along with dialdehyde (methyl signals at δ 2.93 and 3.04 and at δ 2.34 and 3.01, respectively) in a ratio of 65:35. Pure quinone, identical with that previously described,[30,31] was readily obtained by crystallization from acetone at 4 °C.

Resolution of Trans Dihydrodiols. All dihydrodiols (Table I) were resolved as their diesters with (-)-(menthyloxy)acetic acid. Typically, a solution of trans dihydrodiol (0.4 g) and (-)-(menthyloxy)acetyl chloride (1.0 g) in pyridine (1.5 mL) was stored at 4 °C for 1 day. Reaction was terminated by addition of water, and the products were extracted into ether. After standard workup, the esters were purified by passage through a dry silica column eluted with 10–15% ether in cyclohexane. Data for the separation of the diastereomers by HPLC and their properties are given in the text and table. The diastereomeric diesters (100 mg) were hydrolyzed (150 mg of sodium methoxide, 4 mL of 50% methanol in THF, 10–20 min under N_2). Pure samples of dihydrodiols for rotations and CD measurements were obtained by HPLC on Du Pont Zorbax SIL columns eluted with 3–5% methanol and 15% ethyl acetate in hexane.

Reduction of Trans Dihydrodiols to Biphenyl Chromophores. The (-) enantiomers of **3c**, **4c**, and **5c** (0.2 mmol in 30 mL of THF) were agitated under 1 atm of H_2 for 3 days in the presence of added platinum oxide (0.6 mmol). After filtration to remove catalyst and concentration, the reaction products were purified by preparative TLC on silica gel plates eluted 2–3 times with 4% methanol in chloroform. In each case, the higher R_f band corresponded to reduced material. Typically, ~20% of the starting dihydrodiol was reduced. Cited UV spectra which follow were recorded in THF.

(a) *trans*-5,6-Dihydroxy-5,6,9,10,11,12-hexahydrobenzo[*c*]phenanthrene (3d) obtained by reduction of (-)-**3c** was purified by HPLC on a Du Pont Zorbax SIL column (9.45 × 250 mm) eluted with 1.2% ethyl acetate and 12% dioxane in cyclohexane; k' = 3.3 and 4.6 for **3d** and **3c**, respectively. For **3d**: MS (CI, NH_3) 284 (M^+ + 18), 266 (M^+ + 18 - H_2O); NMR (300 MHz, $CDCl_3$) $H_{5/6}$ δ 4.48, 4.56 with $J_{5,6}$ = 10.3 Hz. The UV spectrum showed a broad λ_{max} at 269 nm with ε 13 300 characteristic of a biphenyl chromophore.

(b) *trans*-5,6-Dihydroxy-1,2,3,4,5,6-hexahydrochrysene (4d) obtained by reduction of (-)-**4c** was purified on the above column eluted with 1% methanol and 15% ethyl acetate in cyclohexane; k' = 8.0 and 10.3 for **4d** and **4c**, respectively. For **4d**: MS (EI) 266 (M^+), 248 (M^+ - H_2O); NMR (300 MHz, $CDCl_3$) $H_{5/6}$ δ 4.75 and 5.04 with $J_{5,6}$ = 2.9 Hz. The UV spectrum showed a broad λ_{max} at 277 nm with ε 18 000 characteristic of a biphenyl chromophore.

(c) *trans*-4,5-Dihydroxy-4,5,9,10-tetrahydropyrene (5d) obtained by reduction of (-)-**5c** was purified on the above column eluted with 5% methanol and 15% ethyl acetate in cyclohexane; k' = 1.5 and 1.8 for **5d** and **5c**, respectively. Although the fraction thought to be **5d** appeared homogeneous by HPLC on the SIL column, NMR spectroscopy indicated the presence of a second diol in about twice the amount as **5d**. Further HPLC on a Du Pont Zorbax ODS column (9.45 × 250 mm) eluted with 15% water in methanol allowed separation of **5d** (k' = 0.76) from the major reduction product (k' = 1.26). For **5d**: MS (EI) 238 (M^+), 220 (M^+ - H_2O); NMR (300 MHz, $CDCl_3$) $H_{4/5}$ δ 4.73 and $H_{9/10}$ 2.85 as singlets. The UV spectrum showed a broad λ_{max} at 283 nm (ε 14 500) with shoulders at 274 and 294 nm. The presence of such shoulders has been observed previously in doubly bridged biphenyls.[6,34] The major reduction product proved to be *trans*-4,5-dihydroxy-1,2,3,3a,4,5-hexahydropyrene with unknown stereochemistry(s) at C_{3a}: MS (EI) 240 (M^+), 222 (M^+ - H_2O); NMR (300 MHz, $CDCl_3$) δ H_4 3.50 (t) and H_5 4.80 (d) with $J_{4,5}$ = 9.3 Hz and $J_{3a,4}$ = 10.5 Hz. The UV spectrum showed a sharp λ_{max} at 232 nm with a broad λ_{max} at 287 nm which is only 7% as intense.

Bis(*p*-(dimethylamino)benzoate) of *trans*-5,6-Dihydroxy-5,6-dihydrodibenz[*c*,*h*]acridine ((+)-8c). *p*-(Dimethylamino)benzoyl chloride (16 mg), *p*-(dimethylamino)pyridine (3 mg), and the (+)-dihydrodiol (2 mg) in pyridine (100 μL) were stored at 75 °C for 15 h. Water was added and the product was extracted into chloroform. After standard workup, a THF solution of the crude product was purified by HPLC on a Du Pont Zorbax ODS column (0.62 × 25 cm); initially 50% THF in H_2O with a linear gradient programmed over 6 min to 55% THF in water at a flow rate of 1.5 mL/min. The bis-ester was collected at a retention time of 14.4 min. Instability of the bis-ester precluded obtaining an NMR spectrum. MS (CI-NM_3) m/z 608 (M^+ + 1). Its UV spectrum (55% THF in H_2O) was dominated by a broad band at 320 nm with a shoulder at 295 nm. The starting dihydrodiol has a λ_{max} at 295 nm (ε 23 000) and a weaker absorption at 365 nm (ε 15 800). The 365-nm absorption is also present in the bis-ester but only one-fifth as intense as the exciton interaction band at 320 nm.

Registry No. **1a**, 78306-72-6; **1b**, 78246-26-1; (+)-**1c**, 64440-29-5; (-)-**1c**, 23190-41-2; (±)-**1c**, 25061-61-4; **2**, 56-55-3; **2** (5,6-dione), 18508-00-4; (±)-**2** (cis-diol), 78307-15-0; **2a**, 101313-14-8; **2b**, 101313-15-9; (+)-**2c**, 64440-28-4; (-)-**2c**, 64440-27-3; (±)-**2c**, 67315-17-7; **3**, 195-19-7; **3** (5,6-dione), 734-41-8; **3a**, 99922-15-3; **3b**, 101313-16-0; (+)-**3c**, 100017-13-8; (-)-**3c**, 101313-22-8; (±)-**3c**, 101313-28-4; **3d**, 101226-69-1; **4**, 218-01-9; **4** (5,6-dione), 2051-10-7; (±)-**4** (cis-diol), 101313-29-5; **4a**, 101226-63-5; **4b**, 101313-17-1; (+)-**4c**, 77123-20-7; (-)-**4c**, 101313-23-9; (±)-**4c**, 67175-78-4; **4d**, 101226-70-4; **5**, 129-00-0; **5** (4,5-dione), 6217-22-7; **5** (cis-diol), 51689-88-4; **5a**, 101226-64-6; **5b**, 101313-18-2; (+)-**5c**, 101313-24-0; (-)-**5c**, 101313-25-1; (±)-**5c**, 101226-68-0; **5d**, 101226-71-5; **6a**, 78088-16-1; **6b**, 78031-10-4; (±)-**6c**, 50700-50-0; **7a**, 101226-65-7; **7b**, 101313-19-3; (±)-**7c**, 101313-30-8; (±)-**8** (5,6-oxide), 93716-20-2; **8a**, 101226-66-8; **8b**, 101313-20-6; (+)-**8c**, 101313-26-2; (+)-**8c** (4-(dimethylamino)benzoate), 101226-72-6; (-)-**8c**, 101313-27-3; (±)-**8c**, 93716-21-3; **9**, 57-97-6; **9** (5,6-dione), 18508-00-4; **9** (dialdehyde), 963-87-1; (±)-**9** (cis-diol), 64265-59-4; **9a**, 101226-67-9; **9b**, 101313-21-7; (+)-**9c**, 92693-64-6; (-)-**9c**, 92693-65-7; (±)-**9c**, 75262-88-3; 9,10-phenanthrenedione, 84-11-7.

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Lanthanides in Organic Synthesis. 3. A General Procedure for Five- and Six-Membered Ring Annulation

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An improved method for cyclization of 2-(ω-iodoalkyl)cycloalkanones utilizing samarium diiodide (SmI_2) has been developed. Both five- and six-membered rings can be constructed in excellent yields for the first time by such a process. The reaction takes place under very mild conditions, allowing toleration of a number of functional groups under the reaction conditions. Stereochemical aspects of the reaction have been delineated. The reaction has been found to be highly stereoselective when cyclization takes place onto cyclopentanone substrates and when 2-substituted-2-(ω-haloalkyl)cycloalkanone precursors are utilized.

