Pergamon

Tetrahedron 55 (1999) 3327–3336

TETRAHEDRON

Formation of cyclopropanes by homolytic substitution reactions of 3-iodopropyl radicals: Preparative and rate studies‡

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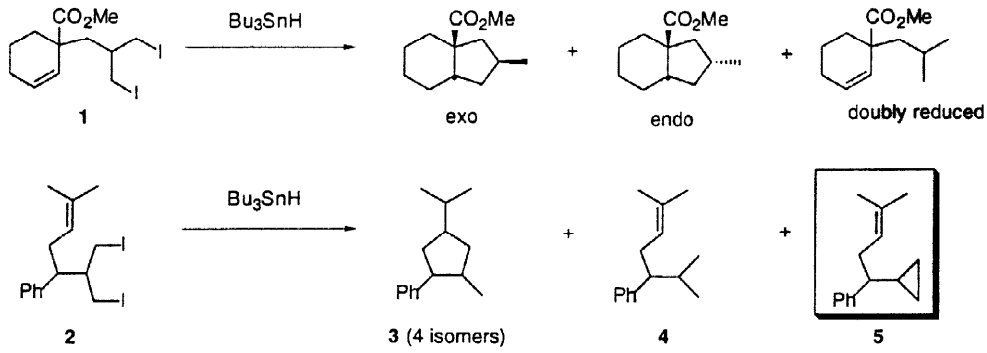
Received 5 October 1998; revised 22 October 1998; accepted 23 October 1998

Summary: *Reduction of 2-substituted 1,3-diiodopropane derivatives with tin hydride provides substituted cyclopropanes. The reaction occurs through a homolytic substitution of the 3-iodopropyl radical, which has a rate constant of about 5 x 10^5 s^{-1} at 80°C.* © 1999 Elsevier Science Ltd. All rights reserved.

Introduction

The vast majority of radical cyclizations to make new carbon-carbon bonds can be classed as addition reactions of radical to multiple bonds.[1] Examples of the other class—cyclization by homolytic substitution (SH2)—are far less common.[2] Our recent work on stereoselection at the steady state has used radical cyclizations to alkenes to identify and study new principles of dynamic stereocontrol in steady state processes.[3] For example, cyclization of **1** with tin hydride gives ratios of exo, endo, and doubly reduced products that vary with the tin hydride concentration and that can be understood in terms of a convergent kinetic model (Scheme 1).[3] In extending this process to acyclic radical precursors, we studied the cyclizations of **2** as a function of tin hydride concentration.[4] These reactions proved quite complex. In addition to the four stereoisomers of **3** and the doubly reduced product **4**, there was a sixth product that grew with decreasing tin hydride concentration. We identified this product as cyclopropane **5**, arising from a homolytic substitution of an intermediate 3-iodoalkyl radical.

Scheme 1



‡In memory of Sir Derek Barton, a pioneer in organic radical chemistry

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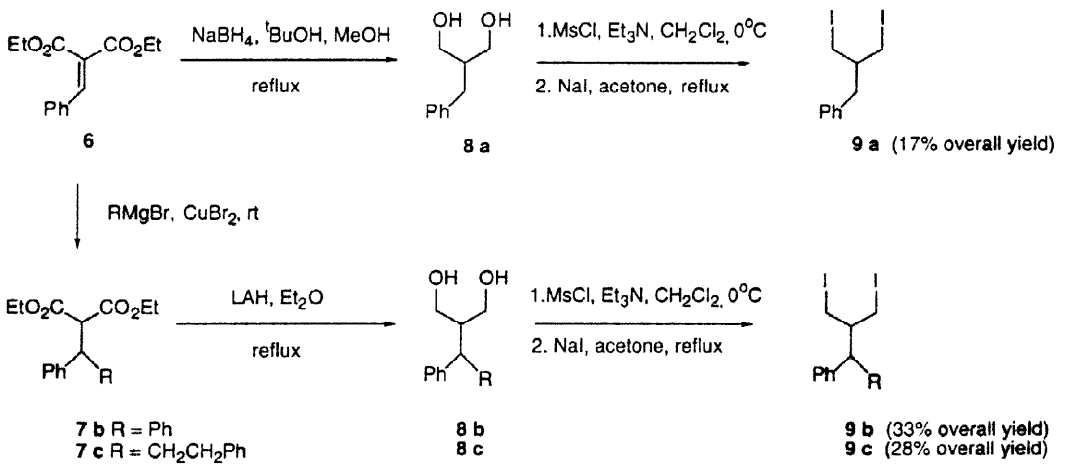
PII: S0040-4020(98)01144-2

