Reactions of Tin(IV) Enolates Obtained from *O*-Stannyl Ketyls under Neutral Free Radical Conditions

Eric J. Enholm,* Paul E. Whitley, and Yongping Xie

Department of Chemistry, University of Florida, Gainesville, Florida 32611

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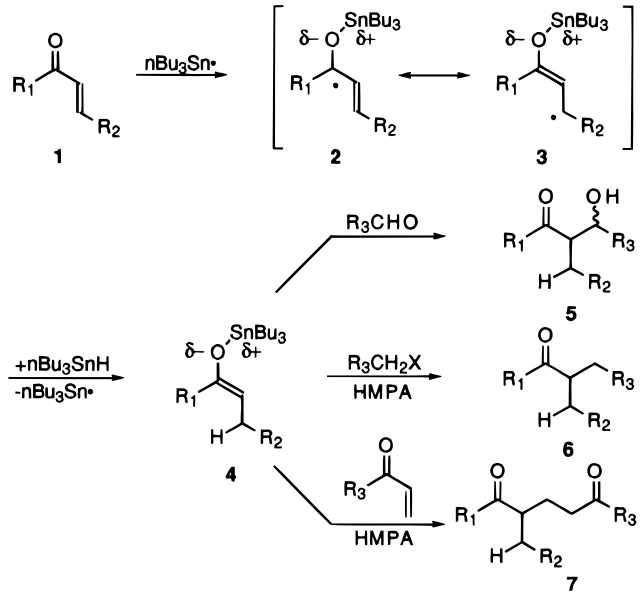
Under mild and neutral free radical conditions, an α,β-unsaturated ketone reacted with tributyltin hydride to produce an intermediate resonance-stabilized allylic *O*-stannyl ketyl. Upon subsequent hydrogen atom abstraction, a tin(IV) enolate was afforded which could be quenched with a variety of electrophiles and form new carbon−carbon bonds. Aldehydes react to produce aldol-type products and both intramolecular and intermolecular carbonyl addition reactions were investigated using this strategy. Using similar methodology, the tin(IV) enolate could be quenched in the presence of HMPA with various alkyl halides and α,β-unsaturated carbonyl compounds (Michael acceptors) to yield alkylated products in good yields. These reactions represent a very mild regioselective alternative to metal enolate formation which usually requires strong bases such as LDA or strongly reductive dissolving metal conditions to achieve success. New carbon skeletons for natural product synthesis can be readily constructed using this chemically neutral approach.

Introduction

Free radicals have been used in organic synthesis to construct a wide variety of carbon and heteroatom skeletons.[1] Ketyl radical anions possess both radical and nucleophilic character; however, the latter has not been studied in detail, particularly in synthetic applications.[2] The preparation of ketyls bearing a variety of metal counterions has been achieved by partial reduction or one-electron transfer to a ketone using photochemical, electrochemical, and metal-mediated approaches.[3] Recent studies in our group utilize a tin-based free radical method which produces delocalized *O*-stannyl ketyl radical anions from the reaction of an α,β-unsaturated carbonyl group with tributytin hydride and a radical initiator.[4−6] Thus, α,β-unsaturated ketone **1** can be reacted with nBu_3SnH under standard free radical conditions to give allylic *O*-stannyl ketyl (**2** ↔ **3**), shown in Scheme 1. After hydrogen atom transfer to the β-position of **3**, a synthetically useful tin(IV) enolate **4** is produced.[6−8]

Scheme 1



This direct and chemically neutral method to prepare tin(IV) enolates remains under-utilized in synthesis. The method is in marked contrast to the strongly reductive conditions of a dissolving metal reaction of an enone, which is one of the most commonly employed methods to prepare metal enolates. Tin(IV) enolates have also been prepared by methods not involving enones. The most common method involves deprotonation and trapping a lithium enolate with nBu_3SnCl, where a strong base is, unfortunately, a necessary prerequisite.[4]

Several aldehydes might be selected to quench enolate **4** and produce aldol-type products **5**.[7] Intramolecular and intermolecular carbonyl addition reactions might be readily applied to this strategy.[6] Using a related approach, the tin(IV) enolate could also be quenched with various alkyl halides to produce α-alkylated products **6.**[8] Conjugate additions using α,β-unsaturated carbonyl compounds (Michael acceptors) provide a different route

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(1) (a) Giese, B. *Radicals in Organic Synthesis: Formation of Carbon-Carbon Bonds*; Pergamon Press: New York, 1986. (b) Ramaiah, M. *Tetrahedron* **1987**, *43*, 3541. (c) Curran, D. P. *Synthesis* **1988**, 417, 489. (d) Hart, D. J. *Science* **1984**, *223*, 883. (e) Motherwell, W. B.; Crich, D. *Free Radical Chain Reactions in Organic Synthesis*; Academic Press: New York, 1992.

(2) For reveiws of ketyl radical anions, see: (a) Hirota, N. *Radical Ions*; Kasiser, E. T., Kevan, L. Eds., Wiley Interscience: New York, 1968; pp 35−85. (b) Russell, G. A. *Radical Ions*; Kasiser, E. T., Kevan, L., Eds., Wiley Interscience: New York, 1968; pp 87−150. (c) Forrester, A. R.; Hay, J. M.; Thompson, R. H. *Organic Chemistry of Stable Free Radicals*; Academic Press: New York, 1968; pp 82−90.

(3) (a) Cossy, J.; Belotti, D.; Pete, J. P. *Tetrahedron Lett.* **1987**, 4547. (b) Shono, T.; Kashimura, S.; Mori, Y.; Hayashi, T.; Soejima, T.; Yamaguchi, Y. *J. Org. Chem.* **1989**, *54*, 6002; (c) Shono, T.; Kise, N.; Suzumoto, T.; Morimoto, T. *J. Am. Chem. Soc.* **1986**, *108*, 4676. (d) Swartz, J. E.; Mahachi, T. J.; Kariv-Miller, E. *J. Am. Chem. Soc.* **1988**, *110*, 3622. (e) Kariv-Miller, E.; Maeda, H.; Lombardo, F. *J. Org. Chem.* **1989**, *54*, 4022. (f) Little, R. D.; Fox, D. P.; Hijfte, L. V.; Dannecker, R.; Sowell, G.; Wolin, R. L.; Moens, R. L.; Baizer, M. M. *J. Org. Chem.* **1988**, 53, 2287. (g) Molander, G. A. *The Chemistry of the Metal-Carbon Bond*; Hartley, F. R., Ed.; J. Wiley & Sons: New York, 1989; Vol. 5, Chapter 8, pp 319−396. (h) Molander, G. A. *Chem. Rev.* **1992**, *92*, 29.

(4) Pereyre, M.; Quintard, J. P.; Rahm A. *Tin in Organic Sythesis*; Butterworths: Boston, 1989.

(5) (a) Enholm, E. J.; Prasad, G. *Tetrahedron Lett.* **1989**, 4939. (b) Enholm, E. J.; Kinter, K. S. *J. Am. Chem. Soc.* **1991**, *113*, 7784. (c) Enholm, E. J.; Burroff, J. A. *Tetrahedron Lett.* **1992**, 1835.

