Single Electron Transfer in Nucleophilic Aliphatic Substitution. Evidence for Single Electron Transfer in the Reactions of 1-Halonorbornanes with Various Nucleophiles

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A series of 1-halonorbornanes was used as a model system in reactions with several nucleophiles in order to determine the involvement of single electron transfer (SET) in nucleophilic aliphatic substitution in the absence of light. The 1-halonorbornanes were allowed to react with Me_3Sn^-, Ph_2P^-, AlH_4^-, $N(iPr)_2^-$, SPh^-, and the 2-nitropropyl anion in ether solvents at room temperature to 0 °C. The results of product analyses, the use of radical and radical anion trapping reagents, the results of deuterium labeling studies, and the nucleofugality effect support a SET mechanism for the reactions involving 1-iodonorbornane. Convincing evidence that reduction of hindered alkyl iodides with $LiAlH_4$ takes place by a SET pathway rather than by an impurity-initiated halogen atom radical chain process followed by an S_N2 pathway, is presented.

Introduction

Due to the pioneering contributions of Kornblum,[1] Russell,[2] and Bunnett[3] in the area of radical nucleophilic substitution, the concept of substitution by single electron transfer (SET) and the $S_{RN}1$ pathway shown in Scheme 1

Scheme 1

$$RX + Nu^- \rightarrow RX^{\bullet -} + Nu^\bullet$$

$$RX^{\bullet -} \rightarrow R^\bullet + X^-$$

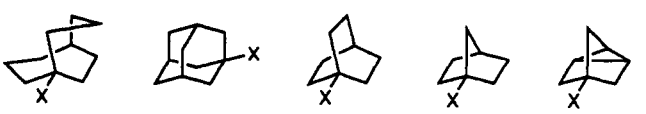
$$R^\bullet + Nu^- \rightarrow RNu^{\bullet -}$$

$$RNu^{\bullet -} + RX \rightarrow RX^{\bullet -} + RNu$$

are well known. The extent and importance of SET as a reaction pathway, competitive with the S_N2 pathway in organic chemistry, has been the subject of much interest in our group,[4] as well as other groups that have contributed greatly in this area. Most notable is the work of Kochi,[5] Kuivila,[6] Rossi,[7] Lund,[8] Pross,[9] and others. Efforts have been made to combine SET and S_N2 pathways as extremes of a hybrid model and several fundamental organic reactions which have been considered to proceed through a polar pathway, now appear to proceed, at least to some extent, via radical intermediates. However, in spite of the growing evidence that SET processes are far more widespread than originally thought, the importance of SET as a reaction pathway to describe well-known reactions and the relationship between SET and polar pathways does not seem to be generally accepted.

Theoretically, S_N2 pathways involve attack of a nucleophile at the backside of the carbon–halogen bond with a concerted departure of the leaving group. Front side attack is "disallowed" because of unfavorable orbital interaction. On the other hand SET involves the pathway described in Scheme 1. Since electron transfer takes place at a longer distance than required for a S_N2 pathway, steric affects in a SET pathway are considered not to be as important as in a S_N2 pathway.[10] Thus, any factors (steric, electronic, or geometric) that operate to inhibit or hinder the coupling process of the S_N2 reaction will tend to favor SET over the polar pathway. In some of these systems, the electron transfer step is spontaneous, but in others, light is needed to catalyze the reaction. In the latter case, the electron transfer occurs by an excited nucleophile and excited substrate or through an excited substrate–nucleophile charge-transfer complex.

It is well known that 1-substituted bridgehead compounds are very unreactive toward nucleophilic substitution. The S_N1 reaction pathway is not favored since the resulting bridgehead carbonium ion cannot assume planarity (although it can be formed photochemically) due to the strain in the molecule. The low reactivity of an S_N1 pathway is indicated by a comparison of the rates of solvolysis of the corresponding bridgehead halides:



(1) (3 × 10⁻⁴) (10⁻⁷) (10⁻¹⁴) (10⁻¹⁹)

Thus, greater activation energy is needed for the bridgehead halide ionization. The S_N2 pathway can also be precluded by the restriction of backside attack at the bridgehead position by the nucleophile. Therefore, it

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(1) Kornblum, N.; Michel, R. E.; Kerber, R. C. *J. Am. Chem. Soc.* **1966**, *88*, 5662.

(2) Russell, G. A.; Dannen, W. C. *J. Am. Chem. Soc.* **1966**, *88*, 5663.

(3) Kim, J. K.; Bunnett, J. F. *J. Am. Chem. Soc.* **1970**, *92*, 7463.

(4) Ashby, E. C. *Pure Appl. Chem.* **1980**, *52*, 55. Ashby, E. C.; Depriest, R. N.; Su, W.-Y. *Organometallics* **1984**, *3*, 1718.

(5) Kochi, J. K. *Organometallic Mechanisms and Catalysis*; Academic Press: New York, 1978.

(6) Kuivila, H. G.; Smith, G. F. *J. Org. Chem.* **1980**, *45*, 2918. Kuivila, H. G. *Ann. N.Y. Acad. Sci.* **1974**, *239*, 351.

(7) Rossi, R. A.; Pierini, A. B.; Palacios, S. M. *Advances in Free-Radical Chemistry*; 1990; Vol. 1.

(8) Lund, H.; Kristenen, L. H. *Acta Chem. Scand.* **1979**, *B33*, 495.

(9) Pross, A. *Acc. Chem. Res.* **1985**, *18*, 212. Pross, A.; Shaik, S. S. *Ibid.* **1983**, *16*, 363.

(10) Kerr, J. A.; Smith, B. J. A.; Thotman-Dickenson, A. F.; Young, J. C. *J. Chem. Soc. A.* **1986**, 510. Kochi, J. K. *Organometallic Mechanisms and Catalysis*; Academic Press: New York, 1978; pp 138–177.

(11) Bringham, R. C.; Schleyer, P. V. R. *J. Am. Chem. Soc.* **1971**, *93*, 3189.

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follows that the reaction of 1-norbornyl halides with nucleophiles should represent an excellent model to observe SET, if indeed significant reaction takes place at all. Although the reaction is reported to be slow with some nucleophiles, the reaction should be rapid via a SET pathway when the nucleophiles employed are good one-electron donors.

Similar studies have been carried out by Rossi and co-workers[12] involving reactions of bridgehead halides, such as the 1-haloadamantanes, 9-halo- and 9,10-dihalotriptycenes with Ph_2P^-, Ph_2As^-, PhS^-, and other nucleophiles. More recently, Rossi and co-workers reported the reactions of 4-halotricyclanes, the most unreactive substrates in solvolytic reactions, with the diphenylphosphide anion.[13] In all of these cases the reactions were initiated by light since they took place very slowly or simply not at all in the dark. From product analyses and trapping experiments, Rossi and co-workers concluded that these reactions proceeded by an $S_{RN}1$ pathway.

The reaction of 1-bromo-4-iodobicyclo[2.2.2]octane with $LiSnMe_3$ in THF at 0 °C has been studied by Adcock and co-workers.[14] On the basis of product distribution studies, the results of specific deuterium labeling experiments, as well as radical trapping experiments, they proposed that the reaction occurred by a radical chain mechanism similar to the $S_{RN}1$ mechanism. However, an additional propagation step involving iodine atom abstraction from the starting material by the 4-(trimethylstannyl)bicyclo[2.2.2]-oct-1-yl radical intermediate was also proposed. On the other hand, the reaction of 1,4-dihalobicyclo[2.2.2]heptane with (trimethylstannyl)lithium[15] indicated that a polar mechanism involving the formation of a carbanion competed effectively with the free radical chain process. The most important revelation to emerge from this study was the suggestion that a competition between the SET and the polar mechanism exists and that competition depends not only on the nature of the leaving group, but also on the nature of the substrate.