The formation of cyclopropanes from 3-iodopropyl radicals was discovered about 30 years ago,[5,6] but in the interim the reaction has received very little attention. Most relevent to our work, in 1973 Newman and coworkers reported a single example of a tin hydride reductive cyclization of a 2,2-disubstituted 1,3-diiodopropane to give a cyclopropane.[5c] Given the complex nature of the kinetic analysis in stereoselective reaction of dihalides like **2**, we deemed it important to design radical precursors in which homolytic substitution could not compete with radical addition to alkene. To do this, we needed information about the rate constant for radical cyclizations of representative 3-iodopropyl radicals, and we report herein the results of a study to measure these rate constants. Typical 3-iodopropyl radicals cyclize with rate constants $k_C \approx 1\text{-}5 \times 10^5\ s^{-1}$ at 80°C. We are now using the information in this study to "design out" the possibility of cyclopropane formation in stereoselectivity experiments, but it is equally possible to use it to "design in" cyclopropane formation when such a transformation is desirable.

Results and Discussion

Primarily interested in dihalides like **1** and **2**, we selected precursors **9a-c** for the kinetic studies by tin hydride reduction.[7] These compounds are readily synthesized as shown in Scheme 2. Reduction of benzylidene malonate **6** followed by mesylation and iodide displacement provided the known diiodide **9a**.[5e] Conjugate addition to **6** followed by an analogous sequence of reduction, mesylation, and iodination provided compounds **9b** and **9c** with additional branches in the chain appended to the 1,3-diiodopropane backbone.

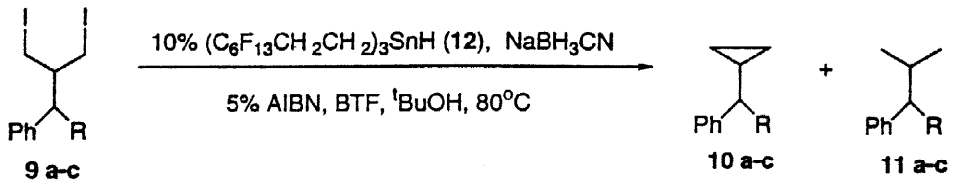
Scheme 2



Prior to kinetic experiments, standard samples of the expected products were made. Reductions of the dimesylates with $LiAlH_4$ provided the doubly reduced propane derivatives **11a-c** free from the cyclopropanes **10a-c**. To make the cyclopropanes **10a-c**, reductions of the diiodides **9a-c** were conducted under preparative conditions by using fluorous tin hydride **12** under a standard catalytic procedure.[8] The easy removal of the tin hydride and the inorganic products by three-phase liquid extraction was helpful in isolating these volatile products. The results of these experiments are shown in Scheme 3; the cyclopropane **10** was the major product in all cases alongside 5-8% of the doubly reduced propane derivative **11**. All three of the cyclopropanes are

known,[9] and we did not attempt to separate them from the minor propane components but simply used the mixtures as NMR and GC standards.

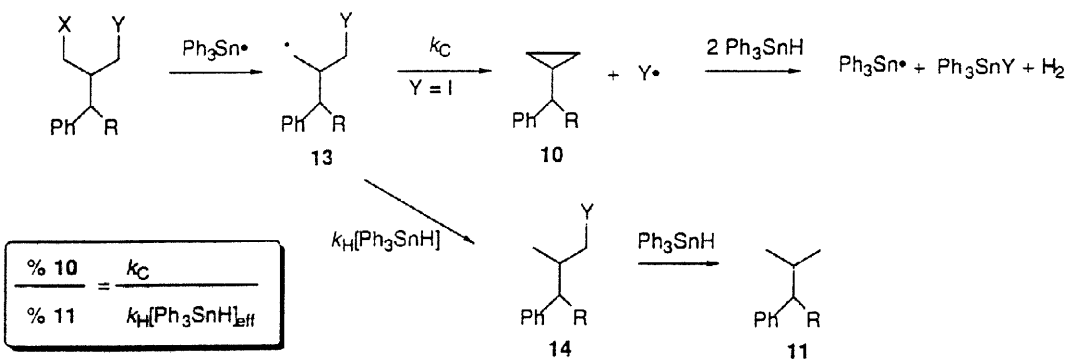
Scheme 3



R	[12]	Cyclized	Reduced	Yield
H (9 a)	0.002M	95% (10 a)	5% (11 a)	90%
Ph (9 b)	0.002M	94% (10 b)	6% (11 b)	73%
CH_2CH_2Ph (9 c)	0.002M	92% (10 c)	8% (11 c)	82%