Ring annulation represents an exceedingly important transformation in organic synthesis. As such, numerous methods have been developed to carry out this type of process.[1] Among the more attractive approaches due to

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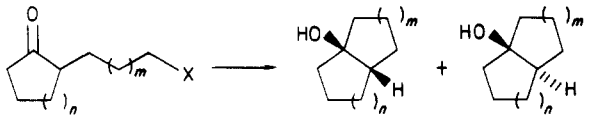
its inherent simplicity is the cyclization of 2-(ω-iodoalkyl)cycloalkanones under reducing conditions to generate the corresponding bicyclic alcohols.



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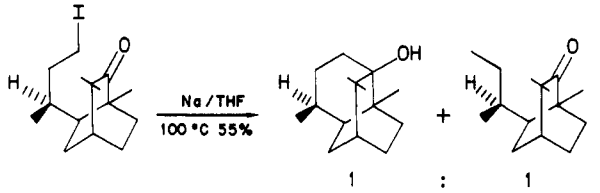
Substrates for this type of cyclization are readily generated through simple alkylation reactions. In principle, a variety of ring systems can be accessed by simple adjustment of the haloalkyl side chain length and cycloalkanone starting material. Ideally, reducing agents used in this process would be highly chemoselective, tolerating a number of functional groups in the desired transformation.

Numerous attempts have been made to accomplish this type of reaction in an efficient manner. Five-, six-, seven-, and even larger-membered rings have been generated from intramolecular coupling of allylic halides with carbonyls utilizing various reducing agents.[2] Far less success has been realized in cyclizations with alkyl halide substrates. Several alkali- and alkaline-earth metals have been utilized in such studies and provide fair to good yields of product when three-,[3] four-,[4] or five-membered rings[4a,b,5] are generated. Most practical procedures provide marginal yields at best in attempts to synthesize six-membered rings.[5c,6]

We believe that difficulties encountered in many previous attempts at such cyclizations are attributable to problems associated with the heterogeneous reaction conditions employed when alkali and alkaline-earth metals are used as reductants.[7] Under such circumstances, cyclization is competitive with simple reductive cleavage of the halide. Five-membered ring cyclizations are apparently rapid enough that intermediate hydrogen abstraction from the solvent (typically THF) does not interfere. As a consequence, five-membered ring carbocycles can generally be isolated in acceptable yields even under heterogeneous reaction conditions.

Such is not the case in attempted six-membered ring cyclizations. Alkylsubstituted cycloalkanones are often major byproducts in these instances,[5c-7] even when nonenolizable ketones are utilized as substrates. It thus appears that hydrogen abstraction from the solvent competes effectively with the cyclization process in these instances.



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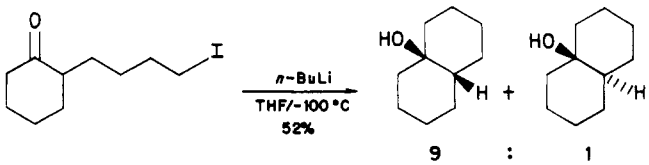
Mechanistic studies to further elucidate factors controlling both heterogeneous and homogeneous reductive coupling reactions and to determine the nature of the intermediates involved in these processes are currently underway in our laboratories.

From a synthetic point of view, we reasoned that soluble reducing agents might alleviate problems associated with six-membered ring cyclizations. In this regard, our attention initially turned to use of organolithiums as reagents for the desired transformation.[8] Treatment of 2-(4-iodobutyl)cyclohexanone with *n*-butyllithium in THF at −100 °C provided a moderate yield of the desired bicyclo[4.4.0]decanol. Various permutations of this reaction



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(utilization or other organolithium reagents and several different solvents) failed to improve yields in this process. Furthermore, we sought milder reagents that might enjoy broader application in syntheses of more complex, multifunctional molecules. As a consequence, we focused on use of samarium diiodide (SmI_2) and other lanthanide reducing agents[9] in an attempt to develop a more general approach to this particular transformation. Samarium diiodide is soluble in tetrahydrofuran (THF) and is readily generated by reaction of samarium metal with diiodoethane. In fact, we have found that SmI_2 works exceedingly well as a reducing agent in these intramolecular Barbier-type syntheses, allowing a quite general approach to syntheses of bicyclic alcohols through this particular methodology.

Results and Discussion

Pioneering studies by Kagan and co-workers demonstrated the effectiveness of SmI_2 as a mild reducing agent for a number of organic functional groups.[9c] Coupling reactions of organic halides with carbonyl substrates were also studied, and these served as the basis for the current study.[9c,g,i-l] Thus, Kagan determined that reaction of alkyl iodides with ketones provides the corresponding alcohols in excellent yield in intermolecular reactions.[9c]

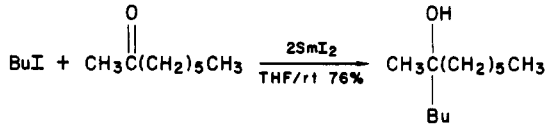

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Table I. Samarium Diiodide Induced Cyclization of 1[a]

entry	startg matrl	n	m	% GC yield (isolated)	ratio 2:3
1	1a	1	1	90 (60)[10]	>99.5:0.5
2	1b	2	1	100 (75)[5c,11]	1.3:1
3	1c	3	1	85 (77)[10b,12]	2.0:1
4	1d	1	2	67[5c,11]	18:1
5	1e	2	2	95 (75)[10b,11a,13]	1:1.5
6	1f	3	2	(83)[12a]	1:2.3

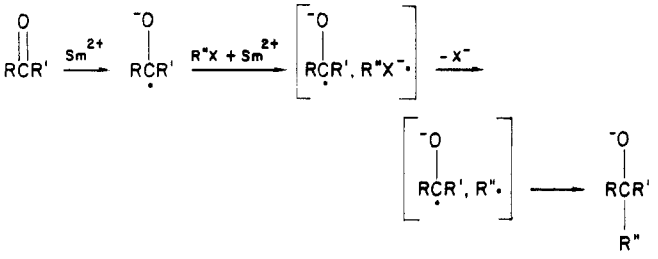
[a] Reactions were run utilizing 2 equiv of SmI_2 in THF at room temperature, with ~1.5 mol % catalyst [$Fe(DBM)_3$].

Table II. ^{13}C NMR Chemical Shift Differences [$\delta_{cis} - \delta_{trans} = \Delta\delta_{cis-trans}$] of Bridgehead Alcohol Carbons in Bicyclo[*n*.*m*.0]alkan-1-ols

bicyclo[*n*.*m*.0]alkan-1-ol	$\Delta\delta_{cis-trans}$
bicyclo[4.3.0]nonan-1-ol	+1.2
bicyclo[4.4.0]decan-1-ol	+1.46
bicyclo[5.3.0]decan-1-ol	+2.14
bicyclo[5.4.0]undecan-1-ol[a]	+1.57

[a] Assignment of stereoisomers made by $\Delta\delta_{cis-trans}$.

The mechanism that is perhaps most consistent with all available data for this conversion involves reduction of ketones to ketyls, with subsequent coupling of these to halide radical anions (or radicals, upon loss of halide ions) to provide the alcohols.[9d]



To test the effectiveness and scope of this reaction cyclization, we prepared a number of 2-(ω-iodoalkyl)cycloalkanones by a variety of standard procedures. Subjection of these substrates to reduction by SmI_2 in THF at room temperature in the presence of a catalytic amount of iron tris(dibenzoylmethane) [$Fe(DBM)_3$] afforded excellent isolated yields of bicyclic alcohols (Table I). Reactions were generally complete within 3 h under these conditions.

In most cases, stereochemistry of products was assigned by comparison with comprehensive spectral data for each isomer described in the literature. Only IR data has been reported for *cis*- and *trans*-bicyclo[5.4.0]undecan-1-ols,[12a] and so we have relied upon correlation of ^{13}C NMR data to assign stereochemistry in this instance. As can be seen in Table II, bridgehead alcohol carbons in cis isomers are consistently shifted 1.2–2.2 ppm downfield of the corresponding carbons in the trans isomers. Other physical characteristics of the bicyclo[5.4.0]undecan-1-ols (e.g., GC retention time, R_f on TLC) were consistent with the assignment by ^{13}C NMR.

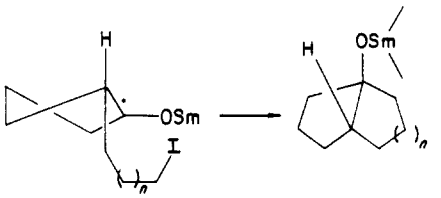
Several features of the reaction are worth noting. First, cyclopentanone substrates provide nearly exclusive formation of the cis ring-fused isomer (entries 1 and 4, Table I). Molecular models of 2-(ω-iodoalkyl)cyclopentanone in the preferred half-chair conformation[14] indicate a great deal of strain is generated in the side chain in order for trans ring fusion to occur. As a consequence, cis isomers are generated exclusively.