In order to avoid competition between polar and SET mechanisms and also to avoid reaction initiation by photochemical light (since light does ionize bridgehead halides),[16] we decided to study the reactions of 1-halonorbornanes with various nucleophiles in the dark. Such a study would involve a reaction that should proceed entirely by a SET mechanism and also one that is not initiated by light. We found the reactions, even in the dark, to be relatively rapid when a nucleophile that is a good one-electron donor is used, a result totally unexpected for a S_N1 or S_N2 process.

Also the use of 1-halonorbornanes as a model system eliminates the competition of a halogen atom radical chain process in the reduction of 1-iodonorbornane with $LiAlH_4$ (and other nucleophiles). Since Newcomb has consistently held that the reduction of hindered alkyl iodides is a result of an impurity-initiated reaction followed by a halogen atom radical chain process followed further by a polar S_N2 process, the results of this study are particularly informative.[17] In this study, where a halogen atom radical chain process is not operable, evidence that the reduction of 1-iodonorbornane by $LiAlH_4$ takes place by a SET process is overwhelming.

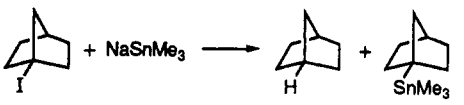
Table 1. Reactions of 1-Iodonorbornane with $NaSnMe_3$ in THF at 0 °C[a]

			% yield[b] (%D)[c]	
entry	solvent	additive (equiv)[d]	 H	 $SnMe_3$
1	THF	none	15	93
2	THF-d_8	none	6 (87% D)	92
3	THF	DCPH (10)	72	28
4	THF	DCPD (10)	14 (56% D)	90
5	THF-d_8	DCPD (10)	9 (99% D)	84

[a] All reactions carried out for 5 min and were conducted in the dark as described in Experiment Section. [b] Determined by gas chromatographic analysis relative to an internal hydrocarbon standard (decane) on the aliquots removed from the reaction mixture periodically. [c] Percent of deuterium incorporation. [d] Ten equivalents used with respect to substrate.

Results and Discussion

Reaction of 1-Halonorbornanes with $NaSnMe_3$. The results of experiments involving the reaction of 1-iodonorbornane with (trimethylstannyl)sodium (eq 1) are listed



(1)

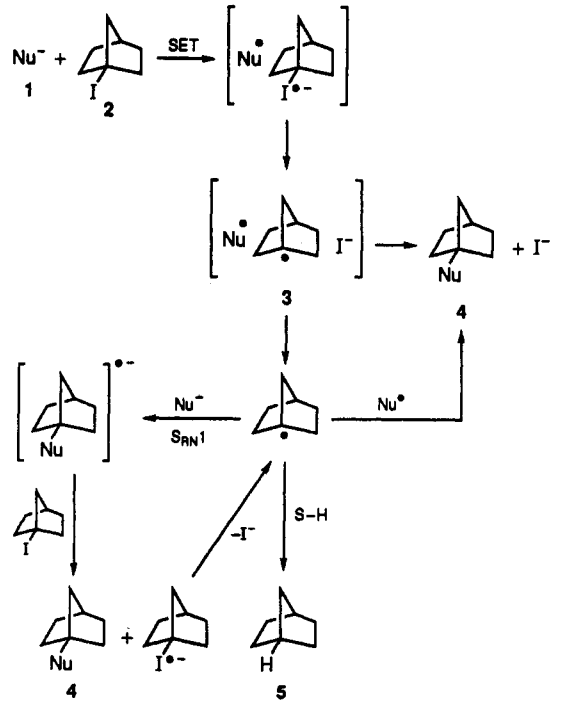
in Table 1. Since the S_N1 and S_N2 pathways are unlikely for reactions of 1-norbornyl halides and since trimethylstannyl sodium has been demonstrated to be an excellent one-electron donor in producing a SET pathway and high yields of substitution product,[4,6] it is suggested that the reaction proceeds through a SET-initiated pathway similar to the mechanism we reported earlier for the reaction of noncyclic alkyl iodides with $NaSnMe_3$ (Scheme 2).[4]

The substitution product **4** is a result of either the coupling of the norbornyl radical with the trimethylstannyl radical (**3**) in the solvent cage or from a $S_{RN}1$ free radical chain process (as shown). The formation of **4** from radical coupling of the norbornyl radical with $Nu^\bullet$ is also possible because of the stability of $Me_3Sn^\bullet$. The reduction product **5** is a result of hydrogen atom abstraction from the solvent (or any other hydrogen atom donor in the reaction mixture) by the norbornyl radical. The formation of **5** necessarily implies a radical precursor.

In order to provide evidence for the intermediacy of the norbornyl radical, several experiments were carried out using deuterium labeling in the solvent and in the trapping agent (Table 1). In THF (expt 1), the reduction product **5** was formed in 15% yield; however, in THF-d_8 solvent (expt 2), the yield of reduction product **5** decreased from 15 to 6% and the deuterium incorporation was 87%. It is clear that 87% of the reduction product is a result of the norbornyl radical being trapped by THF-d_8. If it were not for the primary protium/deterium kinetic isotope effect, the yield of reduction product would have been higher. When a good hydrogen atom donor, such as, dicyclohexylphosphine (DCPH) was added to the reaction

(12) Palacios, S. M.; Santiago, A. N.; Rossi, R. A. *J. Org. Chem.* **1984**, *49*, 4609. *Ibid.* **1982**, *47*, 4654. Rossi, R. A.; Palacios, S. M.; Alonso, R. A. *Tetrahedron* **1985**, *41*, 4147.
(13) Santiago, A. N.; Morris, D. G.; Rossi, R. A. *J. Chem. Soc., Chem. Commun.* **1988**, 220.
(14) Adocock, W.; Lyer, S. W.; Kitching, W.; Youndg, D. *J. Org. Chem.* **1985**, *50*, 3706.
(15) Adocock, W.; Gangodawila, H. *J. Org. Chem.* **1989**, *54*, 6040.
(16) Kropp, P. J.; Adkins, R. L. *J. Am. Chem. Soc.* **1991**, *113*, 2709.
(17) Ashby, E. C. *Acc. Chem. Res.* **1988**, *21*, 414.

Scheme 2



mixture (expt 3), the yield of reduction product increased dramatically (from 15 to 72%) with a corresponding decrease of substitution product (93 to 28%). DCPH is known to be a good radical trapping agent which converts an alkyl radical to the corresponding hydrocarbon by hydrogen atom abstraction.[14,18] We show, later in this report, that it is possible that DCPH is involved in a radical chain process. Thus the results (expts 1–3) show that a significant number of the norbornyl radicals, formed in the reaction of 1-iodonorbornane with $NaSnMe_3$, was trapped by the solvent or DCPH before coupling with the trimethylstannyl radical or anion to form **5**.