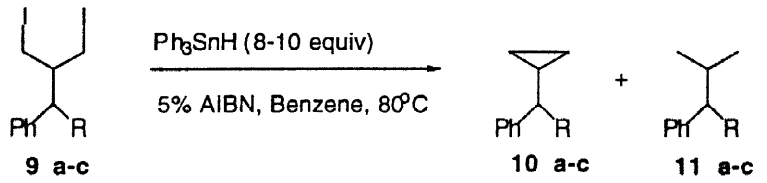
Data from the kinetic experiments were analyzed based on the mechanistic framework shown in Scheme 4 (X = Y = I). Abstraction of iodine from diiodide **9** provides a 3-iodopropyl radical **13** that partitions between cyclization and reduction with tin hydride. We assume that the iodine radical generated in the homolytic substitution ultimately consumes a second equivalent of tin hydride. The monoiodide **14** resulting from reaction of **13** with tin hydride is reductively deiodinated to give the propane **11**. The iodine atoms in **9c** are diastereotopic and can in principle be abstracted at different rates to give diastereomeric radicals **13** which can cyclize at different rates. It seems probable that the rate differences would be small, and these possibilities have been ignored.

Scheme 4



The kinetic experiments and data analysis followed standard procedures.[7] Benzene solutions of diiodides **9a-c** (0.7- 1 mmol), 10 equiv of triphenyltin hydride, and a small amount of AIBN were heated at 80°C overnight, and the reaction mixtures were analyzed by both GC and ^1H NMR spectroscopy. In all cases, the only (non-tin) products evident were the cyclopropane **10** and propane **11**. The ratios of these compounds as a function of starting tin hydride concentrations are shown in Table 1 along with the calculated cyclization rate constants for each experiment. As expected from the mechanistic analysis in Scheme 4, plots (not shown) of $\ln[Ph_3SnH]\cdot k_H$ versus the ratio of cyclized to reduced products (**10/11**) provided straight lines passing through the origin.[10]

Table 1. Product mixtures obtained from the reaction of Ph_3SnH with diiodides.



9 a-c 10 a-c 11 a-c

Entry	R	$[Ph_3SnH]^a$	% 10-GC	% 11-GC	k_c-GC	k_c-^{1}HNMR
1	H	0.148M	23	77	$8.9\ 10^5$	$5.4\ 10^5$
2	H	0.071M	26	74	$4.9\ 10^5$	$2.4\ 10^5$
3	H	0.094M	29	70	$7.7\ 10^5$	$6.5\ 10^5$
4	Ph	0.547M	7	93	$8.3\ 10^5$	$1.3\ 10^5$
5	Ph	0.163M	19	82	$7.7\ 10^5$	$7.2\ 10^5$
6	Ph	0.159M	18.8	81.2	$7.4\ 10^5$	
7	Ph	0.078M	34.5	65.5	$8.2\ 10^5$	
8	Ph	0.075M	31.5	68.5	$6.8\ 10^5$	$6.1\ 10^5$
9	CH_2CH_2Ph	0.103M	12	88	$2.8\ 10^5$	$1.3\ 10^5$
10	CH_2CH_2Ph	0.071M	20	80	$3.5\ 10^5$	$1.1\ 10^5$
11	CH_2CH_2Ph	0.042M	30	70	$3.6\ 10^5$	$2.6\ 10^5$
12	CH_2CH_2Ph	0.029M	49.5	50.5	$5.7\ 10^5$	$6.1\ 10^5$