Table III. Effect of Reducing Agents on Product Stereochemistry in Cyclization of 1c

entry	reducing agent	% GC yield	ratio 2c:3c
1	SmI_2/cat. Fe(III)	85	2.0:1
2	SmI_2	77	3.1:1
3	YbI_2/cat. Fe(III)	59	6.1:1
4	Sm	71	4.1:1
5	Yb	77	6.7:1

Table IV. Effect of Reducing Agents on Product Stereochemistry in Cyclization of 1e

entry	reducing agent	% GC yield	ratio 2e:3e
1	SmI_2/cat. Fe(III)	95	1:1.5
2	SmI_2	71	1:3
3	YbI_2	68	1:5.6



The lack of stereoselectivity observed in cyclizations utilizing cyclohexanone substrates is surprising. Other cyclization reactions which involve coupling of an sp^3 carbon center with an sp^2 carbon center on a ring, regardless of mechanism, often occur with high stereoselectivity to provide the cis ring-fused isomer.[5c,15]

Studies utilizing different reducing agents were initiated in attempts to enhance the observed stereoselectivity. We had some success in improving the stereoselectivity of the reaction by utilizing ytterbium diiodide (YbI_2) as the reducing agent. One important fact concerning lanthanide metals is that filling of 4f orbitals through the lanthanide series causes a steady contraction in ionic sizes. This has several consequences. The first is that ions of metals occurring late in the series (such as Yb) possess shorter metal–oxygen bonds than early series metal ions (such as Sm). Furthermore, the solvated radii of ions such as Yb(III) are much greater than those of the somewhat larger, and, therefore, less polarizing, Sm(III) ion.[16] Given the assumption that lanthanide ketyls play a major role in the mechanism of the reaction, one might conclude that the effective steric bulk of the metal ion and associated solvent should play a major role in controlling the stereochemistry of the process. This seems to be born out in several substrates (Tables III and IV). Unfortunately, the effect of these factors cannot be predicted in all cases. Thus, *cis*-2-(4-iodobutyl)-4-*tert*-butylcyclohexanone reacts with YbI_2 to provide the corresponding bicyclic alcohol ring-fused

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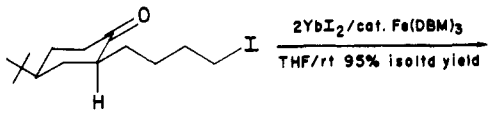
isomers in a ratio of only 1.3:1.



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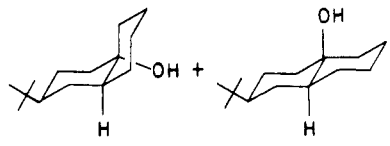

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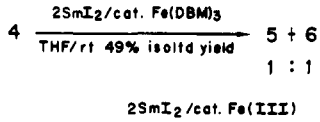
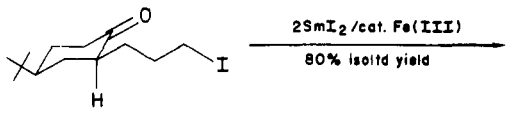
When Sm and Yb metals are used as reductants, one encounters the same problems suffered in utilizing Mg or other metals in intramolecular Barbier-type reactions. While five-membered ring syntheses can be accomplished quite effectively (entries 4 and 5, Table III), generation of six-membered rings cannot be achieved in synthetically useful yields. This again points to the effect that heterogeneous conditions have on these particular reactions.

In addition to determining the effect of various reducing agents on the stereoselectivity, we were interested in the influence that substituents about the cycloalkanone ring might have on the observed stereoselectivity of the reaction. The first such study involved cyclization of 2-(ω-iodoalkyl)-4-*tert*-butylcyclohexanones. As is evident, cis





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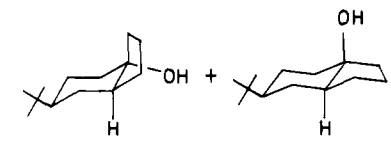
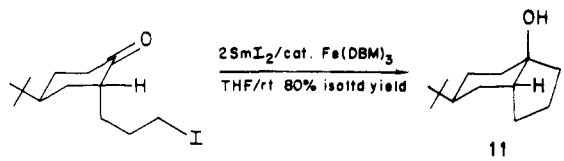


1:1

8 9

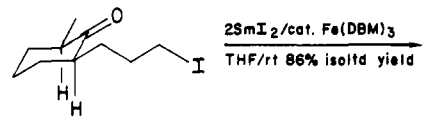
substrate isomers provided equal proportions of the cis and trans ring-fused isomer products. On the other hand, the trans substrate isomer gave a single (cis) ring-fused isomer. The latter reaction is completely stereoselective and obviously takes place under conditions that are mild enough that the starting material is not epimerized.



10 11

Substituents adjacent to the carbonyl at the 6-position also have relatively little effect at controlling stereochemistry. Reaction of *cis*-2-(3-iodopropyl)-6-methylcyclohexanone with SmI_2 under the standard conditions provides a 1.8:1 mixture of ring-fused isomers.

Perhaps most surprising is cyclization of 2-(3-iodopropyl)-3,3,5,5-tetramethylcyclohexanone. Again in this instance, a nearly equal mixture of diastereomers results, in spite of the fact that the cis isomer encounters two 1,3-diaxial interactions in the final product.



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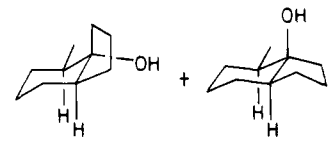
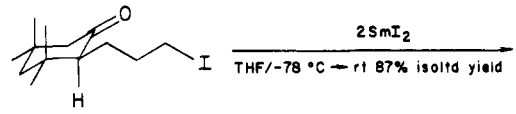


1.8 : 1

13 14



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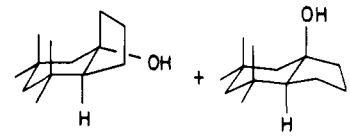
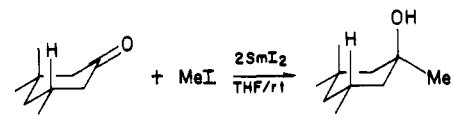


1.1:1

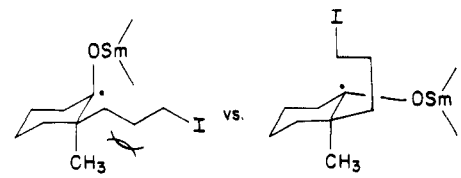
16 17

Intermolecular reactions occur with more predictable stereochemical outcomes. For example, 3,3,5-trimethylcyclohexanone reacts with methyl iodide in the presence of SmI_2 to provide a single diastereomer. As expected, attack occurs exclusively from the equatorial direction, providing the axial alcohol product. The accumulated



data from these studies lead us to the conclusion that stereoelectronic requirements imposed by *intramolecular* coupling allows perhaps several kinetically accessible conformations[5c,17] (e.g., flip-chair, twist-boat, or boat) to be involved in the crucial carbon–carbon bond-forming step. As a consequence, loss of stereoselectivity is observed in several instances.

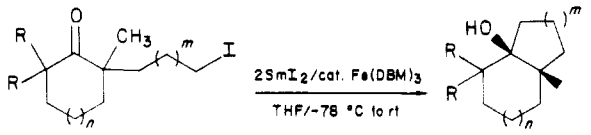
Reliably high stereoselectivity can be achieved when substituents adjacent to the carbonyl at the 2-position are incorporated into the molecule (Table V). Space-filling molecular models suggest torsional[18] and perhaps steric interactions between the haloalkyl side chain and the 2-methyl substituent in the transition state force the reaction to take place from the side opposite the methyl group in any accessible conformation of the molecule. As a consequence, high diastereoselectivity is seen in all of these substrates. Particularly noteworthy is the fact that even fully substituted, highly hindered ketones undergo cyclization with great facility in high yield (Table V, entry 4).



Stereochemistry of the products generated from these cyclizations could be assigned unambiguously by direct

(17) Kellie, G. M.; Riddell, F. G. *Top. Stereochem.* **1974**, *8*, 225.
(18) Cherest, M. *Tetrahedron* **1980**, *36*, 1593.

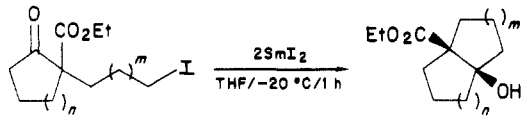
Table V



18 19

entry	startg matrl	R	n	m	% GC yield (isoltd) of **19**
1	**18a**	H	1	1	100 (75)
2	**18b**	H	1	2	(65)
3	**18c**	H	3	2	(57)
4	**18d**	Me	1	1	(90)

Table VI

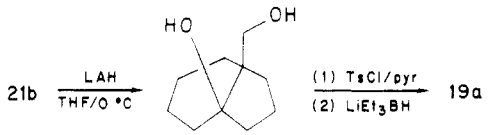


20 21

entry	startg matrl	n	m	% GC yield (isoltd) of **21**
1	**20a**	1	2	68[a]
2	**20b**	2	1	(81)
3	**20c**	3	1	(95)
4	**20d**	4	1	(88)

[a] Reaction performed at room temperature for 16 h.

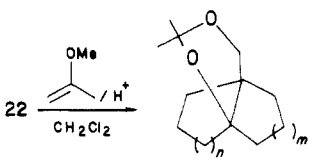
correlation to the ethyl hydroxybicyclo[*n.m.*0]alkanecarboxylates described below by a simple reduction sequence.



22

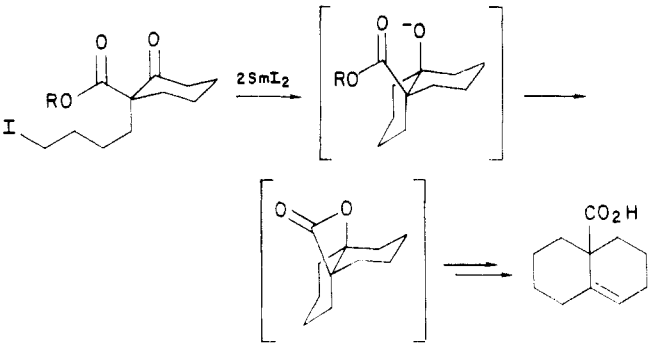
The mild nature of SmI_2 is expected to allow incorporation of a number of functional groups into the substrates to be cyclized. Previous studies have shown that esters, nitriles, and many halides, for example, are virtually inert to SmI_2.[9c] We have incorporated 2-carbalkoxy groups into suitable substrates in order to demonstrate the chemoselectivity of SmI_2 (Table VI).