(6) Enholm, E. J.; Xie, Y.; Abboud, K. A. *J. Org. Chem.* **1995**, *60*, 1112.

(7) Enholm, E. J.; Whitley, P. E. *Tetrahedron Lett.* **1995**, 9157.

(8) Enholm, E. J.; Whitley, P. E. *Tetrahedron Lett.* **1996**, 559.

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Scheme 2

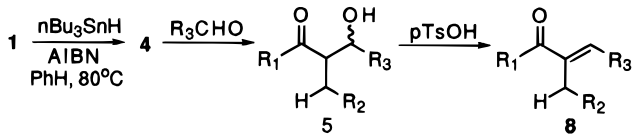


Table 1. Aldol Reactions of Tin(IV) Enolates

Entry	Enone	Ald.	Aldol	Yield (%) (erythro : threo)	Elim. Product	Yield (%) (E : Z)
1	9	12	$R_{1a}CHOHR_{3a}$ **15**	73 (6:1)	R_{1a}=CH-R_{3a} **16**	92 (82:1)
2	9	13	$R_{1a}CHOHR_{3b}$ **17**	59 (6:1)	R_{1a}=CH-R_{3b} **18**	95 (20:1)
3	9	14	$R_{1a}CHOHR_{3c}$ **19**	56 (4:1)	R_{1a}=CH-R_{3c} **20**	89 (13:1)
4	10	12	$R_{1b}CHOHR_{3a}$ **21**	79 (1:1)	R_{1b}=CH-R_{3a} **22**	78 (15:1)
5	10	13	$R_{1b}CHOHR_{3b}$ **23**	62 (3:1)	R_{1b}=CH-R_{3b} **24**	90 (>100:1)
6	10	14	$R_{1b}CHOHR_{3c}$ **25**	63 (1:1)	R_{1b}=CH-R_{3c} **26**	94 (41:1)
7	11	12	$R_{1c}CHOHR_{3a}$ **27**	52 (2.5:1)	R_{1c}=CH-R_{3a} **28**	53 (23:1)
8	11	13	$R_{1c}CHOHR_{3b}$ **29**	45 (4:1)	R_{1c}=CH-R_{3b} **30**	88 (34:1)

Enones used: 2-cyclohexenone (**9**), 2-cyclopentenone (**10**), 4-hexen-3-one (**11**)

Aldehydes used: benzaldehyde (**12**), cyclohexanecarboxaldehyde (**13**), heptanal (**14**)

R_{1a} = 2-cyclohexanone, R_{1b} = 2-cyclopentanone, R_{1c} = 4-(3-hexanone), R_{3a} = Phenyl, R_{3b} = cyclohexyl, R_{3c} = n-hexyl,

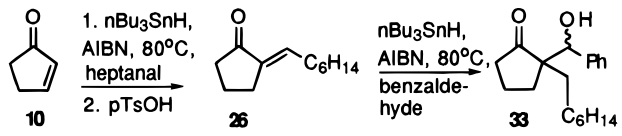
to alkylated products **7**. In these studies, we expected the tin(IV) enolate to be intrinsically less reactive than a lithium enolate, yet be more reactive than a silyl enol ether and exhibit nucleophilicity somewhere between these two related species. Thus, activated and primary alkyl halides, aldehydes, and β-unsubstituted Michael acceptors were selected as electrophiles for the less reactive tin(IV) enolates.

This Article will show that a tin(IV) enolate, formed by the method above, can be quenched with a variety of electrophiles and form new carbon−carbon bonds. Herein, we describe the first examples of carbonyl addition (aldol-type) reactions, alkylations, and conjugate additions of tin(IV) enolates promoted by tributyltin hydride.[6−8]

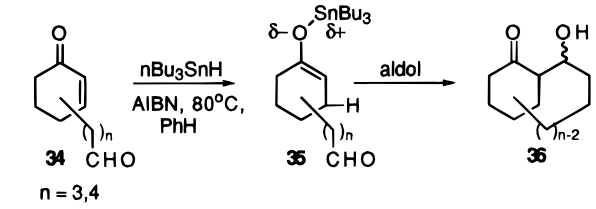
Results and Discussion

Intermolecular Aldol Reactions. The first attempt at an intermolecular aldol reaction was performed with the enone and the aldehyde in the same pot present from the onset of the reaction (see Scheme 2). After consumption of the enone, the major isolated product was indeed the desired aldol product **5**. However, the yields were modest (30−50%), and several undetermined side products were isolated. Next, the tin(IV) enolate was generated first with nBu_3SnH and then subsequently quenched with the aldehyde at 10 °C, which did indeed improve the yields (see Table 1). The aldol diastereomer ratios, estimated by NMR integration due to GC instability, ranged from 1:1 to 6:1, favoring the erythro isomer by

Scheme 3



Scheme 4



modest amounts.[9−11] This is similar to earlier examples of aldol reactions of tin(IV) enolates, where the erythro product becomes more favored, regardless of enolate geometry, at temperatures > −50 °C.[20] Treatment of the aldols **5** with *p*-TsOH readily afforded dehydration products **8** which were much more stable, highly favoring the trans geometric isomer as readily determined by capillary GC.

Yields were highest for the reaction of cyclic unsaturated ketones with benzaldehyde. Although the aldol products gave some modest ratios and yields, the corresponding acid dehydration products, yields and ratios were almost all very high. Only the dehydration producing **28** was special and required careful addition of small portions of acid. Too much *p*-TsOH in that case only decreased the yield and increased the amount of byproducts.

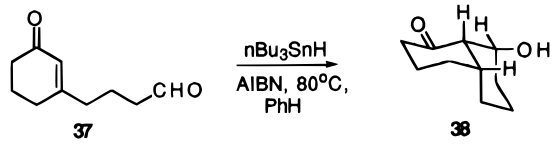
The removal of any excess tributyltin hydride and other tin byproducts was most efficiently accomplished by treatment with 1,8-diazobicyclo[5.4.0]undec-7-ene (DBU) and iodine and rapid filtration through silica gel.[12] The method was found to be very useful, since most of the tin compounds present after the reaction could be removed prior to flash column chromatography.

Because the dehydration products are themselves unsaturated ketones, the feasibility of an additional aldol reaction was studied (see Scheme 3). This reaction used cyclopentanone (**10**) with heptanal as the first aldehyde which was then eliminated to the alkene **26**. Resubjecting it to the same neutral free radical conditions but using a benzaldehyde quench afforded **33** in ca. 40% yield for the three-step process.

Intramolecular Aldol Reactions. The intramolecular variant of the reactions discussed above was studied using cyclohexenone precursors with aldehyde tethers, as shown in Scheme 4.[6] The benefit of this sequence is that it provides an intramolecular aldol from an enone under neutral and nonbasic free radical conditions. The intermolecular reaction was not as successful with the aldehyde present at the onset of the reaction; therefore, we were very concerned at the outset about this sequence. There was no assurance that the aldehyde tethered to the enone might form an undesirable *O*-stannyl ketyl and be reduced to a primary alcohol or lead to non-aldol products.