It was expected that deuterated dicyclohexylphosphine (DCPD) when substituted for DCPH would donate a deuterium atom to the norbornyl radical and generate norbornane-d_1 (expt 4). The results clearly confirm this expectation. In protio THF (expt 4) using DCPD as a trapping agent, 56% deuterium incorporation was found in the product; however, the yield of reduction product did not increase as with DCPH since the primary protium/deuterium kinetic isotope effect would be expected to slow down deuterium atom abstraction relative to substitution.

In an attempt to increase the amount of deuterium incorporation observed, the reaction was carried out in THF-d_8 and DCPD (expt 5). In this case the reduction product contained 99% deuterium. Hence, it is clear that the reduction product is formed from the norbornyl radical by hydrogen atom abstraction from the solvent and DCPH or DCPD when it is present.

Next, we attempted to determine if the reaction of 1-iodonorbornane with $NaSnMe_3$ proceeds by a $S_{RN}1$ free radical chain process.[19] The reaction was carried out in the presence of *p*-dinitrobenzene (PDNB), a radical anion trapping agent, Table 2 (expt 2). 1-Iodonorbornane reacted completely with $NaSnMe_3$ in less than 10 s (expt 1); however, in the presence of 10 mol % PDNB, 10%

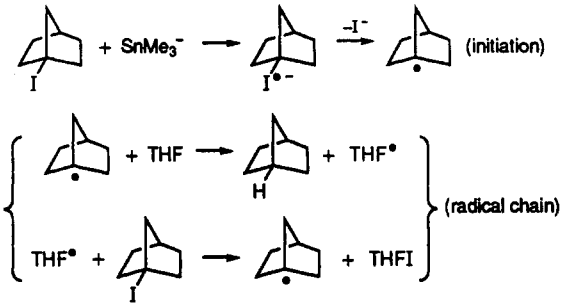
(18) Smith, G. F.; Kuivila, H. G.; Simmon, R. *J. Am. Chem. Soc.* **1981**, *103*, 833.
(19) Kornblum, N. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 734.

Table 2. Reactions of 1-Iodonorbornane with $NaSnMe_3$ in the Presence of Trapping Agents in THF at 0 °C[a]

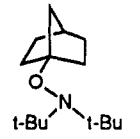
		% yield[b]		
entry	additive (equiv)[c]	H	$SnMe_3$	I
1	none	15	93	0
2	PDNB (0.1)	27	70	10
3[c]	DTBN (0.5)	28	35	18

[a,b] The same as Table 1 except that the reaction time in these cases was 10 s. [c] A trace amount of the radical coupling product of the norbornyl radical and DTBN was detected by GC/MS.

Scheme 3



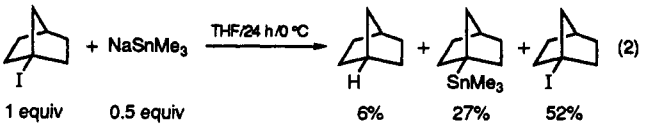
1-iodonorbornane was recovered after 10 s, indicating that the rate of the reaction decreased in the presence of PDNB. Also the presence of PDNB increased the amount of reduction product and decreased the amount of substitution product as expected from Scheme 2. The radical scavenger, di-*tert*-butylnitroxyl radical (DTBN),[20] was also added to the reaction mixture as a radical trap (expt 3). 1-Iodonorbornane was recovered (18%) from the reaction mixture after 10 s and a small amount of the coupling product of DTBN with the norbornyl radical (**A**) was



(A)

identified by GC/MS. These results support the conclusion that a radical intermediate existed which was trapped by DTBN.

In order to obtain more information concerning the reaction of 1-iodonorbornane with $NaSnMe_3$, a reaction was carried out with the ratio of substrate to reagent 1:0.5 (eq 2). The purpose of carrying out such a reaction was



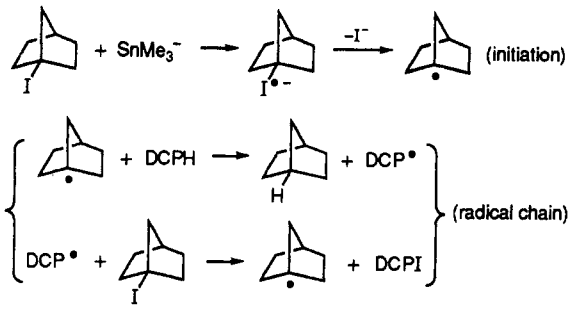
(2)

to determine whether or not a radical chain process involving the THF solvent was in effect (Scheme 3). The fact that 1-iodonorbornane was recovered in 52% yield indicates that a radical chain process involving THF is not involved in this reaction.

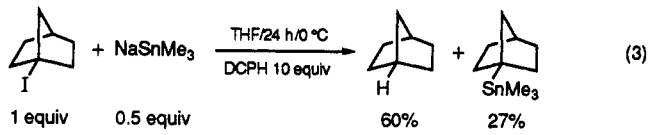
From previous work in this laboratory, it is known that

(20) Scamehorn, R. G.; Bunnett, J. F. *J. Org. Chem.* **1977**, *42*, 1449.

Scheme 4



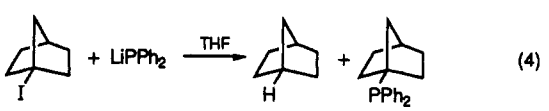
DCPH can induce a radical chain process;[4] therefore, the following reaction (eq 3) was carried out:



No unreacted starting material was detected by GC after 24 h. The fact that all of the starting halide had reacted when only 0.5 equiv of $NaSnMe_3$ was present supports the notion that DCPH can initiate a radical chain reaction. A possible pathway is shown in Scheme 4.

The results of reactions of other 1-halonorbornanes and 1-norbornyl tosylate with $NaSnMe_3$ are reported in Table 3. With respect to the rate of reaction, the effect of leaving group is I > Br > Cl > OTs which is what is expected for a SET process since the reduction potential of the corresponding alkyl halide–tosylate decreases in the same order. If the reaction proceeded by either a S_N1 or S_N2 process, the iodide and tosylate would have reacted at comparable rates since their abilities as leaving groups are comparable. Also the reaction of the bromide in diethyl ether is much more rapid than in THF. The effect of DCPH on the reaction of the bromide is similar to that of the corresponding iodide; namely, the reaction with DCPH speeds up the reaction and also causes more norbornane to be produced relative to the substitution products. It appears that, if SET is involved in the reaction of the bromide, it is probably only to a small extent compared to the corresponding iodide.

Reaction of 1-Halonorbornanes with Lithium Diphenylphosphide. As mentioned in the introduction, diphenylphosphide has been widely used as a nucleophile in reactions with bridgehead halides under photochemical conditions. High yields of the corresponding substitution products were obtained in these reactions. Table 4 lists the results of reactions of 1-halonorbornanes with $LiPPh_2$ (eq 4) in the dark. Although the major reaction product



formed in the reaction of 1-iodonorbornane with $NaSnMe_3$ was the result of substitution, the major product formed in the reactions of 1-iodonorbornane with $LiPPh_2$ was the result of reduction. The substitution product was determined by GC/MS as the corresponding oxide due to the oxidation experienced during product workup. The reason for the formation of such a small amount of substitution product, compared to the amount when similar reactions were carried out photochemically in this laboratory, is not entirely clear. Generally speaking, the steric hindrance and lower one-electron donor capability of Ph_2P^- compared to Me_3Sn^- would contribute to a looser transition state (3) of Scheme 2, thus forming less substitution product in the solvent cage and more reduction product outside of the solvent cage. It was found that the yield of reduction product changed less when DCPH was used as a trapping agent (expt 2) compared to the corresponding reaction with $NaSnMe_3$ and also that the deuterium incorporation in the product on using DCPD was not as great as in the reaction with $NaSnMe_3$ (expt 3); however, the effect of DCPH and DCPD was substantial. The differences observed in the DCPH–DCPD experiments between $NaSnMe_3$ and $LiPPh_2$ are probably due to the Ph_2PH produced in the reaction mixture that is there because (1) some is present in the $LiPPh_2$ (1%) and (2) some is produced when $Ph_2P^•$ abstracts H• from the solvent. Ph_2PH can also react as a hydrogen atom donor and compete with DCPH. When the reaction is carried out in THF-d_8 and DCPD (expt 4), 87% deuterium incorporation was observed compared to 99% in the reaction with $NaSnMe_3$, indicating that the Ph_2PH present had an effect on product distribution.