Stereochemistry of products in this series was established by reduction of the alcohol–ester to the diol and generation of the corresponding acetonide. Diols generated from trans ring-fused isomers are obviously unable to form the acetonide.



The reactivity of these β-keto ester substrates differed markedly from those of simple ketones. Thus, while cyclizations of 2-(ω-iodoalkyl)cycloalkanone generally require approximately 3 h at room temperature in the presence of an Fe(III) catalyst to completely cyclize, corresponding β-keto ester substrates undergo reaction in less than 1 h at −20 °C in the absence of catalyst. This enhanced reactivity might be ascribed to a lower reduction potential of the ketone due to the presence of an electron-withdrawing substituent and/or to the ability of β-keto esters to chelate samarium ions, thereby facilitating electron transfer to the ketone.

Curiously, attempts at generating bicyclo[4.4.0] ring systems (and other larger, more flexible ring systems) failed when β-keto ester substrates were utilized in attempted cyclization reactions. Complex mixtures resulted, from which we were able to isolate unsaturated carboxylic acid derivatives. We attribute such products to formation and decomposition of β-lactones.[19] In systems less highly strained than those depicted in Table VI, formation of β-lactone becomes facile. Decomposition of the β-lactones either under the reaction conditions or upon workup provides the observed mixture of products. We have thus been unable to prevent multiple product formation from these substrates by a variety of alternative reaction and/or workup procedures.



Conclusions

Samarium diiodide has been demonstrated to be an exceedingly effective reagent in inducing intramolecular Barbier-type reactions. For the first time, six-membered rings can be readily generated by this process in synthetically useful yields. Synthesis of both five- and six-membered rings can be accomplished under very mild conditions, allowing incorporation of numerous functional groups into organic substrates. Many stereochemical aspects of the reaction have been delineated. It has been determined that reactions are highly stereoselective when cyclization takes place onto cyclopentanone substrates and when 2-substituted-2-(ω-iodoalkyl)cycloalkanone precursors are utilized. In both instances, exclusive formation of cis ring-fused isomers is found. These factors, coupled with the ease of preparation of necessary starting materials, established the method as a highly useful technique for generation of a number of bicyclic alcohol derivatives.

Experimental Section

Melting points were determined on a Fisher-Johns melting point apparatus. All melting points and boiling points are reported uncorrected. IR spectra were recorded on a Perkin-Elmer 727B infrared spectrophotometer and calibrated by comparison with a standard 0.05-mm-thick polystyrene film. All ^1H NMR and ^{13}C NMR spectra were taken on a JEOL FX-90Q spectrometer unless otherwise specified. NMR samples were dissolved in either $CDCl_3$ or CCl_4. Chemical shifts are reported in parts per million (δ) vs. $CHCl_3$. Low-resolution mass spectra were obtained on a MAT CH5 mass spectrometer. Exact mass spectra were recorded on a VG-7070EQ-HF mass spectrometer employing perfluorokerosene as the internal standard. All mass spectra utilize a 70-eV ionizing potential. Gas–liquid chromatographic analyses were conducted on a Hewlett-Packard Model 5750 chromatographed equipped with a Hewlett-Packard Model 3390 digital integrator. GLC columns (10 ft × $^1/_8$ in.) were packed with 3% Carbowax 20 M on 100/120 AW-DMCS Chromosorb W. Flash chromatography was carried out under standard procedures.[20] Elemental analyses

(19) Stork, G.; Clarke, F. H., Jr. *J. Am. Chem. Soc.* **1961**, *83*, 3114.

were performed by Galbraith Laboratoires, Inc., Knoxville, TN.

Reagents. THF (Fisher) was distilled from $LiAlH_4$, stored over sodium benzophenone ketyl, and distilled from sodium benzophenone ketyl immediately prior to use. 1,2-Diiodoethane (Aldrich) was purified by dissolving it in ether, washing with saturated aqueous $Na_2S_2O_3$ solution, drying over $MgSO_4$, and removing the ether in vacuo to yield a white crystalline solid. All reactions were run under an argon atmosphere employing standard techniques for handling of air-sensitive materials.[21] Samarium metal was purchased from Research Chemicals, Phoenix, AZ.

Starting Materials. 2-Allylcyclopentanone,[22] 2-allylcyclohexanone,[23] 2-allylcycloheptanone,[23,10b] 2-allyl-4-*tert*-butylcyclohexanone,[23,24] 2-allyl-6-methylcyclohexanone,[23] 2-allyl-2-methylcyclohexanone,[25] 2-allyl-2,6,6-trimethylcyclohexanone,[10b,26] 2-allyl-3,3,5,5-tetramethylcyclohexanone,[10b] ethyl 2-oxocycloheptanecarboxylate,[27] ethyl 2-oxocyclooctanecarboxylate,[27] and 2-methylcyclooctanone[28] were prepared according to literature procedures. All 2-(3-bromopropyl)cycloalkanones were prepared from the corresponding 2-allylcycloalkanones by the method of House.[29] Each ethyl 1-(4-bromobutyl)-2-oxocycloalkanecarboxylate[30] and ethyl 1-(3-chloropropyl)-2-oxocycloalkanecarboxylate was prepared by alkylation of the appropriate β-keto ester with either 1,4-dibromobutane or 1-bromo-3-chloropropane. All 2-(4-bromobutyl)cycloalkanones were prepared by decarboxylation of the corresponding β-keto ester.[31] 2-(4-Chlorobutyl)-2-methylcyclohexanone, 2-(4-chlorobutyl)-2-methylcyclooctanone, and *cis*-2-(4-chlorobutyl)-4-*tert*-butylcyclohexanone were prepared by alkylation of the appropriate potassium enoxytriethylborate[23] with 1-chloro-4-iodobutane. All 2-(ω-iodoalkyl)-cycloalkanones and keto esters were prepared by Finkelstein reactions[5c] of the corresponding 2-(ω-haloalkyl)cycloalkanone or keto ester with NaI in acetone.

Cyclization of 2-(ω-Iodoalkyl)cycloalkanones with SmI_2. General Procedure. To a slurry of samarium metal powder (0.30 g, 2.0 mmol) in THF (1 mL) at room temperature was added a solution of 1,2-diiodoethane (0.42 g, 1.5 mmol) and iron(III) tris(dibenzoylmethane)[32] (0.007 g, 0.01 mmol) in THF (2 mL). The mixture was then stirred at ambient temperature for 1 h during which time the reaction's color changed from red to olive-green and finally to a deep blue-violet. The 2-(ω-iodoalkyl)cycloalkanone (0.75 mmol) was then slowly added neat. The resulting mixture was allowed to stir for 12 h at room temperature before being separated between saturated aqueous K_2CO_3 (5 mL) and ether (5 mL). The aqueous layer was extracted with ether (3 × 3 mL). The organic extracts were then washed with brine (2 mL) and dried over $K_2CO_3/MgSO_4$.

Cyclization of 2-(3-Iodopropyl)cyclopentanone (1a). By using the general procedure described above, **1a** (0.19 g, 0.75 mmol) was cyclized to provide ***cis*-bicyclo[3.3.0]octan-1-ol**[10b] **(2a)** (0.68 mmol) 90% by GC analysis (0.06 g, 0.45 mmol), 60% after Kugelrohr distillation: bp 40–45 °C (30 mmHg); ^1H NMR (CCl_4)[33] δ 1.5–2.0 (m); ^{13}C NMR (C_6D_6)[34] δ 26.13, 33.59, 42.16, 52.47, 91.08; IR (CCl_4) 3585, 3360, 2940, 2855, 1450, 1318, 1205, 1009, 982 cm^{-1}; MS, *m/e* (relative intensity) 126 (M^+, 23), 97 (96), 83 (100), 82 (70), 55 (64), 41 (63).

Cyclization of 2-(3-Iodopropyl)cyclohexanone (1b). By using the general procedure described above, **1b** (0.20 g, 0.75 mmol) was cyclized to provide two bicyclo[4.3.0]nonan-1-ols[5c] **2b** and **3b** (0.75 mmol) 100% by GC analysis (0.08 g, 0.56 mmol), 75% by flash chromatography (7% EtOAc in hexane on neutral activity III alumina).

***cis*-Bicyclo[4.3.0]nonan-1-ol (2b):** ^1H NMR (C_6D_6)[33] δ 0.17–1.51 (m); ^{13}C NMR (C_6D_6)[34] δ 20.33, 23.32, 23.93, 28.99, 29.04, 35.29, 36.02, 46.55, 79.92; IR (CCl_4) 3590, 3400, 2910, 2860, 1455, 1345, 1190, 1090, 1035, 975, 880 cm^{-1}; MS, *m/e* (relative intensity) 140 (M^+, 44), 111 (97), 98 (100), 97 (97), 83 (51), 82 (58), 55 (57), 41 (53).