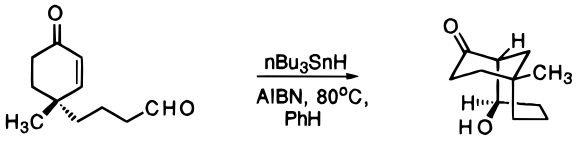
(9) Yamamoto, Y.; Yatagai, H. *J. Chem. Soc., Chem. Commun.* **1981**, 162.
(10) Stille, J. K.; Shenvi, S. *Tetrahedron Lett.* **1982**, *23*, 627.
(11) House, H. O.; Crumrine, D. S. *J. Am. Chem. Soc.* **1973**, *95*, 3310.
(12) Curran, D. P.; Chang, C. *J. Org. Chem.* **1989**, *54*, 3140.

Scheme 5



37 38

Scheme 6



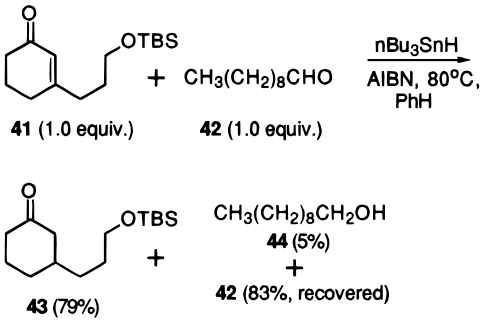
39 40

Enones **37** and **39** were utilized as the cyclohexenones with aldehyde tethers located at two sites, C_3 and C_4, on the ring, as shown in Schemes 5 and 6, respectively. Aldehyde precursor **37**, bearing a carbonyl tether in the C_3-position on a cyclohexanone ring, was readily prepared by a four-carbon alcohol chain extension using the Normant Grignard of 3-chlorobutanol by the method of Godlesky.[13] Decalone alcohol **38**, formed in 81% yield, has three new stereocenters resulting from the cyclization, one bearing the alcohol and two arising from a *cis*-decalin ring fusion. The stereochemistry of **38** was unambiguously established by single crystal X-ray analysis.[14]

A second example, **39**, bearing a different pattern of substitution on the cyclohexanone, was prepared by the introduction of an γ-alcohol appendage to the ring in four steps and a Swern oxidation[16] from the protocol of Becker.[15,17] In this case the tin hydride-mediated cyclization gave a new cis-annulated ring, constructing bicylic alcohol **40** in 62% yield, in which the sterically congested hydroxyl was endo in the bicyclo[4.3.1]nonane skeleton.[14] Spectroscopic, GC, and TLC evidence did not reveal the presence of other diastereomeric products (>2%). The stereochemistry of **40** was also established by single X-ray crystallography.[14] It is interesting to note the formation of a seven-membered ring in **40** from the aldol.

Unlike the intermolecular version, these reactions proved highly stereoselective in the aldol, constructing a single product, readily isolated by flash chromatography in each case. There are very few studies of stereoselective intramolecular aldol reactions and these may be the only aldol cyclizations involving tin(IV) enolates. As a result, the origin of the stereoselectivity is not yet clear and a more in-depth study is warranted.[28] Due to the distances between the alcohol and the ketone oxygens in aldol products **38** and **40**, chelation with the tin atom appears to be excluded. Intramolecular aldol reactions under equilibrating conditions usually give rise to stereochemical mixtures in the products.[28] Because only a single diastereomer was obtained in each reaction and the alcohol is highly hindered in **40**, it is likely that these are the result of kinetic reaction conditions.

Scheme 7



Although products could arise from either carbonyl function reacting with $nBu_3Sn^{\bullet}$, only one pathway prevailed. One explanation for the cyclization is that the tin ketyl forms at the aldehyde carbonyl site and cyclization occurs by attack at the α-position of the alkene.[18] Presumably, hydrogen atom transfer would then trap the radical at the enone β-position in the six-membered ring. This possibility seems remote, because an *O*-stannyl ketyl, formed from the aldehyde, is a nucleophilic radical and intramolecular attack at the electrophilic β-position of the alkene should be favored.[5a,b] A second, more plausible, explanation is that the more stable allylic *O*-stannyl ketyl forms at the cyclohexenone site and hydrogen atom abstraction occurs at the enone β-position in the six-membered ring (see Scheme 4). This leaves the α-position available for nucleophilic attack of the tin(IV) enolate on the aldehyde (vide infra).

A study to distinguish between the ketyls of the aldehyde and the 2-cyclohexenone compared **41** and decanal (**42**) in a simple competition experiment, shown in Scheme 7. As predicted, reduction of **41** to **43** was more rapid than the formation of decanol (**44**) from decanal (**42**), which indicates a preference for the resonance stabilized allylic O-stannyl ketyl of the 2-cyclohexenone over the less stabilized *O*-stannyl ketyl of the aldehyde. The small amount of **44** formed is due either to the dilution of the reaction mixture or to the slight excess (1.2 equiv) of tin hydride used.[18] It may also reflect the difference in the reactivity between the two moieties.

It is now clear that free radicals are not involved in the cyclization step, but rather it proceeds via a two-electron closure. One-electron reduction of the α,β-unsaturated ketone appears to occur first, as shown in Scheme 1. Note that $Bu_3Sn^{\bullet}$ addition to the β-carbon of the alkene may also occur, but it is probably fast and reversible and these products were not observed. If trapped by nBu_3SnH, dehydrostannylation does not occur readily in this situation and such products were never observed even in minor amounts.[4]

Alkylation Reactions. An initial alkylation reaction was performed in a manner similar to the intermolecular tin aldol condensation (vide supra), as shown in Scheme 8. Although no literature precedent existed, it was hoped that direct alkylation of **4** with an organohalide would lead to **6** directly from the nucleophilic tin(IV) enolate in the same pot. In order for the alkylation reaction to be successfully mediated by free radical precursors, the alkyl halide had to be added later to the reaction at a point

(13) (a) Cahiez, G.; Alexakis, A.; Normant, J. F. *Tetrahedron Lett.* **1978**, 3013. (b) Godleski, S. A. Valpey, R. S. *J. Org. Chem.* **1982**, *47*, 381.

(14) Alcohol **38** was converted into its *p*-bromobenzoate ester prior to X-ray diffraction. For single crystal X-ray analyses of **38** and **40**, see: Abboud, K. A.; Xie, Y.; Enholm, E. J. *Acta Crystallogr. C*, in press.

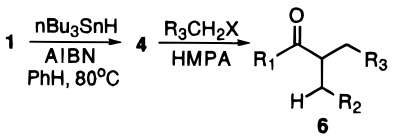
(15) Becker, D.; Birnbaum, D. *J. Org. Chem.* **1980**, *45*, 570.

(16) Mancuso, A. J. and Swern, D. *Synthesis* **1981**, 3, 165.

(17) Heathcock, C. H.; Ellis, J. E.; McMurray, J. E.; Coppolino, A. *Tetrahedron Lett.* **1971**, 4995.

(18) Earlier studies have shown that either an aldehyde or enone moiety can be reduced individually with tin hydride.[4] The reaction was diluted (0.10 M) to separate reactive partners and prevent a bimolecular aldol and allow the tin enolate to remain predominantly unreacted until workup.