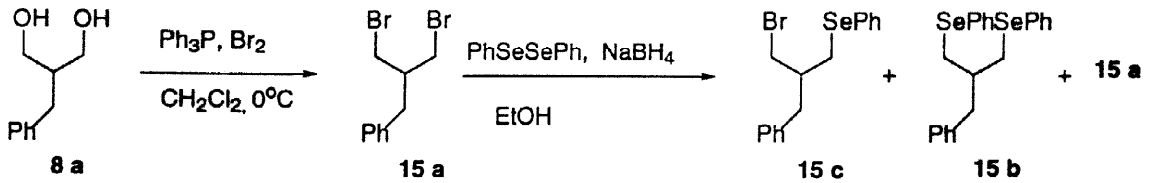
a) k_H for Ph_3SnH at 80°C = 2.0×10^7

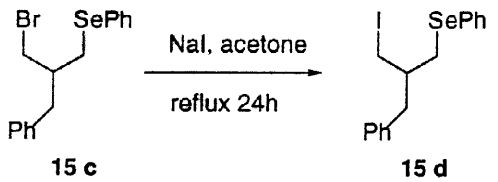
Rate constants for all the cyclizations were in the range of $5 \times 10^5\ s^{-1}$. This is similar to the rate constant for cyclization of the hexenyl radical, and we regard it as in the intermediate range within the big picture of radical rates. In retrospect, we were fortunate to have selected very fast radical cyclizations ($>10^6\ s^{-1}$) for our initial studies of stereoconvergent cyclizations at the steady state.[3] To avoid the complications of cyclopropane formation when studying slower reactions, we sought to identify ways to retard this reaction. Based on the homolytic substitution reaction, the obvious way to do this is to use a poorer radical leaving group than iodine (Scheme 4, Y ≠ I).

To test this notion, we prepared four additional precursors based on the substrate **9a**: dibromide **15a**, bisphenyl selenide **15b**, monobromide/monophenyl selenide **15c**, and monoiodide/monophenyl selenide **15d**. The synthesis of these compounds is outlined in Scheme 5. Diol **8a** is readily converted into the dibromide **15a**. This can be substituted with phenyl selenide anion (1 equiv) under standard conditions to give a mixture of mono- and bisphenyl selenides **15b,c** alongside recovered dibromide. These three products were separated by chromatography. Finkelstein reaction of **15c** provided iodide **15d**.

Reductions of these compounds under an assortment of fixed tin hydride concentrations are shown in Table 2, entries 2-7. In all cases, we could detect only the propane product **11a** and none of the cyclopropane product **10a**. Isolated yields were not determined in these reactions due to the volatility of the product, but the crude reaction mixtures were very clean (aside from the residual tin). A single reduction of **15a** under the catalytic condition with fluorous tin hydride **12** (entry 1) provided a very small amount of the cyclopropane product **10c** (5%) alongside the reduced 2-benzyl propane **11a**. These results show that a change in leaving group in the homolytic substitution of **13** (Scheme 4) from I• to Br• or PhSe• results in at least a one-hundred fold decrease in the rate constant.

Scheme 5



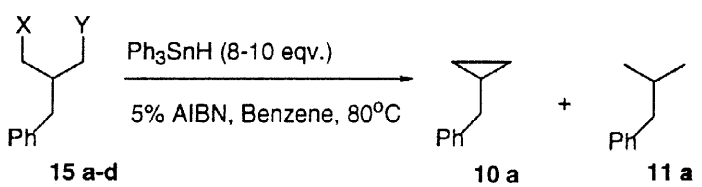


Reaction conditions	15 c	15 b	15 a
0°C to rt, 8h[a]	30%	0%	50%
0°C to rt, 24h[a]	43%	14%	15%
reflux 48h[a]	20%	25%	0%

a) Yields were determined after separation of product mixtures on silica gel.

Especially noteworthy is the result with the iodo selenide **15d**; even though this precursor contains one iodine, it still provides no cyclopropane. This is because iodine is a much better radical precursor than phenyl selenide and it is selectively abstracted by the initial tin radical to give a 3-phenylselenopropyl radical. Thus, only 1,3-diiodides serve as precursors of the 3-iodopropyl radicals that close to cyclopropanes.

Table 2



Entry	X group	Y group	[Ph_3SnH]	% 10 a	% 11 a
1	Br	Br	0.002M[a]	5	95
2	Br	Br	0.058M	0	100
3	Br	Br	0.077M	0	100
4	Br	Br	0.140M	0	100
5	Br	SePh	0.054M	0	100
6	SePh	SePh	0.035M	0	100
7	I	SePh	0.045M	0	100

a) Catalytic experiment using tris(2-(perfluorohexyl)ethyl)tin hydride (**12**).