***trans*-Bicyclo[4.3.0]nonan-1-ol (3b):** ^1H NMR (C_6D_6)[33] δ 0.12–1.18 (m); ^{13}C NMR (C_6D_6)[34] δ 20.24, 21.91, 25.89, 26.39, 28.25, 37.20, 39.47, 47.86, 77.72; IR (CCl_4) 3605, 3375, 2920, 2850, 1450, 1265, 1185, 1070, 955, 932, 873, 850 cm^{-1}; MS, *m/e* (relative intensity) 140 (M^+, 29), 139 (92), 111 (86), 98 (100), 97 (76), 54 (74), 41 (68).

Cyclization of 2-(3-Iodopropyl)cycloheptanone (1c). By using the general procedure described above, **1c** (0.21 g, 0.75 mmol) was cyclized to provide two bicyclo[5.3.0]decan-1-ols[10b] **2c** and **3c** (0.11 g, 0.70 mmol) 93% isolated by flash chromatography (7% EtOAc in hexane on neutral activity III alumina).

***cis*-Bicyclo[5.3.0]decan-1-ol (2c):** ^1H NMR (CCl_4)[33] δ 1.01–2.03 (m); ^{13}C NMR (C_6D_6)[34] δ 23.91, 24.41, 30.11, 31.72, 34.55, 35.69, 40.13, 44.16, 53.24, 83.90; IR (CCl_4) 3590, 3400, 2920, 2850, 1460, 1210, 1020, 980, 970, 920 cm^{-1}; MS, *m/e* (relative intensity) 154 (M^+, 46), 125 (65), 112 (95), 111 (75), 97 (100), 83 (57), 55 (70), 41 (46).

***trans*-Bicyclo[5.3.0]decan-1-ol (3c):** ^1H NMR (C_6D_6)[33] δ 0.18–1.44 (m); ^{13}C NMR (C_6D_6)[34] δ 21.92, 24.66, 26.86, 27.03, 27.24, 32.78, 41.26, 43.84, 47.79, 81.76; IR (CCl_4) 3610, 3475, 2940, 2860, 1365, 1185, 920, 875 cm^{-1}; MS, *m/e* (relative intensity) 154 (M^+, 33), 125 (58), 112 (82), 111 (79), 97 (100), 55 (66), 41 (56).

Cyclization of 2-(4-Iodobutyl)cyclopentanone (1d). By using the general procedure described above, **1d** (0.20 g, 0.75 mmol) was cyclized to provide both **2b** and **2c** (0.50 mmol) 67% by GC analysis.

Cyclization of 2-(4-Iodobutyl)cyclohexanone (1e). By using the general procedure described above, **1e** (0.21 g, 0.75 mmol) was cyclized to provide two bicyclo[4.4.0]decan-1-ols[10b] **2e** and **3e** (0.74 mmol) 98% by GC analysis (0.09 g, 0.56 mmol), 75% isolated by flash chromatography (7% EtOAc in hexane on neutral activity III alumina).

***cis*-Bicyclo[4.4.0]decan-1-ol (2e):** ^1H NMR (CCl_4)[33] δ 0.87–1.69 (m); ^{13}C NMR (C_6D_6)[34] δ 23.3 (br), 28.34, 37 (br), 43.22, 71.09; IR (CCl_4) 3610, 3480, 2930, 2870, 1480, 1460, 1165, 1040, 1005, 965, 945, 865 cm^{-1}; MS, *m/e* (relative intensity) 154 (M^+, 5), 153 (11), 111 (100), 98 (38), 53 (31), 41 (28).

***trans*-Bicyclo[4.4.0]decan-1-ol (3e):** ^1H NMR (CCl_4)[33] δ 0.77–1.73 (m); ^{13}C NMR (C_6D_6)[34] δ 21.97, 26.75, 28.95, 40.33, 44.55, 69.58; IR (CCl_4) 3650, 2945, 2875, 1465, 1185, 970, 930 cm^{-1}; MS, *m/e* (relative intensity) 154 (M^+, 36), 111 (100), 98 (42), 55 (30), 41 (29).

Cyclization of 2-(4-Iodobutyl)cycloheptanone (1f). By using the general procedure described above, **1f** (0.22 g, 0.75 mmol) was cyclized to provide two bicyclo[5.4.0]undecan-1-ols[12a] **2f** and **3f** (0.12 g, 0.74 mmol) 98% isolated by flash chromatography (7% EtOAc in hexane on neutral activity III alumina).

***cis*-Bicyclo[5.4.0]undecan-1-ol (2f):** ^1H NMR (CCl_4)[33] δ 1.1–2.7 (m); ^{13}C NMR (C_6D_6)[34] δ 21.22, 23.08, 23.35, 27.64, 29.85, 30.33, 30.61, 39.02, 42.65, 45.86, 73.55; IR (CCl_4) 3625, 3525, 2930, 2865, 1460, 1005, 945, 905, 870 cm^{-1}; MS, *m/e* (relative intensity) 168 (M^+, 8), 167 (54), 125 (60), 111 (100), 98 (50), 82 (23), 67 (23), 55 (45), 41 (38); exact mass calcd for $C_{11}H_{20}O$ 168.1514, found 168.1522.

***trans*-Bicyclo[5.4.0]undecan-1-ol (3f):** ^1H NMR (CCl_4)[33] δ 1.0–2.7 (m); ^{13}C NMR (C_6D_6)[34] δ 21.18, 21.90, 26.62, 27.00, 27.68, 30.78, 31.10, 41.70, 44.38, 47.48, 71.98; IR (CCl_4) 3640, 3520, 2930, 2860, 1470, 1455, 1205, 990, 940, 905 cm^{-1}; MS, *m/e* (relative intensity) 168 (M^+, 8), 167 (56), 125 (50), 111 (100), 98 (54), 55 (38); exact mass calcd for $C_{11}H_{20}O$ 168.1514, found 168.1516.

Cyclization of *cis*-2-(4-Iodobutyl)-4-*tert*-butylcyclohexanone (4). By using the general procedure described above, **4** (0.08 g, 0.25 mmol) was cyclized to provide two 4-*tert*-butylbicyclo[4.4.0]decan-1-ols[35] **5** and **6** (0.02 g, 0.12 mmol) 48% isolated

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(33) Varian EM-390 NMR spectrometer.
(34) Bruker WM-250 NMR spectrometer.

by flash chromatography (5% EtOAc in hexane on neutral activity III alumina).

***cis*-4α-*tert*-Butylbicyclo[4.4.0]decan-1β-ol (5)**: ^{1}H NMR ($CDCl_3$) δ 0.84 (s, 9 H), 0.93–2.40 (m, 17 H); ^{13}C NMR ($CDCl_3$) δ 20.14, 21.69, 24.88, 25.78, 27.65 (3), 29.76, 31.09, 32.28, 42.09, 42.74, 48.24, 71.64; IR (CCl_4) 3610, 3375, 2940, 2865, 1455, 1395, 1370, 1050, 915 cm^{-1}; MS, *m/e* (relative intensity) 210 (M^+, 40), 209 (100), 167 (63), 135 (73), 111 (99), 95 (73), 67 (50), 58 (77), 55 (55); exact mass calcd for $C_{14}H_{26}O$ 210.1984, found 210.1977.

***trans*-4α-*tert*-Butylbicyclo[4.4.0]decan-1α-ol (6)**: ^{1}H NMR ($CDCl_3$) δ 0.83 (s, 9 H), 0.89–1.78 (m, 17 H); ^{13}C NMR ($CDCl_3$) δ 21.68, 22.39, 26.26, 27.02, 27.62 (3), 28.83, 29.57, 39.37, 40.11, 44.33, 48.20, 69.64; IR (CCl_4) 3600, 3360, 2940, 2855, 1450, 1390, 1365, 1050, 915 cm^{-1}; MS, *m/e* (relative intensity) 210 (M^+, 15), 209 (90), 191 (24), 135 (100), 111 (93), 95 (51), 67 (60), 58 (96), 55 (60); exact mass calcd for $C_{14}H_{26}O$ 210.1984, found 210.1992.

Cyclization of *cis*-2-(3-iodopropyl)-4-*tert*-butylcyclohexanone (7) contaminated with 13% trans isomer (**10**). By using the general procedure described above, the **7,10** mixture (0.24 g, 0.75 mmol) was cyclized to provide three 3-*tert*-butylbicyclo[4.3.0]nonan-1-ols[5c] **8**, **9**, and **11** (0.12 g, 0.60 mmol) 80% isolated by flash chromatography (10% EtOAc in hexane on neutral activity III alumina.)

***cis*-3α-*tert*-Butylbicyclo[4.3.0]nonan-1β-ol (8)**: ^{1}H NMR (CCl_4)[33] δ 0.78 (s, 9 H), 0.92–2.05 (m, 15 H); ^{13}C NMR (CCl_4)[34] δ 21.19, 25.21, 27.70 (3), 30.97, 32.19, 32.76, 34.57, 36.79, 47.62, 48.45, 81.22; IR (CCl_4) 3620, 3510, 2940, 2880, 1480, 1405, 1375, 1205, 1155, 960 cm^{-1}; MS, *m/e* (relative intensity) 196 (M^+, 53), 165 (57), 154 (100), 139 (69), 121 (51), 97 (88), 57 (80).