Scheme 8



where the tin hydride was totally consumed by the α,β-unsaturated ketone. Careful stoichiometry and the order of reagent addition should play an important role here because the rate of a $nBu_3Sn^{\bullet}$ reaction with alkyl halides is generally faster than with unsaturated ketones.[19]

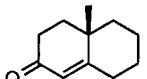
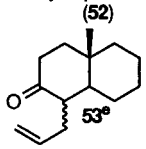
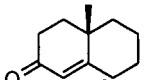
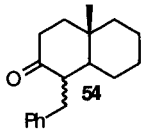
In addition, there is an important new concept demonstrated in Scheme 8. That is, this radical reaction results in a direct contrast to how an α,β-unsaturated ketone classically undergoes additions in free radical reactions with an alkyl halide.[1] The normal attack of the alkyl radical, which forms from the alkyl halide, occurs at the β-position in a 1,4-manner as it does with essentially all one- and two-electron donors. By simply delaying the addition of the alkyl halide reagent, the tin(IV) enolate forms first, and α-alkylation follows. Greater flexibility is now possible in both types of reactions because both use similar starting materials.

Activated or primary alkyl halides were initially chosen due to their increased reactivity with the less-nucleophilic tin(IV) enolate.[4,20,21] Thus, we waited until after the starting cyclohexenone was consumed (by TLC) and presumably the tin enolate generated, then benzyl bromide (4 equiv) was added. Although a small amount of alkylated product was isolated, the major product in these reactions was cyclohexanone. This suggested that the enolate had indeed formed, but was quenched upon workup. The tin(IV) enolate was simply not reactive enough to be alkylated in high yields even with activated alkyl halides.

Additional activation of the tin−oxygen bond in the enolate was next pursued.[22] Alkylation of the enolate was greatly facilitated by coordination with ligands to hexamethylphosphoramide (HMPA). This additive considerably increased the nucleophilic capacity of the tin(IV) enolate in these reactions. Several examples have been compiled in Table 2. The high coordination ability of HMPA allows it to act as a Lewis base and increase the polarity of the tin(IV) enolate. This was found to improve alkylation yields significantly; however, the amount of HMPA caused a variation in the yield, presumably due to an optimal coordination number around the tributyltin moiety. Cyclic unsaturated ketones generally seemed to function better here than the acyclic unsaturated ketone in entry 4.

Several optimization experiments were performed with allyl bromide and enone **9**, which presumably has the coordinated tin(IV) enolate **55** as an intermediate, by varying the equivalents of HMPA, shown in Table 3. When 5.0 equiv of HMPA was added prior to the alkyl halide, yields improved by 50%. When over 5.0 equiv of HMPA was used, the alkylated product formed in better yield than without using HMPA, but not as good as using 5.0 equiv. The DBU method for removal of tin byproducts was again used as in the previously discussed tin aldol reactions.[12]

Table 2. Alkylations of Tin(IV) Enolates

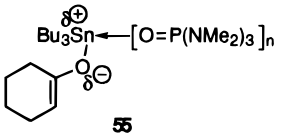
Entry	Halide	Enone	Product	Yield (%)[a]
1	**47**	**9**	2-Allylcyclohexanone[d] (**49**)	71
2	**48**	**9**	2-Benzylcyclohexanone[d] (**50**)	69
3	**45**	**9**	2-Hexylcyclohexanone[d] (**51**)	61
4	**47**	**11**	4-Ethylhept-6-en-3-one (**52**)	48
5	**47**	 **46**[d]	 **53**[e]	76[b]
6	**48**	 **46**[d]	 **54**	65[c]

[a]Yields refer to chromatographically homogeneous material with spectral data consistent with the structure shown.15 [b]Ratio determined to be 4 : 1, β : α by capillary GC. [c]Ratio determined to be 1 : 1, β : α by capillary GC. [d]The preparation of compounds **46**,[17] **49**,[23] **50**,[24] and **51**[25] have been described previously. [e]Epimerization of **53** with DBU (4.0 equiv) in THF led to a 1 : 2, β : α mixture by capillary GC.

Alkyl halides used: allyl bromide (**47**), benzyl bromide (**48**), hexyl iodide (**45**)

Enones used: 2-cyclohexenone (**9**), 4-hexen-3-one (**11**),

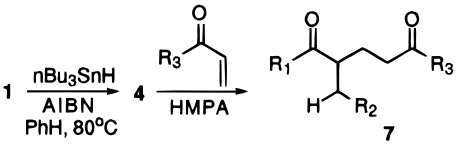
Table 3. Optimization of HMPA in Alkylations



55

Number of Equivalents of HMPA (n)	Yield (%)
0.0	21
5.0	71
8.0	60

Scheme 9



Conjugate Additions. A new tin(IV) enolate reaction was designed based on the assumption that the tin(IV) enolate might behave as a soft nucleophile in Michael additions. An activated alkene was reacted with the tin(IV) enolate, leading to conjugate addition product **7**, as shown in Scheme 9. This reaction also required HMPA; however, it was added with the activated alkene after the tin(IV) enolate was formed. This additive greatly improved the yields in the alkylation experiments (vide supra), but with the conjugate additions, a large amount of undesirable anionic polymerization products were formed. To suppress the polymerizations from occurring, the electron-poor alkene was diluted to 0.5 M in benzene and added slowly via addition funnel. The

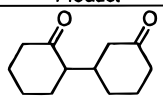
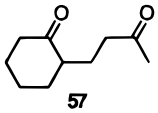
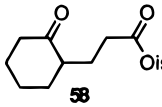
(19) Ingold, K. U.; Lusztyk, J. Scaiano, J. C. *J. Am. Chem. Soc.* **1984**, *106*, 343.

(20) For a review, see: Shibata, I.; Baba, A. *Org. Prep. Proc. Int.* **1994**, *26*, 87.

(21) (a) Nishiyama, H.; Sakuta, K.; Itoh, K. *Tetrahedron Lett.* **1984**, 223; (b) Suzuki, M.; Yanagishawa, A.; Noyori, R. *J. Am. Chem. Soc.* **1985**, *107*, 3348; (c) Odic, Y.; Pereyre, M. *J. Organomet. Chem.* **1973**, *55*, 273.

(22) (a) Shibata, I.; Suzuki, T.; Baba, A.; Matsuda, H. *J. Chem. Soc., Chem. Commun.* **1988**, 882; (b) Baba, A.; Yasuda, M.; Yano, K.; Shibata, I.; Matsuda, H. *J. Chem. Soc. Perkin I.* **1990**, 3205; (c) Yasuda, M.; Oh-hata, T.; Shibata, I.; Baba, A.; Matsuda, H. *J. Chem. Soc., Perkin Trans. 1* **1993**, 859.

Table 4. Conjugate Additions of Tin(IV) Enolates

Entry	Enone	Activated Alkene	Product	Yield (%)[a]
1	9	9	 56	41
2	9	Methylvinyl Ketone	 57	31
3	9	Isodecyl Acrylate	 58	38

[a]Yields refer to chromatographically homogeneous material with spectral data consistent with the structure shown.

Enone and activated alkenes used: 2-Cyclohexenone (**9**)

desired Michael products were observed using these conditions in modest yields. The results are shown in Table 4.