Conclusions

Data from this brief series of kinetic and preparative experiments fulfill the goals outlined in the introduction. 2-Substituted 3-iodopropyl radicals cyclize via a relatively rare homolytic substitution pathway at carbon to provide cyclopropanes with rate constants on the order of 5 x 10^5 s^{-1}. In

designing stereoconvergent cyclizations of 1,3-halides, this undesirable competing process can be avoided either by conducting very rapid cyclization reactions or, if slower cyclization are being conducted, by selecting a radical precursor which is not a diiodide.

Turning the tables and thinking about the homolytic substitution as a desirable method to form cyclopropanes, the results suggest that there is unrecognized potential in this previously known reaction. 1,3-Dihalides and related compounds can be reductively cyclized to cyclopropanes by metal reduction, halogen-metal exchange, and metal hydride reduction.[11] Many of these processes probably involve intramolecular S_N2 (nucleophilic) substitutions, although some (especially the hydride reductions) may involve S_H2 processes. Compared to these metal-based methods, the tin hydride mediated reductive cyclopropanation has the disadvantage that it is largely restricted to diidoides, but it comes with the usual advantages of mildness of reaction conditions and functional group tolerance that accompany most radical reactions. Thus, the tin hydride mediated S_H2 process could find use in forming cyclopropanes in complex, multifunctional molecules where metal-based methods are disadvantageous.

Experimental

General methods A-C

Method A: *General procedure for the LAH reduction of malonic acid diethyl ester derivatives* **7b,c**.
To a 0°C stirred Et_2O solution (150ml) of the corresponding malonic acid diethyl ester (7.8 mmol) was added LAH (15.6 ml, 15.6 mmol, 1.0M solution in Et_2O). The resulting mixture was allowed to warm to room temperature and then heated at reflux overnight. After cooling, the reaction was quenched by addition of a chilled saturated aq. solution of potassium sodium tartrate and extracted with Et_2O. The combined extracts were washed with water and brine, and dried over $MgSO_4$. The solvent was removed under reduced pressure to yield the crude product (diols **5** or **8**). The product was sufficiently pure for subsequent reaction.

Method B: *General procedure for the mesylation of diol derivatives* **8a-c**.
Methanesulfonyl chloride (1.48 ml, 19.2 mmol) was added dropwise to a chilled solution of the corresponding diol derivative (8.0 mmol) and triethylamine (3.2 ml, 24 mmol) in dry CH_2Cl_2 (150 ml). The resulting suspension was allowed to warm to room temperature and stirred overnight. The reaction was quenched with H_2O and the product was extracted with CH_2Cl_2. The combined organic phases were washed with 2N HCl, aq. $NaHCO_3$ solution (5%) and brine, dried over $MgSO_4$ and concentrated under reduced pressure to give the corresponding methanesulfonic acid ester derivative. The product was used in the next step without further purification.

Method C: *General procedure for the iodination of the methanesulfonic acid ester derivatives.*
The corresponding mesylated derivative (3.5 mmol) was added to NaI (35 mmol) in dry acetone (100 ml). The mixture was refluxed for 2 days. The acetone was evaporated under reduced pressure. The residue was dissolved in H_2O and extracted with pentane. The combined organic phases were washed with brine, dried over $MgSO_4$ and then concentrated under reduced pressure. The crude

product was purified by column chromatography on silica gel using either pentane or hexane for elution.

(3-Iodo-2-iodomethylpropyl)-benzene (9a):
The reduction of diethyl benzylmalonate (**6**) following the method of Harnden[12] gave 2-Benzyl-propane-1,3-diol (**8a**). Subsequent mesylation according to *method B* afforded methanesulfonic acid 2-benzyl-3-methanesulfonyloxy-propyl ester, which was reacted with NaI following *method C* to give the title compound **9a**. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.64 (m, 1H), 2.72 (d, J = 7Hz, 2H), 3.18 (dd, J = 6.1 and 10Hz, 2H), 3.39 (d, J = 4.4 and 10Hz, 2H), 7.21-7.33 (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.69, 39.83, 42.51, 126.62, 128.56, 128.80, 138.18; IR (film, NaCl, cm^{-1}) 3062, 3029, 2959, 2929, 1600, 1494, 1416, 1260, 1093, 1027, 799; LRMS (70eV, EI) *m/z* (rel int %) 386 (M^+, 30), 259 (12), 131 (76), 117 (16), 91 (100), 77 (7), 65 (28). HRMS *m/z* calcd for $C_{10}H_{12}I_2$ (M^+) 385.9028, found 385.9018.

