzene (6.4 ml). The mixture was heated to 80 °C and then irradiated with a UV lamp. When the reaction was complete (12 h), the mixture was cooled to 23 °C and diluted with THF (10 ml). TBAF (1 M, 4.7 ml, 4.7 mmol) was added to the above mixture. After 2 h, the mixture was concentrated and the residue was purified by flash chromatography (hexane–EtOAc = 3:1) to provide **51** (0.24 g, 64%).

Phenyl 4-bromo-5-*tert*-butyldimethylsilyloxy-6-methylheptanoate (50). δ_H 7.55 (m, 2 H), 7.42 (m, 1 H), 7.25 (m, 2 H), 4.55 (m, 1 H), 3.00 (m, 2 H), 2.34 (m, 3 H), 1.52 (s, 3 H), 1.45 (s, 3 H) and 1.03 (s, 9 H); δ_C 171.4, 150.7, 125.9, 121.6, 73.7, 54.4, 51.9, 35.6, 32.9, 31.7, 28.9, 25.9, 18.1 and –1.9; m/z 373, 217, 195, 173, 123, 95, 73 and 65 [HRMS calc. for $C_{16}H_{24}O_3Si^{79}Br$ 371.0678. Found 371.0679].

Phenyl 6-hydroxy-6-methylheptanoate (51). δ_H 7.42 (m, 2 H), 7.29 (m, 1 H), 7.11 (m, 2 H), 2.63 (t, $J = 7.3$ Hz, 2 H), 1.82 (m, 1 H), 1.55 (m, 4 H) and 1.27 (s, 6 H); δ_C 172.2, 150.8, 129.5, 125.8, 121.6, 70.9, 43.5, 34.4, 29.3, 25.5 and 23.9; ν_{max}/cm^{-1} 3387br, 2912, 1738, 1628, 1581, 1516, 1479, 1360, 1184, 1061, 922, 898, 748, 684 and 659; m/z (CI) 254, 236, 219, 160, 143 and 75.

Acknowledgements

We thank the National Institutes of Health and NATO for partial funding of this work. We also thank Dr C. Chatgililoglu for helpful discussions.

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Paper 5 05083I

Received 31st July 1995

Accepted 30th August 1995