Conclusion

A new neutral free radical reaction involving several reactions of tin(IV) enolates from allylic *O*-stannyl ketyls has been developed. The tin(IV) enolate can be reacted with an aldehyde in both intra- or intermolecular fashion to form aldol-type products. Reactions with alkyl halides formed α-alkylated ketone products. Activated alkenes such as unsaturated carbonyls formed conjugate addition products. Because the enolate forms on the alkene side of the ketone, the reaction is regioselective. The free radical conditions directly contrasts current highly basic/reductive methods to form enolates which rely on LDA, LHMDS, and dissolving metal reductions. The interesting combination of free radical and enolate chemistry required in this reaction exemplify the newly-emerging class of sequential one- and two-electron reactions.[26]

Experimental Section

General. Melting points were determined on a capillary melting point apparatus and are uncorrected. All reactions were run under an inert atmosphere of argon using flame or heat-dried apparatus. All reactions were monitored by thin layer chromatography (TLC) and judged complete when starting material was no longer visible in the reaction mixture. All yields reported refer to isolated material judged to be homogeneous by thin layer chromatography and NMR spectroscopy. Temperatures above and below ambient temperature refer to bath temperatures unless otherwise stated. Solvents and anhydrous liquid reagents were dried according to established procedures by distillation under nitrogen from an appropriate drying agent: ether, benzene, and THF from benzophenone ketyl; CH_2Cl_2 from CaH_2. Other solvents were used "as received" from the manufacturer.

Analytical TLC was performed using precoated silica gel plates (0.25 mm) with phosphomolybdic acid in ethanol as an indicator. Column chromatography was performed using Kieselgel silica gel 60 (230−400 mesh) by standard flash chromatographic techniques. Product ratios were determined on a capillary gas chromatograph using a fused silica capillary column (30 m; film thickness 0.25 μm), unless otherwise noted.

General Procedure for Intermolecular Aldol Reactions. The unsaturated ketone (1 equiv), tributyltin hydride (1.1 equiv), and azobis(isobutyronitrile) (0.2 equiv) were dissolved in benzene (0.5 M). The solution was degassed for 0.3 h with a steady stream of argon. The reaction mixture was then refluxed until starting material was consumed as shown by TLC (*ca.* 4 h). After the reaction vessel had been placed in an ice−water bath and cooled to 10 °C, the appropriate aldehyde was added. The reaction was allowed to stir for 8−12 h, concentrated under reduced pressure, and diluted with diethyl ether. Following addition of DBU (1,8-diazobicylco-[5.4.0]undec-7-ene) (1.2 equiv) and 2−3 drops of water, an ethereal solution of iodine was added dropwise until the iodine color persisted. Rapid suction filtration through silica gel was performed, and the solution was concentrated and subjected to flash column chromatography to afford the pure aldol products **15**, **17**, **19**, **21**, **23**, **25**, **27**, and **29**.

2-(Phenylhydroxymethyl)cyclohexanone (15).[11] Data for mixture of erythro and threo isomers: ^{1}H NMR ($CDCl_3$) δ 7.2−7.4 (m, 5H), 5.4 (apparent t, J = 3 Hz, 1H(erythro)), 4.9 (d of d, J = 2, 8 Hz, 1H(threo)), 3.0 (s, OH), 2.6−2.3 (m, 3H), 2.0 (m, 1H), 1.9−1.6 (complex m, 5H); ^{13}C NMR ($CDCl_3$) δ 211.0, 136.8, 128.2, 127.0, 125.8, 70.7, 57.2, 42.7, 27.9, 26.1, 24.9.

2-(Cyclohexylhydroxymethyl)cyclohexanone (17). Data for mixture of erythro and threo isomers: R_f = 0.56 (35% THF/hexane); IR (neat) 3534, 1697 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 3.75 (d of d, J = 2, 9 Hz, 1H (threo)), 3.48 (d of d, J = 3, 7 Hz, 1H (erythro)), 3.2 (broad s, OH), 2.5−2.0 (m, 3H), 2.0 (m, 2H), 1.9−1.1 (m, 1H), 1.8−1.0 (m, 14H); ^{13}C NMR ($CDCl_3$) δ 216.0, 75.8, 52.9, 43.0, 39.7, 30.9, 30.4, 27.9, 26.6, 26.3, 25.1; mass spectrum (FAB) 211 (M + 1, 29.8), 193 (100.0). Anal. Calcd: C, 74.24; H, 10.54. Found: C, 74.22; H, 10.83.

2-(1-Hydroxyheptyl)cyclohexanone (19). Data for erythro isomer: R_f = 0.47 (35% THF/hexane); IR (neat) 3474, 1699 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 4.1 (broad s, OH), 3.7 (apparent t, J = 8 Hz, 1H), 2.4−2.2 (m, 2H), 2.1 (m, 1H), 2.0−1.4 (complex m, 16H), 0.9 (m, 3H); ^{13}C NMR ($CDCl_3$) δ 208.0, 71.6, 56.0, 42.9, 33.7, 31.9, 29.4, 27.8, 26.8, 25.0, 22.6, 16.6, 14.0; mass spectrum (CI, methane) 213 (M + 1, 19.8), 195 (100.0). Anal. Calcd: C, 73.52; H, 11.40. Found: C, 73.27; H, 11.33.

2-(Phenylhydroxymethyl)cyclopentanone (21). Data for erythro isomer: R_f = 0.46 (35% THF/hexane); IR (neat) 3445, 1732 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.4−7.2 (m, 5H), 5.25 (apparent t, J = 3 Hz, 1H), 3.15 (broad s, OH), 2.4−1.4 (complex m, 7H); ^{13}C NMR ($CDCl_3$) δ 220.4, 143.2, 128.3, 127.2, 125.6, 71.4, 56.2, 39.2, 22.7, 20.5; mass spectrum (FAB) 191 (M + 1, 4.5), 173 (100.0). Anal. Calcd: C, 75.76; H, 7.42. Found: C, 75.67; H, 7.51.

2-(Cyclohexylhydroxymethyl)cyclopentanone (23). Data for erythro isomer: mp 80−81 °C; R_f = 0.54 (35% THF/hexane); IR (Nujol) 3499, 1714 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 4.0 (broad s, OH), 3.55(d, J = 8 Hz, 1H), 2.5−1.1 (complex m, 18H); ^{13}C NMR ($CDCl_3$) δ 224.1, 76.1, 51.3, 41.1, 38.5, 30.1, 26.6, 26.4, 25.5, 20.6; mass spectrum (CI, methane) 197 (M + 1, 42.4), 179 (100.0). Anal. Calcd: C, 73.41; H, 10.28. Found: C, 73.05; H, 10.37.

2-(1-Hydroxyheptyl)cyclopentanone (25). Data for erythro isomer: R_f = 0.48 (35% THF/hexane); IR (neat) 3446, 1733 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 4.2 (s,OH), 4.1 (m, 1H), 2.4−2.0 (m, 3H) 1.9−1.7 (m, 2H) 1.6−1.2 (m, 12H), 0.9 (t, J = 3, 7 Hz, 3H); ^{13}C NMR ($CDCl_3$) δ 208.0, 69.7, 54.4, 39.1, 34.9, 31.8, 29.2, 26.0, 23.0, 22.6, 20.6, 14.0; mass spectrum (CI, methane) 199 (M + 1, 39.2), 181 (100.0). Anal. Calcd: C, 72.68; H, 11.18. Found: C, 72.51; H, 11.37.