1,3-Diiodo-2-benzhydrylpropane (9b):
Compound **9b** was obtained according to the following procedures; Grignard addition of phenylmagnesium bromide to diethyl benzylmalonate (**6**) in the presence of cuprous bromide following the method of Patra[13] gave 2-benzhydryl-malonic acid diethyl ester (**7b**). According to *method A* this was converted into 2-benzhydrylpropane-1,3-diol (**8b**). Subsequent mesylation following *method B* afforded methanesulfonic acid 2-benzhydryl-3-methanesulfonyloxy-propyl ester, which was reacted with NaI according to *method C* to give the title compound **9b**. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.16 (m, 1H), 3.13 (dd, J = 6.76 and 10.14Hz, 2H), 3.56 (dd, J = 2.7 and 10.1Hz, 2H), 3.79 (d, J = 10.98Hz, 1H), 7.21-7.39 (m, 10); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.4, 43.45, 56.04, 125.6, 127.02, 129.05, 141.91; IR (film, NaCl, cm^{-1}) 3059, 3025, 1597, 1492, 1451, 1418, 1236, 1164, 757, 703; LRMS (70eV, EI) *m/z* (rel int %) 462 (M^+, 9), 180 (9), 167 (100), 152 (37), 139 (7), 128 (18), 115 (21), 104 (9), 91 (34), 77 (9), 58 (26). HRMS *m/z* calcd for $C_{16}H_{16}I_2$ (M^+) 461.9341, found 441.9344.

1,3-Diiodo-2-(1,3-diphenyl-propyl)-propane (9c):
Reaction of diethyl benzylmalonate (**6**) with the Grignard reagent prepared from (2-iodoethyl)benzene in the presence of cuprous bromide afforded 2-(1,3-diphenylpropyl)malonic acid diethyl ester (**7c**). This was converted into 2-(1,3-diphenylpropyl)propane-1,3-diol (**8c**) following *method A*. Subsequently mesylation according to *method B* afforded methanesulfonic acid 2-methanesulfonyloxy-3,5-diphenyl ester, which was reacted with NaI following *method C* to give the tittle compound **9c**. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.43 (m, 1H), 1.79 (m, 1H), 2.03 (m, 1H), 2.21 (m, 2H), 2.45 (m, 1H), 2.78 (m, 1H), 3.13 (dd, J = 2.72 and 10.21Hz, 1H), 3.33 (dd, J = 6 and 10.3Hz, 1H), 3.62 (dd, J = 3.5 and 10.3Hz, 1H), 7.06-7.39 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.42, 13.77, 33.68, 35.27, 46.68, 49.98, 126.13, 127.11, 128.32, 128.89, 141.48, 141.66; IR (film, NaCl, cm^{-1}) 3058, 3024, 2944, 1600, 1492, 1452, 1419, 1231, 1215, 737; LRMS (70eV, EI) *m/z* (rel int %) 490 (M^+, 36), 195 (14), 131 (16), 117 (30), 104 (8), 91 (100), 65 (5). HRMS *m/z* calcd for $C_{18}H_{20}I_2$ (M^+) 489.9654, found 489.9647.

(3-Bromo-2-bromomethylpropyl)benzene (15a):
To the well stirred suspension of triphenylphosphine (3.3g, 12.8mmol) in dry CH_2Cl_2 (25 ml) cooled in an ice bath, bromine (0.6ml, 12mmol) was added dropwise at such a rate that the mixture remained colorless. After addition was completed, a solution of **8a** (1g, 6 mmol) in CH_2Cl_2 (10ml) was added over a period of 20 min. The mixture was stirred for 2 h, then poured into a cold saturated aq. solution of $NaHCO_3$ and extracted with pentane. The combined extracts were washed with water, brine, dried over $MgSO_4$ and concentrated under reduced pressure to yield the crude product. Purification by column chromatography on silica gel using pentane for elution provided the title compound in 65% yield. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.28 (m, 1H), 2.79 (d, J = 7.2Hz, 2H), 3.45 (dd, J = 6 and 10.18Hz, 2H), 3.59 (dd, J = 4.3 and 10.3Hz, 2H), 7.21-7.36 (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 35.81, 37.36, 43.72, 126.72, 128.69, 129.02, 138.16; IR (film, NaCl, cm^{-1}) 3057, 1589, 1435, 1192, 1119, 754, 723, 692; LRMS (70eV, EI) *m/z* (rel int %) 292 (M^+, 100), 172 (19), 131(8), 115 (18), 91 (58). HRMS *m/z* calcd for $C_{10}H_{12}Br_2$ (M^+) 291.9285, found 291.9289