In order to determine if the reaction proceeds through a $S_{RN}1$ free radical chain process, PDNB was used as a radical anion scavenger in the reaction as shown in expt 5. In the presence of 10 mol % of PDNB, about 70% of the 1-iodonorbornane was recovered unreacted after 24 h. The fact that this reaction was profoundly inhibited by PDNB suggests that it occurs via a $S_{RN}1$ mechanism. We also carried out the reaction of $LiPPh_2$ with 1-iodonorbornane in 0.5:1 ratio; however, the reaction was so slow that only about 25% of the norbornane and a trace amount of substitution product was formed after 48 h. Since $LiPPh_2$ is not stable beyond 48 h at 0 °C, the study was not carried further. All the data suggest that reaction of 1-iodonorbornane with $LiPPh_2$ in THF takes place according to Scheme 2.

When 1-bromonorbornane was allowed to react with $LiPPh_2$ in diethyl ether or THF for 24 h, no reaction took place. Since naphthalene radical anion is a well-known one-electron donor, we suspected that if we added it to the reaction mixture of 1-bromonorbornane and lithium diphenylphosphide, the reaction would be initiated. On allowing 1 mole equiv of naphthalene radical anion to react with 1 mol equiv of 1-bromonorbornane in the absence of $LiPPh_2$, only a small amount of norbornane was formed and a large amount of the starting material was recovered; however, when 5 mol equiv of naphthalene radical anion was used, the reaction was complete in 10 min, and norbornane was the only product (Table 5, expt 1). On the other hand, the reaction between 1-bromonorbornane and $LiPPh_2$ in the presence of 5 mol equiv of naphthalene radical anion (Table 5, expt 2) produced 5% of the substitution product, indicating that reaction could be initiated by the naphthalene radical anion. The same experiment was carried out with 1-chloronorbornane as the substrate; however, no substitution product was detected and about 80% of the starting material was recovered after 24 h. This result is consistent with the difference in reduction potentials exhibited by alkyl halides.

It is clear that, although 1-bromonorbornane does not react with $LiPPh_2$ in THF in 24 h, it does react in the presence of the naphthalene radical anion to initiate

Table 3. Reactions of 1-Halonorbornanes with $NaSnMe_3$ at Room Temperature[a]

					% yield[b]		
entry	halogen	solvent	time	additive (equiv)	H	$SnMe_3$	X
1	I	THF	10 s	none	15	93	0
2	I	THF	5 min	DCPH (10)	72	28	0
3	Br	THF	2 h	none	trace	18	89
4	Br	THF	2 h	DCPH (10)	12	14	76
5	Br	Et_2O	5 h	none	trace	100	0
6	Cl	Et_2O	48 h	none	trace	0	99
7	OTs	Et_2O	48 h	none	0	0	100

[a,b] The same as Table 1 except for the reaction times.

Table 4. Reactions of 1-Iodonorbornane with $LiPPh_2$ in THF at Room Temperature[a]

			% yield[b] (%D)[c]	
entry	time	additive (equiv)	H	PPh_2[f]
1	180 min	none	72[d]	17
2	180 min	DCPH (10)	82	10
3	180 min	DCPD (10)	78 (39% D)	15
4[e]	180 min	DCPD (10)	67 (87% D)	29
5[g]	24 h	PDNB (0.1)	15	trace

[a-d] The same as Table 1 except for the reaction times. [e] THF-d_8 used instead of THF. [f] The substituted product was isolated and detected as the oxide. [g] There is 70% unreacted 1-iodonorbornane present.

Table 5. Reactions of 1-Halonorbornanes with $LiPPh_2$ Using 5 Equiv of Naphthalene Radical Anion in THF at 0 °C[a]

				% yield[b]		
entry	halogen	Nu	time	H	PPh_2	X
1	Br	none	10 min	95	0	0
2	Br	$LiPPh_2$	1 h	85	5	0
3	Cl[c]	none	10 min	20	0	78
4	Cl	$LiPPh_2$	24 h	21	0	80

[a,b] The same as in Table 1 except for the reaction times. [c] The yield does not change after 10 min.

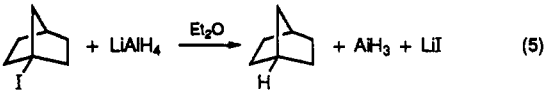
Table 6. Reactions of 1-Halonorbornanes with LAH or LAD in Diethyl Ether at Room Temperature[a]

entry	halogen	Nu	time (h)	H
1	I	LAH	48	98
2	I	LAD	48	97 (12% D)
3[d]	I	LAH	48	98 (10% D)
4[d]	I	LAD	48	95 (89% D)
5	Br	LAD	96	92 (9% D)
6[e]	Cl	LAD	96	21 (4% D)

[a-c] The same as in Table 1 except for the reaction times. [d] Carried out in Et_2O-d_{10}. [e] 79% of the unreacted 1-chloronorbornane was recovered.

reaction and produce both reduction and substitution product which is formed via the norbornyl radical.

Reaction of 1-Halonorbornanes with Lithium Aluminum Hydride. The reduction of an alkyl halide to the corresponding hydrocarbon by lithium aluminum hydride (LAH) is a well-known reaction that has been studied in some detail by a number of laboratories.[21,22] A variety of mechanisms, including S_N2 and radical pathways, have been proposed to describe the details of this reaction. We have reported the results of a mechanistic study and have provided evidence for electron transfer in the reaction of secondary and hindered primary alkyl iodides with LAH in THF.[21,22] The results of our studies using LAH as a nucleophile in its reactions with 1-halonorbornanes (eq 5)



(5)

are reported in Table 6.