4-(Phenylhydroxymethyl)-3-hexanone (27). Data for erythro isomer: R_f = 0.54 (35% THF/hexane); IR (neat) 3446, 1705 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.2−7.4 (m, 5H), 4.8 (d of d, J = 3, 6 Hz, 1H), 2.9 (s, OH), 2.8 (m, 1H), 2.4−2.0 (m, 2H), 1.8−

(23) Tsuda, T.; Saegusa, T. *J. Org. Chem.* **1986**, *51*, 421.
(24) Guindon, Y.; Yoakim, C. *J. Org. Chem.* **1984**, *49*, 3912.
(25) Suzuki, A.; Yamada, K. *Bull. Chem. Soc. Jpn.* **1979**, *52*, 275.
(26) (a) Enholm, E. J.; Trivellas, A. *Tetrahedron Lett.* **1994**, 1627. (b) Takai, K.; Nitta, K.; Fujimura, O; Utimoto, K. *J. Org. Chem.* **1989**, *54*, 4732. (c) Curran, D. P.; Fevig, T. L.; Totleben, M. J. *Synlett* **1990**, 733. (d) Molander, G. A.; Harring, L. S. *J. Org. Chem.* **1990**, *55*, 6171. (e) Molander, G. A.; Kenny, C. *J. Org. Chem.* **1991**, *56*, 1439. (f) Curran, D. P.; Fevig, T. L.; Jasperse, C. P.; Totleben, M. J. *Synlett* **1992**, 943. (g) Totleben, M. J.; Curran, D. P.; Wipf, P. *J. Org. Chem.* **1992**, *57*, 1740. (h) Curran, D. P.; Totleben, M. J. *J. Am. Chem. Soc.* **1992**, *114*, 6050. (i) Molander, G. A.; McKie, J. A. *J. Org. Chem.* **1992**, *57*, 3132.

1.6 (m 2H), 1.0−0.8 (m, 6H); ^{13}C NMR ($CDCl_3$) δ 216.0, 142.0, 128.3, 127.8, 126.2, 74.2, 60.5, 38.1, 20.7, 12.1, 7.1; mass spectrum (FAB) 207 (M + 1, 18.6), 189 (46.2). Anal. Calcd: C, 75.69; H, 8.80. Found: C, 75.50; H, 9.01.

4-(Cyclohexylhydroxymethyl)-3-hexanone (29). Data for erythro isomer: R_f = 0.59 (35% THF/hexane); IR (neat) 3462, 1704 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 3.45 (d of d, J = 4, 7 Hz, 1H), 2.9 (broad s, OH), 2.7 (m, 1H), 2.5 (m, 2H), 1.8−1.5 (m, 7H), 1.4−1.0 (m, 9H), 0.9 (t, J = 8 Hz, 3H); ^{13}C CMR ($CDCl_3$) δ 216.0, 75.6, 54.9, 40.8, 37.1, 29.6, 28.5, 26.3, 26.1, 25.9, 19.2, 12.3, 7.4; mass spectrum (CI, methane) 213 (M + 1, 41), 100 (100.0). Anal. Calcd: C, 73.52; H, 11.40. Found: C, 73.44; H, 11.37.

General Procedure for the Dehydration of Aldol Products. The aldol product was dissolved in benzene (0.68 M), and a catalytic amount of *p*-toluenesulfonic acid was added. The reaction was refluxed in a flask equipped with a Dean−Stark tube for 0.5 h. The crude mixture was diluted to 3× volume with ether, extracted with sodium bicarbonate (aqueous saturated), dried over sodium sulfate, concentrated under reduced pressure, and subjected to flash column chromatography to afford the α,β-unsaturated ketone products **16**, **18**, **20**, **22**, **24**, **26**, **28**, and **30**.

2-(Phenylmethylidene)cyclohexanone (16): *E*/*Z* = 82/1 (GC); IR (neat) 1674 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.25−7.1 (m, 6H), 3.95−3.85 (m, 2H), 2.5 (t, J = 7 Hz, 2H), 1.9 (m, 2H), 1.75 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 193.3, 136.8, 135.6, 130.4, 130.3, 128.5, 128.4, 40.3, 28.9, 23.9, 23.4. Anal. Calcd: C, 83.83; H, 7.58. Found: C, 83.60; H, 7.57.

2-(Cyclohexylmethylidene)cyclohexanone (18): R_f = 0.65 (35% THF/hexane); *E*/*Z* 20/1 (GC); IR (neat) 1688 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.43 (d, J = 10Hz, 1H), 2.5 (m, 4H), 2.2 (m, 1H), 1.8−1.5 (m, 9H), 1.4−1.1 (m, 5H); ^{13}C NMR ($CDCl_3$) δ 201.2, 144.0, 134.5, 40.1, 36.7, 31.8, 26.6, 25.9, 25.6, 23.7, 23.3; mass spectrum (FAB) 193 (M + 1, 100.0). Anal. Calcd: C, 81.20; H, 10.48. Found: C, 81.05; H, 10.67.

2-Heptylidenecyclohexanone (20): R_f = 0.67 (35% THF/hexane); *E*/*Z* 13/1 (GC); IR (neat) 1687 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.6 (m, 1H), 2.4(m, 2H), 2.05 (q, J = 8 Hz, 2H), 1.8−1.2 (complex m, 14H), 0.9 (m, 3H); ^{13}C NMR ($CDCl_3$) δ 203.3, 139.7, 136.2, 40.1, 31.7, 29.1, 28.5, 27.8, 26.7, 23.6, 23.5, 22.6, 14.0; mass spectrum (EI) 194 (M$^+$, 60.3), 137 (100.0). Anal. Calcd: C, 80.34; H, 11.42. Found: C, 80.13; H, 11.37.

2-(Phenylmethylidene)cyclopentanone (22): R_f = 0.53 (35% THF/hexane); *E*/*Z* 15/1 (GC); IR (neat) 3062, 1678 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.6−7.25 (m, 6H), 3.0 (m, 2H), 2.4 (t, J = 8 Hz, 2H), 2.0 (t, J = 8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 200.0, 136.1, 132.3, 130.7, 130.5, 129.3, 128.7, 37.8, 29.3, 20.2; mass spectrum (FAB) 173 (M + 1, 100.0). Anal. Calcd: C, 83.68; H, 7.03. Found: C, 83.95; H, 6.83.

2-(Cyclohexylmethylidene)cyclopentanone (24): R_f = 0.58 (35% THF/hexane); *E*/*Z* > 100/1 (GC); IR (neat) 1721 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.4 (d, J = 10 Hz, 1H), 2.6 (t, J = 7 Hz, 2H), 2.4 (m, 2H), 2.15 (m, 1H), 1.9 (m, 2H), 1.8−1.6 (m, 5H), 1.4−1.1 (m, 5H); ^{13}C NMR ($CDCl_3$) δ no vis carbonyl, 140.8, 135.3, 38.8, 38.5, 31.7, 26.6, 25.9, 25.5, 19.9; mass spectrum (EI) 178 (M$^+$, 83.8), 97 (100.0). Anal. Calcd: C, 80.84; H,-10.18. Found: C, 80.77; H, 10.14.