***trans*-4α-*tert*-Butylbicyclo[4.3.0]nonan-1-ol (9)**: ^{1}H NMR (CCl_4)[33] δ 0.88 (s, 9 H); 0.26–2.40 (m, 15 H); ^{13}C NMR (C_6D_6)[34] δ 21.10, 22.92 26.53, 28.05 (3), 28.26, 32.57, 37.06, 39.07, 48.52, 48.72, 77.41; IR (CCl_4) 3645, 2960, 2880, 1485, 1410, 1375, 970, 930, 875 cm^{-1}; MS, *m/e* (relative intensity) 196 (M^+, 63), 165 (47), 154 (100), 139 (53), 121 (52), 97 (74), 57 (92).

***cis*-3α-*tert*-Butylbicyclo[4.3.0]nonan-1α-ol (11)**: ^{1}H NMR (CCl_4)[33] δ 0.80 (s, 9 H), 0.97–2.34 (m, 15 H); ^{13}C NMR (C_6D_6)[34] δ 20.08, 23.04, 25.25, 27.28, 27.71 (3), 30.00, 34.76, 40.99, 41.76, 45.54, 77.26; IR (CCl_4) 3610, 2960, 2880, 1375, 1215, 1030 cm^{-1}; MS, *m/e* (relative intensity) 196 (M^+, 59), 154 (79), 139 (51), 97 (76), 57 (100). Anal. Calcd for $C_{13}H_{24}O$: C, 79.53; H, 12.32. Found: C, 79.38; H, 12.40.

Cyclization of *cis*-2-(3-Iodopropyl)-6-methylcyclohexanone (12). By using the general procedure described above, **12** (0.21 g, 0.75 mmol) was cyclized to provide two 2-methylbicyclo[4.3.0]nonan-1-ols **13** and **14** (0.75 mmol) 100% by GC analysis (0.10 g, 0.64 mmol), 86% isolated by flash chromatography (10% EtOAc in hexane on neutral activity III alumina).

***cis*-2α-Methylbicyclo[4.3.0]nonan-1β-ol (13)**: ^{1}H NMR ($CDCl_3$) δ 0.91 (d, J = 7.2 Hz, 3 H), 0.91–2.27 (m, 15 H); ^{13}C NMR ($CDCl_3$) δ 16.32, 19.76, 25.51, 29.19, 29.57, 31.71, 32.58, 40.38, 48.42, 85.00; IR (CCl_4) 3620, 3390, 2925, 2875, 1460, 1375, 1260, 1195, 1045, 955, 880 cm^{-1}; MS, *m/e* (relative intensity) 154 (M^+, 9), 153 (73), 125 (68), 112 (86), 111 (56), 97 (100), 83 (79), 55 (61). Anal. Calcd for $C_{10}H_{18}O$: C, 77.86; H, 11.76. Found: C, 78.01; H, 11.74.

***trans*-2α-Methylbicyclo[4.3.0]nonan-1α-ol (14)**: ^{1}H NMR ($CDCl_3$) δ 0.82 (d, J = 5.7 Hz, 3 H) 0.82–2.27 (m, 15 H); ^{13}C NMR ($CDCl_3$) 15.95, 19.93, 25.21, 25.94, 28.00, 29.95, 37.02, 40.57, 48.53, 80.49; IR (CCl_4) 3630, 3480, 2935, 2880, 1454, 1373, 1260, 1190, 946, 874 cm^{-1}; MS, *m/e* (relative intensity) 154 (M^+, 8), 153 (31), 125 (42), 111 (86), 97 (86), 84 (66), 83 (54), 71 (94), 58 (100), 55 (52). Anal. Calcd for $C_{10}H_{18}O$: C, 77.86; H, 11.76. Found: C, 78.01; H, 11.74.

Cyclization of 2-(3-Iodopropyl)-3,3,5,5-tetramethylcyclohexanone (15). By using the general procedure described above, **15** (0.24 g, 0.75 mmol) was cyclized to provide two 3,3,5,5-tetramethylbicyclo[4.3.0]nonan-1-ols[14] **16** and **17** (0.13 g, 0.65 mmol) 87% isolated by flash chromatography (5% EtOAc in hexane on neutral activity III alumina).

***cis*-3,3,5,5-Tetramethylbicyclo[4.3.0]nonan-1-ol (16)**: ^{1}H NMR (CCl_4)[36] δ 0.80 (s, 3 H), 0.89 (s, 3 H), 1.16 (s, 6 H), 1.10–1.80 (m, 12 H); ^{13}C NMR ($CDCl_3$) δ 19.08, 26.22, 29.83, 30.47, 30.90, 31.27, 32.34, 36.06, 43.71, 45.39, 47.53, 53.95, 81.39; IR (CCl_4) 3615, 2955, 1455, 1385, 1370, 1215, 1160, 1030 cm^{-1}; MS, *m/e* (relative intensity) 196 (M^+, 12), 182 (43), 181 (100), 162 (78), 153 (75), 139 (92), 111 (36), 97 (92), 82 (54).

***trans*-3,3,5,5-Tetramethylbicyclo[4.3.0]nonan-1-ol (17)**: ^{1}H NMR (CCl_4)[36] δ 0.79 (s, 3 H), 0.82 (s, 3 H), 1.04 (s, 3 H), 1.14 (s, 3 H), 0.50–1.80 (m, 12 H); ^{13}C NMR ($CDCl_3$) δ 19.59, 21.86, 22.32, 29.03, 32.50, 32.99, 34.72, 36.38, 41.94, 49.27, 54.67, 54.97, 81.28; IR (CCl_4) 3615, 2985, 1455, 1365, 1260, 1220, 1085, 1020, 855 cm^{-1}; MS, *m/e* (relative intensity) 196 (M^+, 7), 181 (100), 153 (55), 139 (89), 97 (42), 55 (40).

Cyclization of 2-(3-Iodopropyl)-2-methylcyclohexanone (18a). By using the general procedure described above, **18a** (0.21 g, 0.75 mmol) was cyclized to provide ***cis*-5-methylbicyclo[4.3.0]nonan-1-ol (19a)** (0.75 mmol) 100% by GC analysis (0.09 g, 0.56 mmol), 75% after Kugelrohr distillation: bp 40–45 °C (1.0 mmHg); mp 71.5–72.0 °C; ^{1}H NMR ($CDCl_3$) δ 0.86 (s, 3 H), 0.62–2.25 (m, 15 H); ^{13}C NMR ($CDCl_3$) δ 18.30, 19.68, 21.74, 23.66, 33.53, 35.64, 35.86, 37.67, 44.20, 81.44; IR (CCl_4) 3615, 3485, 2940, 2865, 1467, 1452, 1376, 1340, 1154, 1055, 974, 948, 908, 733 cm^{-1}; MS, *m/e* (relative intensity) 154 (M^+, 4), 112 (100), 98 (40), 97 (39), 55 (25). Anal. Calcd for $C_{10}H_{18}O$: C, 77.86; H, 11.76. Found: C, 77.64; H, 11.91.

Cyclization of 2-(4-Iodobutyl)-2-methylcyclohexanone (18b). By using the general procedure described above, **1b** (0.22 g, 0.75 mmol) was cyclized to provide ***cis*-6-methylbicyclo[4.3.0]decan-1-ol (19b)** (0.08 g, 0.49 mmol) 65% isolated by flash chromatography (10% EtOAc in hexane on neutral activity III alumina): ^{1}H NMR ($CDCl_3$) δ 0.93 (s, 3 H), 0.98–2.22 (m, 17 H); ^{13}C NMR ($CDCl_3$) δ 21.39, 22.36, 22–24 (br), 32–37 (br), 37.32, 73.15; IR (CCl_4) 3600, 3465, 2920, 2860, 1465, 1450, 1380, 1160, 1050, 1005, 980, 940, 915 cm^{-1}; MS, *m/e* (relative intensity) 168 (M^+, 11), 125 (12), 112 (100), 83 (22), 67 (21), 55 (38); exact mass calcd for $C_{11}H_{20}O$ 168.1514, found 168.1520.

Cyclization of 2-(4-Iodobutyl)-2-methylcyclooctanone (18c). By using the general procedure described above, **18c** (0.24 g, 0.75 mmol) was cyclized to provide ***cis*-6-methylbicyclo[6.4.0]dodecan-1-ol (19c)** (0.08 g, 0.43 mmol) 57% isolated by flash chromatography (5% EtOAc in hexane on neutral activity III alumina): ^{1}H NMR ($CDCl_3$) δ 0.93 (s, 3 H), 1.02–1.92 (m, 21 H); ^{13}C NMR ($CDCl_3$) δ 21.47 (2), 21.77, 22.07, 22.77, 23.23, 27.19, 27.76, 36.40, 37.02, 39.46, 39.62, 75.29; IR (CCl_4) 3620, 3500, 2950, 2880, 1470, 1165, 970 cm^{-1}; MS, *m/e* (relative intensity) 196 (M^+, 24), 179 (7), 153 (8), 139 (18), 125 (18), 111 (85), 98 (42), 82 (39), 67 (37), 55 (80), 41 (100); exact mass calcd for $C_{13}H_{24}O$ 196.1827; found 196.1826.