Since these reactions were so slow in THF, they were carried out in diethyl ether. Norbornane was the only detectable product. On the basis of all of the data reported in Table 6, it is suggested that SET is involved in the reaction of LAH/LAD with the iodide, bromide, and chloride. Deuterium incorporation was not detected when LAH was allowed to react with 1-iodonorbornane and then quenched with D_2O, which implies that metal–halogen exchange is not involved in the formation of 1-lithionorbornane which would hydrolyze in D_2O to form 1-deuterionorbornane. In view of the high protium (12%) incorporation (expt 2) when LAD was the nucleophile, the reaction is proposed to proceed mainly via the norbornyl radical which abstracts hydrogen from the solvent. Although the norbornyl radical can abstract a hydrogen atom from either LAD or solvent, due to the primary protium/deterium kinetic isotope effect, most of the hydrogen atom abstraction came from the solvent. When the reaction was carried out with LAH in Et_2O-d_{10} (expt 3), still only a small amount of deuterium product (10%) was produced. Presumably because of the primary protium/deterium kinetic isotope effect, the majority of hydrogen atom abstraction is from the LAH. Only when the reaction was carried out in Et_2O-d_{10} and LAD did the deuterium incorporation reached 89%. (Higher deuterium incorporation was not possible since the LAD contained only 95% deuterium.) These results give good evidence for the existence of the 1-norbornyl radical as the major, if not the sole intermediate, and also provides a beautiful picture of the balanced hydrogen atom donating competition between LAH/LAD and the solvent because of the primary protium/deuterium kinetic isotope effect. All of the data reported here are consistent with the mechanistic

(21) Ashby, E. C.; Pham, T. N.; Amrollah-Madjdabodi, A. (and references contained therein). *J. Org. Chem.* **1991**, *56*, 1596.
(22) Ashby, E. C.; Depriest, R. N.; Goel, A. B. *J. Org. Chem.* **1984**, *49*, 3545.

Scheme 5

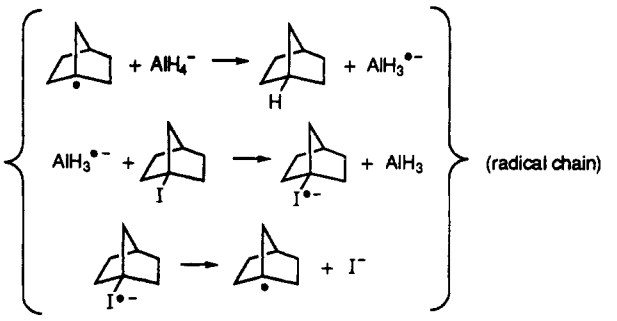


Table 7. Reactions of 1-Halonorbornanes with LDA in THF for 48 h[a]

entry	halogen	Nu	H
1	I	LDA	97 (0% D)[f]
2[d]	I	LDA	95 (0% D)
3	I	LDA-d_2	94 (10% D)
4[d]	I	LDA-d_2	90 (74% D)
5	Br[e]	LDA	0

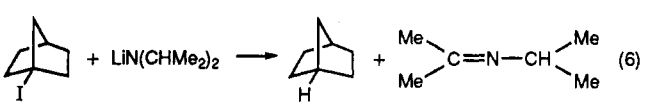
[a-c] The same as in Table 1 except for reaction times. [d] Solvent is THF-d_8. [e] No product detected. [f] Reaction mixture hydrolyzed with D_2O.

conclusions reported earlier for the reaction of $LiAlH_4$ with hindered primary alkyl iodides.[20] The mechanism of reaction is presented in Scheme 5.

The low deuterium content of the norbornane produced when either 1-bromo- or 1-chloronorbornane was allowed to react with LAD is evidence (for the same reasons mentioned above for the corresponding 1-iodo compound) that the majority of norbornane is produced by an electron transfer pathway involving the 1-norbornyl radical. The slower reaction rate involving the bromide and chloride with respect to the corresponding iodide is due to the ease of reduction of alkyl halides in the order I > Br > Cl.

Reaction of 1-Iodonorbornane with Lithium Diisopropylamide (LDA). We have recently shown that LDA can act as a one electron donor toward sterically hindered primary alkyl iodides.[23] The mechanistic pathway that describes this reaction depends not only on the structure of the alkyl halide, but also on the nature of the halogen. Reaction of a sterically hindered primary alkyl iodide formed radical, carbanion, and carbene intermediates whereas the reaction of LDA with the corresponding bromide and chloride produced predominantly a carbene intermediate.

The results of the reaction of LDA with 1-iodonorbornane (eq 6) can be found in Table 7. When 1-iodonorbornane was allowed to react with LDA in THF, norbornane was formed in 97% yield (expt 1). Since no deuterium incorporation was found in the product after the reaction mixture was quenched with D_2O, it suggests that norbornane is not formed via metal–halogen exchange. It is



(6)

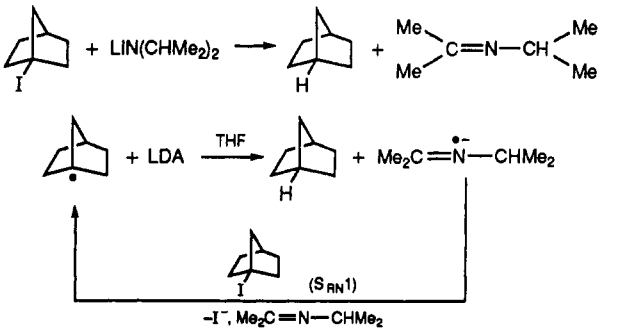
(23) Winiarski, J.; Bunnett, J. F. *J. Am. Chem. Soc.* **1985**, *107*, 5271. See controversy described in Ashby, E. C. *Acc. Chem. Res.* **1988**, *21*, 414. Ashby, E. C.; Park, B.; Patil, G. S.; Gadru, K.; Gurumurthy, R. *J. Org. Chem.* **1993**, *58*, 424.

Table 8. Reactions of 1-Iodonorbornane with Other Nucleophiles at Room Temperature[a]

entry	Nu	solvent	time	H
1	$LiC(Me)_2NO_2$	THF	48 h	trace
2	$LiC(Me)_2NO_2$	DMF	48 h	0
3	$LiSPr^i$	THF/Et_2O[c]	120 min	0

[a,b] The same as Table 1 except for reaction times. [c] 28% of THF is contained.

Scheme 6



possible that norbornane was produced via the 1-norbornyl radical abstraction of hydrogen from THF or from the α-position of LDA. In an attempt to determine the source of hydrogen in the reduction of 1-iodonorbornane by LDA in THF, the reaction was carried out in THF-d_8 (expt 2). Since deuterium incorporation was not observed in the product, then THF-d_8 was not the source of hydrogen in this reaction. Of course the C–H bond of THF was strengthened in the THF-d_8; therefore, it cannot be concluded that hydrogen atom abstraction in the case of protio THF did not come from THF. In the next experiment (expt 3), 1-iodonorbornane was allowed to react with LDA-d_2 in THF. In this case norbornane was formed in 94% yield and the product contained 10% deuterium. On the other hand, when 1-iodonorbornane was allowed to react with LDA-d_2 in THF-d_8 (expt 4), norbornane was formed in 90% yield with 74% deuterium incorporation. These data show that the hydrogen involved in the reduction comes from both THF and LDA. These data also show that if the reduction by LDA was polar (hydride ion attack), then deuterium incorporation in the product by THF-d_8 would not have been expected. The reason 100% deuterium incorporation was not observed is because the LDA-d_2 contained only 95% deuterium. The 5% protium in the LDA-d_2 and the fact that the ratio of 1-iodonorbornane to LDA-d_2 was 1:5 indicates that there was 25 mol % protium available in this reaction, and considering the primary protium/deuterium kinetic isotope effect, 74% deuterium incorporation in the product is not an unreasonable result. When the THF is deuterated, the hydrogen comes from the LDA; on the other hand, when the LDA is deuterated, the hydrogen comes predominantly from THF. These results are consistent with the formation of the 1-norbornyl radical followed by hydrogen atom abstraction from both THF and LDA, consistent with the mechanism reported earlier for this reaction (Scheme 6).[23] The reaction of LDA with the corresponding bromide did not take place, a result consistent with a SET mechanism and a less-favorable reduction potential of the bromide compared to the iodide.