2-Heptylidenecyclopentanone (26): R_f = 0.60 (35% THF/hexane); *E*/*Z* 41/1 (GC); IR (neat) 1719 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.5 (m, 1H) 2.6 (m, 2H), 2.25 (t, J = 8 Hz, 2H), 2.15 (m, 2H), 1.95 (m, 2H), 1.4−1.2 (m, 8H), 0.9 (m, 3H); ^{13}C NMR ($CDCl_3$) δ 206.8, 137.2, 136.2, 38.5, 31.6, 29.6, 29.0, 28.3, 26.7, 22.5, 19.8, 13.9; mass spectrum (EI) 180 (M$^+$, 37.3), 123 (100.0). Anal. Calcd: C, 79.93; H, 11.19. Found: C, 79.55; H, 11.21.

1-Phenyl-2-ethyl-1-penten-3-one (28): R_f = 0.60 (35% THF/hexane); *E*/*Z* 23/1(GC); IR(neat) 1660 cm^{-1};^{1}H NMR ($CDCl_3$) δ 7.4 (m, 6H), 2.9 (m, 2H), 2.5 (m, 2H), 1.2−1.0 (m, 6H); ^{13}C NMR ($CDCl_3$) δ 192.0, 137.5, 134.3, 129.7, 128.9, 128.5, 128.3, 31.0, 19.9, 13.7, 8.8; mass spectrum (EI) 188 (M$^+$, 33.2) 131 (100.0). Anal. Calcd for $C_{13}H_{16}O$: C, 82.93; H, 8.57. Found: C, 83.07; H, 8.75.

1-Cyclohexyl-2-ethyl-1-penten-3-one (30): R_f = 0.72 (35% THF/hexane); IR (neat) 1668 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.35 (d, J = 10 Hz, 1H), 2.65 (q, J = 7 Hz, 2H), 2.3 (q, J = 8 Hz, 2H) 1.8−1.0 (m, 14H), 0.95 (t, J = 8 Hz, 3H); ^{13}C NMR ($CDCl_3$) δ 202.7, 146.8, 141.1, 38.0, 32.4, 30.7, 30.5, 25.7, 19.2, 14.8, 8.9; mass spectrum (EI) 194 (M$^+$, 13.9), 179 (18.0), 165 (100.0). Anal. Calcd: C, 80.34; H, 11.42. Found: C, 80.03; H, 11.48.

2-Heptyl-2-(Phenylhydroxymethyl)cyclopentanone (33): R_f = 0.53 (35% THF/hexane); ^{1}H NMR ($CDCl_3$) δ 7.4−7.2 (m, 5H), 4.8 (s, 1H), 3.2 (s, OH), 2.3−1.2 (complex m, 18H), 0.9 (t, J = 7 Hz, 3H); ^{13}C NMR ($CDCl_3$) δ no vis carbonyl, 140.0, 127.9, 127.7, 127.4, 76.7, 56.5, 39.6, 32.7, 32.6, 31.8, 30.5, 29.1, 24.7, 22.6, 19.1, 14.1. Anal. Calcd: C, 79.11; H, 9.79. Found: C, 79.05; H, 9.76.

General Procedure for the Intramolecular Aldol Reactions. A solution of **37** or **39** (1.0 mmol) in benzene (4.0 mL) with AIBN (0.10 mmol) and nBu$_3$SnH (2.0 mmol) was degassed for 15 min and heated to 80 °C for 12 h. The reaction was quenched with water (10 mL), extracted with ether (3 × 20 mL), dried over Na_2SO_4, and concentrated to an oil. Flash chromatography over silica gel gave the desired bicyclic products **38** or **40**, respectively.

Compound 37 was prepared by the method of Godleski.[13]

Compound 39 was prepared by the method of Becker.[15,17]

(±)-Octahydro-8-hydroxy-1-(2*H*)-naphthalenone (38): R_f = 0.35 (35% THF−hexanes); ^{1}H NMR ($CDCl_3$) δ 4.19 (t, 1H), 2.46 (s, 1H), 2.45 (m, 2H), 2.32 (m, 2H), 1.86−2.07 (m, 2H), 1.79 (m, 2H), 1.63 (m, 3H), 1.44 (m, 3H); ^{13}C NMR ($CDCl_3$) δ 213.5, 66.8, 58.9, 39.7, 37.2, 32.7, 28.8, 27.7, 24.3, 20.0; IR (neat) 3404, 1605 cm^{-1}. Anal. Calcd: C, 71.39; H, 9.59. Found: C, 71.31; H, 9.91.

(±)-*endo*-5-Hydroxy-1-methylbicyclo[4.3.1]decan-7-one (40): R_f = 0.43 (35% THF−hexanes); mp 67−69 °C (uncorrected); ^{1}H NMR ($CDCl_3$) δ 3.61 (m, 2H), 2.72 (q, 1H), 2.50 (m, 2H), 2.14 (m, 1H), 1.20−1.89 (m, 9H), 0.98 (s, 3H);^{13}C NMR ($CDCl_3$) δ 199.1, 75.2, 50.5, 38.2, 37.6, 37.2, 37.0, 35.8, 31.9, 31.2, 19.5; IR (KBr film) 3013, 1631 cm^{-1}. Anal. Calcd: C, 72.49; H, 9.95. Found: C, 72.35; H, 10.06.

3-[4′-(*tert*-butyldimethylsiloxy)butane]-2-cyclohexenone (41). A solution of alcohol precursor (3.40 g, 20.2 mmol) prepared by the literature method,[11] TBSCl (3.81 g, 25.3 mmol), and imidazole (3.03 g, 44.5 mmol) in DMF (40 mL) was stirred for 15 h at room temperature. The mixture was then diluted with 100 mL of hexane and washed (3 × 25 mL) with water, dried, evaporated. The residue was subjected to column chromatography to give a thick oil (5.10 g, 89.2%); R_f = 0.60 (35% THF−hexanes); ^{1}H NMR ($CDCl_3$) δ 5.87 (s, 1H), 3.62 (t, 2H), 2.21−2.39 (m, 6H), 1.98 (m, 2H), 1.54 (m, 4H), 0.89 (s, 9H), 0.05 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 199.8, 166.4, 125.6, 62.5, 37.7, 37.3, 32.2, 29.5, 25.9, 23.2, 22.6, 18.2; IR (neat) 2931 cm^{-1}. Anal. Calcd: C, 68.03; H, 10.71. Found: C, 68.01; H, 10.92.

3-[4′-(*tert*-Butyldimethylsiloxy)butane]cyclohexanone (43): R_f = 0.66 (35% THF−hexanes); ^{1}H NMR ($CDCl_3$) δ 3.60 (t, 2H), 2.18−2.47 (m, 4H), 1.5−2.08 (m, 7H), 1.18−1.41 (m, 4H), 0.89 (s, 9H), 0.05 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 213.4, 62.9, 48.1, 41.5, 39.0, 36.3, 32.8, 31.2, 25.9, 25.2, 22.9, 18.3; IR (neat) 1715 cm^{-1}. Anal. Calcd: C, 67.54; H, 11.34. Found: C, 67.43; H, 11.52.