Preparation of compounds 15b and 15c.
Diphenylselenide (481.6 mg, 1.54 mmol) was dissolved in EtOH (50 ml) with ice cooling. Sodium borohydride (120mg, 3.12mmol) was carefully added in small portions. The bright yellow solution turned almost colorless and a solution of compound **15a** (800 mg, 2.74 mmol) in EtOH (25 ml) was added dropwise over a period of 30 min. The mixture was stirred and warmed to either room temperature or reflux (see Scheme 5). The reaction was quenched by addition of H_2O and extracted with Et_2O. The combined organic organic phases were washed with brine, dried over $MgSO_4$ and then concentrated under reduced pressure to yield a mixture of **15a-c**. All the products were separated by column chromatography on silica gel using hexane for elution (R_f= 0.23, 0.17 and 0.11 respectively). Modification of both temperature and reaction time resulted in significant changes in the yield of products. Information concerning the individual yield of products is summarized in Scheme 5.

(3-Phenylselanyl-2-phenylselanylmethylpropyl)benzene (15b):
^{1}H NMR (300 MHz, $CDCl_3$) δ 2.21 (m, 1H), 2.86 (d, J = 6.9Hz, 2H), 3.07 (d, J = 6.1Hz, 4H), 7.08-7.43 (m, 15H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 32.67, 40.19, 41.18, 126.33, 126.87, 128.49, 129.17, 129.37, 130.38, 132.55, 139.56; IR (film, NaCl, cm^{-1}) 3058, 2919, 2360, 2340, 1575, 1472, 1436, 1020, 730, 684; LRMS (70eV, EI) *m/z* (rel int %) 446 (M^+, 70), 368 (25), 312 (56), 291 (100), 269 (15), 157 (19), 131 (69), 115 (15), 101 (29), 84 (94). HRMS *m/z* calcd for $C_{22}H_{22}Se_2$ (M^+) 446.0061, found 446.0040.

(2-Bromomethyl-3-phenylselanylpropyl)benzene (15c):
^{1}H NMR (300 MHz, $CDCl_3$) δ 2.13 (m, 1H), 2.81 (m, 2H), 3.02 (m, 2H), 3.42 (dd, J = 4.4 and 10.2Hz, 1H), 3.65 (dd, J = 4.1 and 10.1Hz, 1H), 7.14-7.44 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 31.69, 38.9, 39.42, 42.68, 127.18, 127.76, 129.26, 129.88, 130.46, 135.36, 139.64; IR (film, NaCl, cm^{-1}) 3065, 2925, 1581, 1479, 1434, 1249, 1032, 1019, 738, 634; LRMS (70eV, EI) *m/z* (rel int %) 367 (M^+, 40), 158 (26), 131 (72), 117 (15), 91 (100), 77 (14), 65 (1). HRMS *m/z* calcd for $C_{16}H_{17}BrSe$ (M^+) 367.9678, found 367.9680.

(2-Iodomethyl-3-phenylselanylpropyl)benzene (15d):

Compound **13** was prepared following *method C* using compound **15c** as starting material. The crude product was purified by passing through a plug of silica gel eluting with hexane to provide the title compound in 75% yield. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.68 (m, 1H), 2.67 (dd, J = 7.9 and 13.7Hz, 1H), 2.81 (dd, J = 6.2 and 13.7Hz, 1H), 2.9 (dd, J = 7.6 and 12.6Hz, 1H), 3.02 (dd, J = 5.5 and 12.6Hz, 1H), 3.22 (dd, J = 4.3 and 9.9Hz, 1H), 3.47 (dd, J = 4.3 and 9.9Hz, 1H), 7.14-7.46 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 15.05, 33.10, 40.31, 41.09, 126.49, 127.04, 128.53, 129.08, 129.15, 129.6, 132.77, 138.92; IR (film, NaCl, cm^{-1}) 3054, 3024, 2920, 2852, 1725, 1578, 1476, 1436, 1270, 1216, 1072, 805, 735, 696; LRMS (70eV, EI) *m/z* (rel int %) 416 (M^+, 41), 284 (15), 171 (11), 157 (33), 131 (83), 117 (32), 104 (11), 91 (100), 77 (35), 65 (38). HRMS *m/z* calcd for $C_{16}H_{17}ISe$ (M^+) 415.9540, found 415.9517.