Reaction of 1-Iodonorbornane with Other Nucleophiles. From work carried out by Kornblum and coworkers,[24] we know that the lithium salt of 2-nitropropane is a very good electron donor in many of its reactions with various alkyl halides. For this reason we attempted to react 1-iodonorbornane with this nucleophile; however, no reaction in DMF was observed after 48 h and only a trace amount of reduction product (norbornane) was formed in THF after the same amount of time. No trace of substitution product was detected. Since the lithium salt of 2-nitropropane is known to be a good one electron donor, it was anticipated that reduction of 1-iodonorbornane would take place to form the 1-norbornyl radical which would then form norbornane by hydrogen atom abstraction from THF. Steric hinderance between the norbornyl radical and the 2-nitropropyl anion would be greater than that expected for the trimethylstannyl anion or the diphenylphosphide anion (compare the bond lengths of the C–Sn, C–P, and C–C bonds); therefore, it is not surprising that substitution product was not formed.

Lithium 2-propanethiolate (i-PrSLi), a reasonably good nucleophile for S_N2 reactions and also a weak electron donor, failed to react with 1-iodonorbornane. The steric effect mentioned above may be one of the factors for the failure of the reaction; more importantly, however, is the fact that lithium 2-propanethiolate may not be a sufficiently strong one-electron donor to reduce 1-iodonorbornane.

Conclusions

On the basis of product analyses, the results of trapping experiments, deuterium labeling studies, and the order of nucleofugality exhibited in the reactions: I > Br > Cl > OTs, it appears that a single electron transfer pathway producing a radical intermediate is involved in the reaction of 1-halonorbornanes with several nucleophiles in THF. The product distribution was strongly affected by steric and electronic effects of the nucleophiles, the reduction potential of the alkyl halide, the primary protium/deuterium kinetic isotope effect of the H(D) atom donor, and the concentrations of the intermediates involved. Enhancement of the rate of reaction by the solvent was shown to be in the order: diethyl ether > THF > DMF > HMPA.

Experimental Section

Materials. Norcamphor, PCl_5, PCl_3, bromine, $AlCl_3$, $AlBr_3$, PBr_3, lithium suspension in mineral oil, sodium, resublimed iodide, toluenesulfonyl chloride, hexamethylditin, diphenylphosphine, lithium aluminum hydride, lithium hydride, di-*tert*-butylnitroxyl radical, and *p*-dinitrobenzene were purchased from Aldrich and used as received.

Anhydrous pentane was purchased from Aldrich and distilled from anhydrous $AlCl_3$ prior to use. Tetrahydrofuran, diethyl ether and benzene were purchased from Fisher and distilled from deep purple solutions of sodium benzophenone ketyl prior to use. Dimethylformamide and dimethyl sulfoxide were purchased from Fisher and distilled under reduced pressure from calcium hydride and stored over 4-Å molecular sieves. 2-Propanethiol and diisopropylamine were distilled from calcium hydride prior to use. Dicyclohexylphosphine was purchased from Strem Chemical and distilled under reduced pressure prior to use. Methyllithium and *sec*-butyllithium were purchased from Aldrich and the concentrations determined by Watson–Eastham titration prior to use. Diethyl ether-d_{10}, THF-d_8, and lithium aluminum deuteride were purchased from Aldrich or CIL and used as received. 2-Nitropropane was purchased and fractionally distilled to 99.5% purity.

General Procedures. All glassware was flame-dried and cooled under a nitrogen flush or under vacuum with a nitrogen backfill. All syringes and cannulas were oven-dried and cooled under a nitrogen flush. Solid reagents were transferred in an oxygen-free dry box filled with nitrogen. Liquids were either transfered in a dry box or by syringe or cannula.

A typical procedure for carrying out a reaction between a 1-norbornyl halide and a nucleophile is the following: A flame-dried 25-mL round-bottom flask was wrapped with aluminum foil and equipped with a Teflon stirring bar and a T-bore ground-glass stopcock attached to a 14/20 standard tapered ground-glass joint. A solution of the nucleophile was then transferred to the flask via syringe and diluted to 0.1 M with the solvent. The reaction flask was then cooled to the temperature at which the reaction was to be studied and the additives added at this point, and the solution of the 1-substituted norbornane (~0.02 M) was added to the reaction flask immediately via syringe. (Aliquots of 0.2 mL were periodically extracted from the solution using a syringe and analyzed by GC.) The reactions were conducted for the times shown in the tables and then quenched with either H_2O or D_2O. Whenever the % d_1 incorporation was needed, the products were subjected to mass spectral analysis. The crude products of the reactions of the 1-halonorbornanes with lithium diphenylphosphide were oxidized with 5% H_2O_2 in methylene chloride prior to analysis.

Proton and carbon NMR spectra were obtained on a Gemini 300 instrument with chemical shifts reported relative to TMS. IR spectra were recorded on a Beckman IR 4240 instrument in CCl_4 solution or on salt plates. Analytical gas chromatograms were obtained using a Varian Model 3700 gas chromatograph equipped with a FID detector and a 30-m DB-5 capillary column. Preparative GLC was carried out on a F&M Model 720 equipped with a TC detector and a 6 ft × 1/4 in. Apiezon column. Mass spectral analyses were performed using a Varian MAT-112S spectrometer.

1-Chloronorbornane. This compound was prepared by a modification of a literature method[25] and had the same spectral characteristics as those reported in the literature. In a dry box, a dry 500-mL three-neck round-bottom flask, equipped with a Teflon stirring bar, drying tube, and solid-addition funnel, was charged with 48.61 g (441 mmol) of norcamphor and 31.4 mL (360 mmol) of PCl_3. The solid-addition funnel was charged with 94.38 g (453 mmol) of PCl_5 in a N_2-filled dry box. The solution was then cooled to 0 °C in an ice–salt bath and PCl_5 added over a 2-h period with stirring. The mixture was then allowed to warm to room temperature overnight. The contents of the flask were poured over 600 g of ice and extracted with pentane. The extract was dried over $MgSO_4$ and the solvent evaporated under reduced pressure. Distillation of residual liquid under reduced pressure gave 53.9 g (75% yield) of 2,2-dichloronorbornane, bp 69–71 °C (11 mm).

In a N_2-filled dry box, a dry 1000-mL, three-neck flask was equipped with a solid-addition funnel and a reflux condenser with a drying tube. The addition funnel was charged with 11.8 g (88.2 mmol) of $AlCl_3$ and the flask was charged with 31.1 g (188 mmol) of 2,2-dichloronorbornane. The apparatus was stoppered with a septum and removed from the dry box. Dry pentane (400 mL) was added by cannula and the stopper rapidly replaced with a sleeved mechanical stirrer. Aluminum trichloride was then added with stirring over a 4-h period. The mixture was then stirred for 40 h at which point the pentane was decanted and the resulting sludge thoroughly extracted with pentane. The decanted pentane and pentane extracts were combined and washed with saturated brine and then with water. The organic layer was dried over anhydrous $MgSO_4$ and evaporated under reduced pressure. The residue was then distilled under reduced pressure through a 3 × 30 cm vacuum-jacketed column packed with glass

(24) Kornblum, N.; Davies, T. M.; Earl, G. W. *J. Am. Chem. Soc.* **1976**, *89*, 725. Kornblum, N.; Boyd, D.; Stuchal, F. W. *J. Am. Chem. Soc.* **1970**, *92*, 5783.