General Procedure for Alkylation Reactions. The unsaturated ketone (1 equiv), tributyltin hydride (1.1 equiv), and azobis(isobutyronitrile) (0.2 equiv) were dissolved in benzene (1.0 M). The solution was degassed for 0.3 h with a steady stream of argon. The reaction mixture was then refluxed until starting material was consumed by TLC (*ca.* 4 h). The reaction vessel was cooled to room temperature and HMPA (5 equiv) was added; the reaction mixture was stirred for 2−3 m. Alkyl halide (4 equiv) was added, and the reaction was allowed to reflux for 14 h. The reaction mixture was then cooled to room temperature, diluted to 3× volume with diethyl ether, and washed 4× with brine. To the organic layer were added DBU (1.2 equiv) and 2−3 drops of water; an ethereal solution of iodine was added dropwise to the stirring solution until the iodine color persisted, and the solution was rapidly filtered through silica gel with ether. Finally, the filtrate was concentrated under reduced pressure and subjected to flash column chromatography (ether/hexanes) to afford the pure alkylated products **49**−**54**.

2-Allylcyclohexanone (49):[23] R_f = 0.64 (35% THF/hexane); ^{1}H NMR ($CDCl_3$) δ 5.75 (m, 1H), 5.0 (m, 2H), 2.5 (m, 1H), 1.65

(m, 2H), 2.4−1.8 (complex m, 8H); ^{13}C NMR ($CDCl_3$) δ 212.5, 136.5, 116.2, 50.3, 42.0, 33.8, 33.4, 27.9, 25.0.

2-Benzylcyclohexanone (50):[24] R_f = 0.60 (35% THF/hexane); ^{1}H NMR ($CDCl_3$) δ 7.3−7.1 (m, 5H), 3.3−3.1 (d of d, J = 5, 14 Hz, 1H), 2.6−2.2 (complex m, 4H), 2.0 (m, 2H), 1.8−1.4 (complex m, 4H); ^{13}C NMR ($CDCl_3$) δ 212.5, 140.4, 129.2, 128.3, 126.0, 52.5, 42.2, 35.5, 33.5, 28.1, 25.1; mass spectrum CI (methane) 189 (M + 1, 100.0).

2-Hexylcyclohexanone (51):[25] R_f = 0.68 (35% THF/hexane); ^{1}H NMR ($CDCl_3$) δ 2.4−2.2 (m, 3H), 2.2−2.0 (m, 2H), 1.9−1.6 (m, 4H), 1.4−1.2 (m, 10H), 0.9 (t, J = 7 Hz, 3H); ^{13}C NMR ($CDCl_3$) δ 213.0, 50.8, 41.9, 33.8, 31.8, 29.4 (high intensity; probably 2 coincidental C's), 28.0, 27.2, 24.8, 22.6, 14.1.

4-Ethylhept-6-en-3-one (52): R_f = 0.70 (35% THF/hexane); IR (neat) 3079, 1713 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 5.75−5.6 (m, 1H), 5.0 (m, 2H), 2.5−2.1 (complex m, 5H), 1.7−1.4 (m, 2H), 1.1−1.0 (t, J = 7 Hz, 3H), 0.9−0.8 (t, J = 7 Hz, 3H); ^{13}C NMR ($CDCl_3$) δ 208.0, 135.9, 116.5, 53.2, 35.8, 35.6, 24.4, 11.7, 7.5; mass spectrum (CI, methane) 141 (M + 1, 100). Anal. Calcd: C, 77.08; H, 11.51. Found: C, 77.31; H, 11.76.

Allyl ketone 53: R_f = 0.71 (35% THF/hexane); IR (neat) 3074, 1712 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 5.8−5.6 (m, 1H), 5.0 (m, 2H), 22.6−2.2 (m, 5H), 1.9−1.0 (complex m, 11H), 1.3 (minor), 1.07 (major) (s, 3H); mass spectrum (CI, methane) 207 (M + 1, 100). Anal. Calcd: C, 81.49; H, 10.75. Found: C, 81.63; H, 10.83.

Benzyl ketone 54: R_f = 0.66 (35% THF/hexane); IR (neat) 3026, 1710 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.3−7.1 (m, 5H), 3.1−2.2 (complex m, 5H), 1.8−1.0 (complex m, 11H), 1.2,1.05 (s, 3H); mass spectrum CI (methane) 257 (M + 1, 93.7), 239 (60.6). Anal. Calcd: C, 84.31; H, 9.44. Found: C, 84.04; H, 9.33.

General Michael Procedure. The unsaturated ketone (1 equiv), tributyltin hydride (1.1 equiv), and azobis(isobutyronitrile) (0.2 equiv) were dissolved in benzene (1.0 M). The solution was degassed for 0.3 h with a steady stream of argon. The reaction mixture was then refluxed until starting material was consumed by TLC (*ca.* 4 h). The reaction vessel was cooled to room temperature, and HMPA (5 equiv) was added; the reaction mixture was stirred for 2−3 m. Unsaturated carbonyl (1.2 equiv) was diluted to 0.5 M in benzene, added via addition funnel (approximately 10 drops/min), and the reaction was allowed to reflux for 14−18 h. The reaction mixture was then cooled to room temperature, diluted to 3× volume with diethyl ether, and washed 4× with brine. To the organic layer were added DBU (1.2 equiv) and 2−3 drops of water; an ethereal solution of iodine was added dropwise to the stirring solution until the iodine color persisted, and the solution was rapidly filtered through silica gel with ether. Finally, the filtrate was concentrated under reduced pressure and subjected to flash column chromatography (ether/hexanes) to afford the pure conjugate addition products **56**−**58**.

2-(3-Oxocyclohexyl)cyclohexanone (56): ^{1}H NMR ($CDCl_3$) δ 2.5−2.2 (complex m, 5H), 2.1−2.0 (m, 2H), 1.95−1.4 (complex m, 11H). High-resolution MS (M + 1): Calcd, 195.1307; found, 195.1259.

2-(3-Oxobutyl)cyclohexanone (57):[27] IR(neat) 2926, 2857, 1708, 1449, 1360 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 2.6−2.2 (complex m, 5H), 2.1 (s,3H), 2.0−1.8 (complex m, 4H), 1.7−1.3 (complex m, 4H); ^{13}C NMR ($CDCl_3$) δ 212.8, 208.6, 49.8, 42.1, 41.3, 34.3, 29.8, 28.0, 25.0, 23.8.

8-Methylnonyl 3-(2-oxocyclohexyl)propanoate (58): ^{1}H NMR ($CDCl_3$) δ 4.0 (q, J = 7 Hz, 2H), 2.4−2.2 (m, 3H), 2.1−2.0 (m, 2H), 1.8−1.0 (complex m, 17H), 0.9−0.7 (m, 10H). Anal. Calcd: C, 73.49; H, 11.04. Found: C, 73.27: H, 10.89.

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Supporting Information Available: Spectral data for compound **56** (1 page). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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(27) Rathke, M. W.; Olsen, R. S. *Synth. Commun.* **1986**, *16*, 1133.
(28) For a review, see C. H. Heathcock. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed; Pergamon Press: London, 1991; Chapter 1.5, pp 166−169.