Cyclization of 2-(3-Iodopropyl)-2,6,6-trimethylcyclohexanone (18d). By using the general procedure described above, **18d** (0.23 g, 0.75 mmol) was cyclized to provide ***cis*-2,5,5-trimethylbicyclo[4.3.0]nonan-1-ol (19d)** (0.12 g, 0.68 mmol) 90% isolated by Kugelrohr distillation: bp 35–40 °C (0.80 mmHg); ^{1}H NMR ($CDCl_3$) δ 0.84 (s, 3 H), 0.96 (s, 3 H), 1.01 (s, 3 H), 1.04–2.25 (m, 13 H); ^{13}C NMR ($CDCl_3$) δ 17.79, 18.71, 20.52, 22.45, 27.43, 35.50, 36.61, 37.02, 38.65, 40.79, 45.42, 85.13; IR (CCl_4) 3625, 3500, 2900, 2860, 1695, 1464, 1385, 1380, 1120, 1075, 1050, 970, 940, 875 cm^{-1}; MS, *m/e* (relative intensity) 182 (M^+, 3), 140 (10), 98 (100), 81 (39), 69 (22), 55 (19); exact mass calcd for $C_{12}H_{21}O$ ($M - 1$) 181.1593, found 181.1599.

Cyclization of Ethyl 1-(ω-Iodoalkyl)-2-oxocycloalkanecarboxylates with SmI_2. General Procedure. To a slurry of samarium metal powder (0.30 g, 2.0 mmol) in THF (1 mL) at room temperature was added a solution of 1,2-diiodoethane (0.42 g, 1.5 mmol) in THF (2 mL). The mixture was stirred at ambient temperature for 1 h, during which time the reaction's color changed from olive-green to a deep blue-green. The reaction was cooled to −20 °C, and the ethyl 1-(ω-iodoalkyl)-2-oxocycloalkanecarboxylate (0.75 mmol) was then slowly added neat. The resulting mixture was allowed to stir at −20 °C for 1 h before having been separated between saturated aqueous K_2CO_3 (5 mL) and ether (5 mL). The aqueous layer was extracted with ether (3 × 3 mL). The organic extracts were washed with brine (3 mL) and dried over $K_2CO_3/MgSO_4$.

Cyclization of Ethyl 1-(4-Iodobutyl)-2-oxocyclopentanecarboxylate (20a). The general procedure described above was followed, except the reaction mixture was allowed to warm to room temperature and stirred for 16 h. In this manner **20a** (0.25 g, 0.75

(35) Gream, G. E.; Laffer, M. H.; Serelis, A. K. *Aust. J. Chem.* **1978**, *31*, 803.

(36) Magnachem A-200 NMR spectrometer.

mmol) was cyclized to provide **ethyl *cis*-5-hydroxybicyclo[4.3.0]nonane-1-carboxylate (21a)** (0.51 mmol) 68% by GC analysis: ^{1}H NMR ($CDCl_3$) δ 1.13 (t, J = 7.4 Hz, 3 H), 1.27–2.42 (m, 14 H), 3.74 (d, J = 1.4 Hz, 1 H), 4.02 (q, J = 7.4 Hz, 2 H); ^{13}C NMR ($CDCl_3$) δ 13.94, 18.79, 22.56, 23.61, 32.90, 34.01 (2), 34.31, 55.71, 60.18, 81.06, 177.25; IR (CCl_4) 3525, 2940, 2870, 1710, 1545, 1460, 1330, 1300, 1240, 1195, 1150, 1040, 990, 895, 870 cm^{-1}; MS, m/e (relative intensity) 212 (M^+, 30), 170 (54), 138 (29), 122 (100), 121 (72), 111 (31), 110 (33), 93 (24), 79 (25), 67 (37); exact mass calcd for $C_{12}H_{20}O_3$ 212.1412, found 212.1419.

Cyclization of Ethyl 1-(3-Iodopropyl)-2-oxocyclohexanecarboxylate (20b). By using the generation procedure described above, **20b** was cyclized to **21a** (0.13 g, 0.60 mmol) 80% isolated by flash chromatography (20% EtOAc in hexane on silica gel).

Cyclization of Ethyl 1-(3-Iodopropyl)-2-oxocycloheptanecarboxylate (20c). By using the general procedure described above, **20c** (0.26 g, 0.75 mmol) was cyclized to provide **ethyl *cis*-5-hydroxybicyclo[5.3.0]decane-1-carboxylate (21c)** (0.15 g, 0.64 mmol) 86% isolated by flash chromatography (20% EtOAc in hexane on silica gel): ^{1}H NMR ($CDCl_3$) δ 1.17 (t, J = 7.1 Hz, 3 H), 1.29–2.62 (m, 16 H), 4.03 (d, J = 1.4 Hz, 1 H), 4.08 (q, J = 7.1 Hz, 2 H); ^{13}C NMR ($CDCl_3$) δ 14.00, 20.28, 21.72, 23.66, 27.89, 34.64, 38.35, 38.59, 39.62, 59.66, 60.21, 84.02, 177.60; IR (CCl_4) 3510, 2940, 2870, 1705, 1460, 1385, 1300, 1190, 1115, 1025, 955, 895 cm^{-1}; MS, m/e (relative intensity) 226 (M^+, 5), 225 (12), 209 (9), 180 (27), 136 (100), 135 (65), 123 (29), 111 (22), 97 (48), 67 (54); exact mass calcd for $C_{13}H_{21}O_3$ (M – 1) 225.1491, found 225.1504.

Cyclization of Ethyl 1-(3-Iodopropyl)-2-oxocyclooctanecarboxylate (20d). By using the general procedure described above, **20d** (0.28 g, 0.75 mmol) was cyclized to provide **ethyl *cis*-5-hydroxybicyclo[6.3.0]undecane-1-carboxylate (21d)** (0.16 g, 0.66 mmol) 88% isolated by flash chromatography (20% EtOAc in hexane on silica gel): ^{1}H NMR ($CDCl_3$) δ 1.19 (t, J = 7.1 Hz, 3 H), 1.28–2.58 (m, 18 H), 4.09 (q, J = 7.1 Hz, 2 H), 4.34 (d, J = 1.4 Hz, 1 H); ^{13}C NMR ($CDCl_3$) δ 14.05, 18.74, 22.04, 23.96, 25.40, 27.78, 33.77, 35.72, 37.21, 40.70, 57.66, 60.12, 83.50, 178.04; IR (CCl_4) 3510, 2940, 2875, 1710,, 1475, 1450, 1375, 1305, 1190, 1145, 1050, 950, 865 cm^{-1}; MS, m/e (relative intensity) 240 (M^+, 5), 239 (11), 223 (58), 194 (23), 166 (100), 143 (39), 123 (21), 111 (10), 97 (16), 67 (20); exact mass calcd for $C_{14}H_{24}O_3$ 240.1725, found 240.1733.

Reduction of Ethyl *cis*-5-Hydroxybicyclocarboxylates. General Procedure. To a slurry of $LiAlH_4$ (0.08 g, 2.0 mmol) in THF (1 mL) at 0 °C was slowly added a solution of the ethyl *cis*-5-hydroxybicyclocarboxylate (1.0 mmol) in THF (2 mL). The resulting mixture was allowed to stir and warm to room temperature over 5 h, after which time the mixture was again cooled to 0 °C, and $Na_2SO_4 \cdot 10H_2O$ was added until no H_2 evolution was observed. An excess of $Na_2SO_4 \cdot 10H_2O$ was added, and the products were filtered through a sintered glass frit.

Reduction of Ethyl *cis*-5-Hydroxybicyclo[4.3.0]nonane-1-carboxylate (21a). By using the general procedure described above, **21a** (0.21 g, 1.0 mmol) was reduced to provide ***cis*-5-(hydroxymethyl)bicyclo[4.3.0]nonan-1-ol (22a)** (0.14 g, 0.83 mmol) 83% isolated by flash chromatography (8% MeOH in CH_2Cl_2 on silica gel): ^{1}H NMR ($CDCl_3$) δ 0.93–2.03 (m, 14 H), 3.50 (d, J = 11.4 Hz, 1 H), 3.68 (d, J = 11.4 Hz, 1 H), 4.32 (br s, 2 H); ^{13}C NMR ($CDCl_3$) δ 18.05, 21.44, 22.91, 30.87, 31.06, 34.23, 36.99, 46.55, 66.82, 83.01; IR (CCl_4) 3610, 3325, 2940, 2880, 1545, 1460, 1125, 1060, 920 cm^{-1}; MS, m/e (relative intensity) 152 (M – 18, 26), 139 (9), 125 (13), 111 (9), 97 (12), 85 (21), 71 (28), 57 (41), 18 (100).

Reduction of Ethyl *cis*-5-Hydroxybicyclo[5.3.0]decane-1-carboxylate (21c). By using the general procedure described above, **21c** (0.23 g, 1.0 mmol) was reduced to provide ***cis*-5-(hydroxymethyl)bicyclo[5.3.0]decan-1-ol (22c)** (0.16 g, 0.86 mmol) 86% isolated by flash chromatography (8% MeOH in CH_2Cl_2 on silica gel): ^{1}H NMR ($CDCl_3$) δ 0.97–1.95 (m, 16 H), 3.21–3.82 (m, 2 H), 3.98 (br s, 2 H); ^{13}C NMR ($CDCl_3$) δ 22.53, 23.29, 23.66, 30.74, 37.70, 38.16, 40.79, 43.82, 50.64, 70.06, 86.02; IR (CCl_4) 3600, 3355, 2940, 2865, 1520, 1460, 1225, 1080, 920 cm^{-1}; MS, m/e (relative intensity) 166 (M – 18, 7), 148 (40), 136 (42), 129 (39), 108 (44), 93 (72), 81 (87), 67 (99), 55 (42), 41 (100).