(25) Bixler, R. L.; Niemann, C. *J. Org. Chem.* **1958**, *23*, 742.

helices to afford 13.2 g (54% yield) of 1-chloronorbornane (bp 70–72 °C) as a low-melting solid which was shown by GC to be 99.2% pure with the following spectral properties: ^{13}C NMR ($CDCl_3$) C1 69.53, C2,6 38.10, C3,5 30.60, C4 34.51, C7 46.52 ppm; IR (CCl_4) cm^{-1} 1460, 1317, 1304, 1031, 993, 950, 910, 841.

1-Bromonorbornane. The procedure adapted to make this compound was based on a literature procedure.[26] The spectral properties of the product agreed with those reported.

In a N_2-filled dry box, a three-neck, 250-mL round-bottom flask, equipped with a Teflon stirring bar, drying tube, and addition funnel, was charged with 15.0 g (136.2 mmol) of norcamphor and 10.5 mL (111 mmol) of PBr_3. The addition funnel was charged with 7.85 mL (152 mmol) of bromine and the apparatus removed from the dry box. The solution was cooled to 0 °C in an ice–salt bath and the bromine added dropwise over a 2-h period with stirring. The orange solution was allowed to warm to room temperature overnight. The contents of the flask were poured onto 200 g of ice and the mixture extracted with pentane and dried over anhydrous $MgSO_4$. The solvent was evaporated under reduced pressure and distillation of the residual liquid under reduced pressure afforded 18.3 g (53% yield) of 2,2-dibromonorbornane (bp 95–98 °C/9 mmHg).

In a N_2-filled dry box, a 250-mL three-neck round-bottom flask was equipped with a solid-addition funnel, a reflux condenser with a drying tube, and a rubber septum. The addition funnel was charged with 13.5 g (50.5 mmol) of $AlBr_3$ and the apparatus removed from the dry box. A solution of 12.8 g (44 mmol) of 2,2-dibromonorbornane in 150 mL of pentane was added to the flask by cannula and the septum rapidly replaced with a sleeved mechanical stirrer. The $AlBr_3$ was added in small portions over a 4-h period with stirring at room temperature. A brown sludge began to accumulate on the sides of the flask after about 10 min. The mixture was allowed to stir for 40 h at which point the pentane was decanted from the sludge. The pentane solution was washed with water and saturated brine and then dried over anhydrous $MgSO_4$. The solvent was evaporated under reduced pressure, and distillation under reduced pressure afforded 3.16 g (41% yield) of 1-bromonorbornane (bp 61–65 °C/18 mmHg). The distilled product was further refined to 99.8% purity by preparative gas chromatography: ^{13}C NMR ($CDCl_3$) C1 61.96, C2,6 39.67, c3,5 31,37, C4 34.56, C7 47.91 ppm; IR (CCl_4) cm^{-1} 2980, 2927, 2882, 1457, 1312, 1301, 1258, 1222, 982, 941, 901, 833; MS (EI) *m/e* (relative intensity) 176 (27.7), 174 (28.3), 147 (24.3), 145 (24.8), 95 (100), 67 (28.3).

1-Iodonorbornane. This compound was prepared as follows and showed identical properties to the product prepared by a published method.[27,28] In a N_2-filled dry box, a 250 mL, three-neck flask was equipped with a sintered-glass fritted filter with vacuum adapter to which was attached a 50-mL round-bottom flask. The other two necks were equipped with a reflux condenser attached to a T-bore stopcock and a pressure-equalizing addition funnel. To the flask was added a Teflon stirring bar and 4.13 g (165 mmol) of 30% lithium and 2% sodium in a mineral oil suspension. The mineral oil was removed by vacuum filtration followed by repeated rinsing with dry cyclohexane. The lithium was then rinsed from the frit with 20 mL of cyclohexane and the 50-mL flask replaced with a 250-mL flask. The apparatus was removed from the dry box, a nitrogen line was connected to the stopcock, and 20 mL of a solution of 4.77 g (36.5 mmol) of 1-chloronorbornane in cyclohexane was transferred to the addition funnel via a cannula. One-half of the solution was added to the lithium with stirring and the flask heated in an oil bath to 80 °C, at which point an exothermic reaction was observed. The rest of the solution of 1-chloronorbornane was added to the flask dropwise over 20 min and the mixture stirred at reflux temperature for 1 h. The flask was allowed to cool, the condenser replaced by a stopper, and the apparatus returned to the dry box. The cyclohexane was vacuum-filtered from the lithium chloride and excess lithium and the residue extracted with dry pentane. The filtrate was collected in the 250-mL flask attached to the sintered glass filter. The flask was equipped with a pressure-equalizing jacketed dropping funnel and a Teflon stirring bar and then removed from the dry box. The solution was then evaporated under vacuum to about 5 mL. Dry ether (10 mL) was added to the flask, and 9.26 g (36.5 mmol) of iodine in 30 mL of dry ether was added to the funnel. The jacket on the addition funnel was loaded with ice–salt and the flask immersed in an ice–salt bath at 0 °C. The iodine solution was added dropwise with stirring until a pink color was observed. The flask was allowed to warm to room temperature, and the solution washed with 20 mL of 10% aqueous sodium thiosulfate, 20 mL of saturated brine, followed by 20 mL of water and the resulting ether solution was dried over anhydrous sodium sulfate. The product was purified by column chromatography; GC analysis showed it to be 99.8% pure: ^{13}C NMR ($CDCl_3$) C1 37.7, C2,6 43.3, C3,5 32.44, C4 34.86, C7 51.14 ppm; MS (EI) *m/e* (relative intensity) 22 (33.7), 127 (3.8), 95 (100), 67 (38), 55 (7); IR (CCl_4) cm^{-1} 2960, 2875, 1450, 1309, 1253, 972, 892.

1-Norbornyl Tosylate. This compound was prepared by a modified known procedure and had spectral characteristics in agreement with the literature values.[9] To a 50-mL round-bottom flask, equipped with a stirring bar, was added 0.50 g (4.5 mmol) of 1-norbornanol.[29] To this flask, was added 20 mL of dry benzene, 5 mL of pyridine, and 0.715 g (3.75 mmol) of *p*-toluenesulfonyl chloride. The flask was fitted with a reflux condenser and a Dean–Stark trap and the solution allowed to reflux for 12 h. Analysis by GC showed no unreacted alcohol. The mixture was slurried with 100 g of ice and 100 mL of 20% aqueous HCl, resulting in the separation of the benzene layer. The benzene layer was washed with 20% aqueous HCl and dried over anhydrous $MgSO_4$. The solvent was removed under vacuum and the residue separated by preparative GC to yield 0.50 g of the tosylate (mp 97.0–97.5): ^1H NMR ($CDCl_3$) 7.66 (m, 4H), 2.49 (s, 3H), 2.20 (m, 1 H), 1.2–2.1 (m, 10H) ppm.

(Trimethylstannyl)sodium. This compound was prepared according to a modified literature method.[30] To a 100-mL three-neck round-bottom flask, equipped with a Hershberg stirrer and a T-bore stopcock, was added 0.36 g (16 mmol) of finely cut sodium which had been washed with dry THF. The flask was cooled in an ice-salt bath, and an ice-cooled solution of 2.25 g (6.84 mmol) of hexamethylditin in 17 mL of THF was added via a cannula. The mixture was stirred vigorously at 0 °C for 4 h and allowed to warm to room temperature. The black precipitate was allowed to settle and the supernatant transferred under nitrogen to four dried test tubes that were stoppered with serum sleeve stoppers. The solutions were centrifuged and the supernatants transferred via cannula to a flask equipped with a T-bore stopcock. The flask was stored under nitrogen at −10 °C. The purity of the compound was determined by ^1H and ^{13}C NMR and found to be 99.5+%. No starting material was detected.