Preparation of cyclopropane authentic samples (10a-c):
In a typical catalytic experiment, a suspension of the corresponding radical precursor (0.085 mmol), tris(2-perfluorohexyl)ethyl)tin hydride (0.0085 mmol), sodium cyanoborohydride (0.238 mmol) and 10% AIBN in BTF (2.1 ml) and ^{t}BuOH (2.1 ml) was heated in a sealed tube at reflux overnight. The solvent was evaporated under reduced pressure and the residue partioned between water (5 ml), benzene (10 ml) and perfluoromethylcyclohexane (15 ml). The three layers were separated and both the aqueous and fluorous phases were reextracted with benzene. The combined organic phases were washed with brine, dried over $MgSO_4$ and then concentrated under reduced pressure. The product obtained was sufficiently pure for characterization. Cyclopropane products were identified by spectroscopic comparison to be identical to the known compounds: cyclopropylmethylbenzene (**10a**),[9a-d] benzhydrylcyclopropane (**10b**),[9a,e] 1-cyclopropyl-1,3-diphenylpropane (**10c**).[9e]

Preparation of doubly reduced authentic samples (11b,c):

Benzhydrylpropane (11b):
Methanesulfonic acid 2-benzhydryl-3-methanesulfonyloxypropyl ester (0.7 mmol) was treated with LAH (2 ml, 2 mmol, 1.0 M in Et_2O) as in *method A*. The crude product was purified by column chromatography on silica gel using pentane for elution. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.77 (d, J = 6Hz, 6H), 2.39 (m,1H), 3.30 (d, J = 10.5Hz, 1H), 7.03-7.17 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 21.82, 31.83, 60.86, 125.89, 127.97, 128.34, 144.9; IR (film, NaCl, cm^{-1}) 3023, 2927, 1594, 1490, 1447, 740, 704; LRMS (70eV, EI) *m/z* (rel int %) 210(M^+, 30), 167 (100), 152 (20), 115 (9), 91 (10). HRMS *m/z* calcd for $C_{16}H_{18}$ (M^+) 210.1408, found 210.1399.

(4-Methyl-3-phenylpentyl)benzene (11c):
Methanesulfonic acid 2-methanesulfonyloxy-3,5-diphenyl ester (0.7mmol) was treated with LAH (2 ml, 2 mmol, 1.0 M in Et_2O) as in *method A*. The crude product was purified by column chromatography on silica gel using pentane for elution. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.67 (d, J = 6.6Hz,3H), 0.88 (dd, J = 6.6Hz, 3H), 1.82 (m, 2H), 2.04 (m, 1H), 2.31 (m, 3H), 7.03-7.29 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 20.64, 20.91, 33.5, 34.1, 34.82, 52.61, 125.53, 125.87, 128.01, 128.18, 128.33, 128.59, 142.80, 144.10; IR (film, NaCl, cm^{-1}) 3023, 2958, 2867, 1604, 1490, 1449, 702; LRMS (70eV, EI) *m/z* (rel int %) 238 (M^+, 87), 224 (6), 195 (7), 133 (5), 117 (100), 104 (19), 91 (92), 77 (6), 65 (11), 59 (5). HRMS *m/z* calcd for $C_{18}H_{22}$ (M^+) 238.1721, found 238.1719.

General procedure for the kinetic experiments:
In a typical experiment, the radical precursor (0.07 mmol-1.0 mmol) was dissolved in a solution of Ph_3SnH (10 equiv) in dry benzene in a sealed tube. The amount of benzene was calculated according to the desired concentration of the tin hydride. A spatula tip of AIBN was added and the stirred mixture was heated in an oil bath at 80°C overnight. After cooling, the solution was passed down through a short plug of silica gel eluting with hexane. The product mixture was analyzed by GC and ^1H NMR.

Acknowledgments. We thank the National Science Foundation for funding. We also thank Mr. M. Juhasik for help preparing radical precursors.

References and Notes

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