Lithium Diphenylphosphide. To a 100-mL flask, equipped with an addition funnel, a stirring bar, and a T-bore stopcock, was added 20 mL of THF and 1.0 mL of diphenylphosphine (5.75 mmol) via syringe under nitrogen. The flask was cooled to −78 °C in a dry ice–acetone bath, and 3.8 mL (5.7 mmol) of 1.48 M *sec*-butyllithium was added dropwise. The reaction was stirred for 8 h after which time the contents were stored under nitrogen at −10 °C. The purity of the compound was determined by ^1H and ^{31}P NMR and found to be 99+%.[31] Aliquots (1.00 mL) of the above solution (equilibrated at 0 °C) were removed by syringe and quenched with 20 mL of distilled water and then titrated with 0.0100 N HCl to a clear end point using phenolphthalein as the indicator.

Lithium Aluminum Hydride and Lithium Aluminum Deuteride. Solutions of both of these compounds were prepared and titrated according to known procedures.[32]

Lithium Diisopropylamide. An amount of 2.50 mmol of lithium diisopropylamide was prepared by the reaction of 4.20 mL (3.00 mmol) of diisopropylamine and 1.85 mL (2.50 mmol)

(26) Keese, R.; Krebs, E. *Angew. Chem., Int. Ed. Engl.* **1878**, *10*, 262.
(27) Poindexter, G. S.; Kropp, P. J. *J. Org. Chem.* **1976**, *41*, 1215.
(28) Lansbury, P. T.; Pattison, V. A.; Sidler, J. D.; Bieber, J. B. *J. Am. Chem. Soc.* **1966**, *88*, 78.
(29) Lansbury, P. T.; Pattison, V. A.; Sidler, J. D.; Bieber, J. B. *J. Am. Chem. Soc.* **1974**, *96*, 7142.
(30) Smith, G. F.; Kuivila, H. G.; Sierra, R.; Sultan, L. *J. Am. Chem. Soc.* **1981**, *103*, 833.
(31) Ashby, E. C.; Gurumurthy, R.; Ridlehuber, R. W. *J. Org. Chem.* **1993**, *58*, 5832.
(32) Krishnamurthy, S.; Brown, H. C. *J. Org. Chem.* **1980**, *45*, 849. Ashby, E. C.; Boone, J. R. *J. Am. Chem. Soc.* **1976**, *98*, 5524.

of MeLi at −78 °C in THF for 30 min.[23] The temperature was then allowed to increase to room temperature while the solvent was removed under vacuum. Finally dry THF was added to the resulting white-powered LDA while cooling in an ice–salt bath. The concentration was determined by titrating with *sec*-butanol in xylene with 2,2′-bipyridine as the indicator and the purity (98+%) was determined by quenching with D_2O followed by deuterium analysis of the resulting diisopropylamine.

Lithium Salt of 2-Nitropropane. This compound was prepared according to a known procedure.[33] In the dry box, 0.3913 g (49.53 mmol) of LiH was added to 50 mL of absolute ethyl alcohol. After the solution became clear, 4.5 g (50.56 mmol) of 2-nitropropane was added and the solvent removed under vacuum. When the solution became viscous, but before precipitation, 350 mL of dry diethyl ether was added to cause precipitation of a solid. The solid was filtered, transferred to a flask, and dried under vacuum for 48 h. The compound was titrated with ethanolic picric acid and found to be 98.5% pure.

Lithium 2-Propanethiolate. A three-neck, 100-mL flask was equipped with a dropping funnel, a T-bore stopcock, and a stirring bar and cooled to −78 °C in a dry ice–acetone bath. A volume of 3.8 mL (42 mmol) of 2-propanethiol in 10 mL of dry ether was added to the flask. The solution was allowed to cool and 20.0 mL (30 mmol) of a solution of 1.50 M methyllithium in ether was added dropwise. The mixture was stirred for 1 h and allowed to warm to room temperature. The ether and excess 2-propanethiol were removed under vacuum, and 60 mL of THF added to dissolve the residue. Aliquots of 1.00 mL of the resulting solution were quenched with 20-mL portions of distilled water and titrated with 0.0500 M HCl to a clear endpoint using phenophthalein as the indicator.

Deuteriodicyclohexylphosphine (DCPD). In the dry box, a flask was filled with 3.2 g (16 mmol) of dicyclohexylphosphine in 30 mL of dry ether. An amount of 1.35 g (16 mmol) of phenyllithium was then added dropwise. A solid began to form, and the solution was filtered and quenched with D_2O carefully. A volume of 5 mL of dry ether was added to the mixture, and the organic layer was separated and dried over $MgSO_4$. The solvent was then removed using a rotary evaporator and the residue distilled under reduced pressure (bp 81–84 °C/0.1 mmHg) to afford 2 g of DCPD. The purity of the compound was determined by ^1H NMR; no starting material was detected: ^1H NMR (C_6D_6) 2.0–1.7 (m, 12H), 1.65–1.5 (m, 10H) ppm. The compound was compared to an authentic sample, prepared by a different method,[34] by infrared analysis and found to be identical. Mass spectral analysis was not successful due to the facile oxidation of DCPD.

Diisopropylamine(2-d_2). This compound was prepared from acetone, sodium cyanoborodeuteride, and ammonium acetate by a published procedure[35] and found to contain the α-deutero compound in 95% purity.

Norbornane. This compound was separated from the reaction mixture by column chromatography over silica gel by elution with pentane: ^1H NMR ($CDCl_3$) 2.2 (s, 2H), 1.0–1.5 (m, 10H) ppm; MS (EI) (relative intensity) 96.1 (21.0), 81.1 (87.8), 67.1 (100.0), 54.1 (49.9), 41.0 (23.7), 39.0 (29.9).

1-Norbornyldiphenylphosphine Oxide. This compound was separated by column chromatography over silica gel by elution with ether and hexane: ^1H NMR ($CDCl_3$) 7.35–7.9 (m, 10H), 2.4 (s, 1H), 1.1–1.9 (m, 10H); MS (EI) (relative intensity) 296.2 (60.3), 267.1 (100.0), 201.1 (98.7), 77.1 (40.1); calcd mass 296.1330; obsd mass 296.1334.

1-Norbornyltrimethyltin. This compound was separated in the reaction mixture by preparative GC: column temperature (130 °C), flow rate (40/min); ^1H NMR (CCl_4) 0.01 (5, 9H), 1.05–1.55 (m, 11H); MS (EI) (relative intensity) 260 (4.3), 258 (3.1), 245 (100.0), 165 (43.6), 163 (32.0), 95 (14.0), 67 (11.2), 41 (11.5).

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(33) Kerber, R. C.; Urray, G. W.; Kornblum, N. *J. Am. Chem. Soc.* **1965**, *87*, 4520.

(34) Ashby, E. C.; Depriest, R. N.; Su, W.-Y. *Organometallics* **1984**, *3*, 1718.

(35) Newcomb, M.; Varick, T. R.; Goh, S.-H. *J. Am. Chem. Soc.* **1990**, *112*, 5186.