Ketalization of 2-Methoxypropene with (Hydroxymethyl)bicyclanols. General Procedure. To a solution of (hydroxymethyl)bicyclanol (0.50 mmol) and pyridinium *p*-toluenesulfonate[37] (0.01 g, 0.05 mmol) in dry CH_2Cl_2 (2 mL) at 0 °C was slowly added 2-methoxypropene. After having been stirred for 1 h at 0 °C, the mixture was separated between water (4 mL) and CH_2Cl_2 (4 mL). The aqueous layer was extracted with CH_2Cl_2 (3 × 2 mL). The organic extracts were dried over $K_2CO_3/MgSO_4$.

Ketalization of 2-Methoxypropene with *cis*-5-(Hydroxymethyl)bicyclo[4.3.0]nonan-1-ol (22a). By using the general procedure described above, **22a** (0.08 g, 0.50 mmol) was used to ketalize 2-methoxypropene to provide ***cis*-5-(hydroxymethyl)bicyclo[4.3.0]nonan-1-ol acetonide (23a)** (0.09 g, 0.43 mmol) 86% isolated by flash chromatography (6% EtOAc in hexane on silica gel): ^{1}H NMR ($CDCl_3$) δ 1.38 (s, 3 H), 1.43 (s, 3 H), 1.53–2.15 (m, 14 H), 3.41 (d, J = 11.4 Hz, 1 H), 3.67 (d, J = 11.4 Hz, 1 H); ^{13}C NMR ($CDCl_3$) δ 19.06, 22.09, 23.15, 27.54, 28.97, 31.82, 33.42, 33.74, 37.37, 40.62, 63.65, 82.93, 97.64; IR (CCl_4) 2940, 2870, 1540, 1455, 1380, 1370, 1250, 1200, 1090, 1010 cm^{-1}; MS, m/e (relative intensity) 195 (M – 15, 25), 152 (14), 135 (100), 123 (13), 111 (28), 93 (33), 81 (42), 67 (53); exact mass calcd for $C_{12}H_{19}O_2$ (M – 15) 195.1385; found 195.1382.

Ketalization of 2-Methoxypropene with *cis*-5-(Hydroxymethyl)bicyclo[5.3.0]decan-1-ol (22c). By using the general procedure described above, **22c** (0.09 g, 0.50 mmol) was used to ketalize 2-methoxypropene to provide ***cis*-5-(hydroxymethyl)bicyclo[5.3.0]decan-1-ol acetonide (23c)** (0.10 g, 0.46 mmol) 91% isolated by flash chromatography (6% EtOAc in hexane on silica gel): ^{1}H NMR ($CDCl_3$) δ 1.32 (s, 3 H), 1.38 (s, 3 H), 1.43–2.17 (m, 16 H), 3.29 (d, J = 10.9 Hz, 1 H), 3.44 (d, J = 10.9 Hz, 1 H); ^{13}C NMR ($CDCl_3$) δ 22.66, 24.42, 24.56, 27.67, 28.08, 31.30, 37.35, 38.56, 39.73, 41.27, 47.20, 68.76, 87.89, 98.78; IR (CCl_4) 2925, 2855, 1535, 1455, 1380, 1370, 1230, 1170, 1110, 1075, 995 cm^{-1}; MS, m/e (relative intensity) 224 (M^+, 3), 209 (13), 166 (18), 149 (62), 123 (35), 106 (22), 95 (41), 81 (58), 71 (71), 57 (100); exact mass calcd for $C_{14}H_{24}O_2$ 224.1776, found 224.1751.

Ketalization of 2-Methoxypropene with *cis*-5-(Hydroxymethyl)bicyclo[6.3.0]undecan-1-ol (22d). By using the general procedure described above, **22d** (0.10 g, 0.50 mmol) was used to ketalize 2-methoxypropene to provide ***cis*-5-(hydroxymethyl)bicyclo[6.3.0]undecan-1-ol acetonide (23d)** (0.12 g, 0.49 mmol) 98% isolated by flash chromatography (6% EtOAc in hexane on silica gel): ^{1}H NMR ($CDCl_3$) δ 1.36 (s, 3 H), 1.41 (s, 3 H), 1.45–2.29 (m, 18 H), 3.35 (d, J = 11.7 Hz, 1 H), 3.78 (d, J = 11.7 Hz, 1 H); ^{13}C NMR ($CDCl_3$) δ 21.01, 22.64, 24.26, 26.43, 26.48, 26.64, 29.14, 33.74, 37.24, 38.24, 40.46, 44.55, 66.14, 86.64, 97.86; IR (CCl_4) 2930, 2860, 1540, 1465, 1405, 1395, 1220, 1170, 1090, 1000, 925 cm^{-1}; MS, m/e (relative intensity) 238 (M^+, 2), 223 (8), 180 (13), 163 (42), 137 (22), 122 (26), 106 (33), 95 (58), 81 (100), 67 (72); exact mass calcd for $C_{15}H_{26}O_2$ 238.1933, found 238.1906.

Preparation of *cis*-5-((Tosyloxy)methyl)bicyclo[4.3.0]nonan-1-ol. To a solution of *cis*-5-(hydroxymethyl)bicyclo[4.3.0]nonan-1-ol (**22a**) (0.07 g, 0.42 mmol) and *N*,*N*-dimethylaminopyridine (0.01 g, 0.10 mmol) in freshly distilled pyridine (2 mL) at 0 °C was added *p*-toluenesulfonyl chloride (0.09 g, 0.46 mmol) in a single portion. The reaction mixture was allowed to stir and warm to room temperature over 12 h, and then warmed to 50 °C for an additional 3 h before being separated between water (4 mL) and CH_2Cl_2 (4 mL). The aqueous layer was extracted with CH_2Cl_2 (3 × 2 mL). The organic extracts were washed with saturated aqueous $CuSO_4$ (2 × 3 mL) and brine (2 mL) and dried over $MgSO_4$. The product, *cis*-5-((tosyloxy)methyl)bicyclo[4.3.0]nonan-1-ol (0.09 g, 0.27 mmol, 65%) was isolated by flash chromatography (2% MeOH in CH_2Cl_2 on silica gel): ^{1}H NMR ($CDCl_3$)[21] δ 1.03–2.02 (m, 14 H), 2.46 (s, 3 H), 3.91–4.17 (m, 2 H), 7.12–7.92 (m, 5 H); IR (CCl_4) 3600, 3540, 2930, 2870, 1595, 1470, 1365, 1180, 1100, 955 cm^{-1}.

Reduction of *cis*-5-((Tosyloxy)methyl)bicyclo[4.3.0]nonan-1-ol.[38] To a solution of *cis*-5-((tosyloxy)methyl)bicyclo[4.3.0]nonan-1-ol (0.09 g, 0.27 mmol) in THF (1 mL) at 0 °C was added lithium triethylborohydride (0.82 mL of a 1.0 M THF solution, 0.82 mmol). The mixture was heated to reflux for 2.5

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h, and then cooled to room temperature followed by addition of water (1 mL), 3 N aqueous NaOH (2 mL), and 33% aqueous H_2O_2 (2 mL). After having been stirred an additional hour at room temperature, the mixture was separated. The aqueous layer was extracted with hexane (3 × 2 mL). The organic extracts were washed with brine (2 mL) and dried over $K_2CO_3/MgSO_4$. The product, *cis*-5-methylbicyclo[4.3.0]nonan-1-ol (**19a**) (0.03 g, 0.18 mmol) 66% was isolated by flash chromatography (10% EtOAc in hexane on neutral activity III alumina) and found to be identical with the *cis*-5-methylbicyclo[4.3.0]nonan-1-ol (**19a**) prepared via the cyclization of 2-(3-iodopropyl)-2-methylcyclohexanone (**18a**).

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Registry No. **1a**, 83587-99-9; **1b**, 83587-93-3; **1c**, 83588-00-5; **1d**, 93494-17-8; **1e**, 76402-75-0; **1f**, 101493-08-7; **2a**, 52318-93-1; **2b**, 13366-92-2; **2c**, 27935-18-8; **2e**, 3574-58-1; **2f**, 27935-20-2; **3b**, 13366-91-1; **3c**, 27935-17-7; **3e**, 1654-87-1; **3f**, 27935-19-9; **4**, 101493-09-8; **5**, 101517-30-0; **6**, 69007-51-8; **7**, 101493-10-1; **8**, 83587-33-1; **9**, 83587-34-2; **10**, 101493-11-2; **11**, 83587-95-5; **12**, 101517-31-1; **13**, 101493-12-3; **14**, 101493-13-4; **15**, 83587-96-6; **16**, 83587-97-7; **17**, 83587-98-8; **18a**, 101493-14-5; **18b**, 101493-16-7; **18c**, 101493-17-8; **18d**, 101493-19-0; **19a**, 101493-15-6; **19b**, 5173-74-0; **19c**, 101493-18-9; **19d**, 101493-20-3; **20a**, 101493-21-4; **20b**, 101493-23-6; **20c**, 101493-24-7; **20d**, 101493-26-9; **21a**, 101493-22-5; **21c**, 101493-25-8; **21d**, 101493-27-0; **22a**, 101493-28-1; **22a** (tosylate), 101493-33-8; **22c**, 101493-29-2; **22d**, 101493-31-6; **23a**, 101517-32-2; **23c**, 101493-30-5; **23d**, 101493-32-7; ,MeC(OMe)=CH_2, 116-11-0; SmI_2, 32248-43-4.

Liquid-Phase Regioselective 1,4-Hydrogenation of Benzylidene Ketones on $Rh/AlPO_4$ Catalysts

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The liquid-phase catalytic hydrogenation of α,β-unsaturated carbonyl compounds, in the p-$XC_6H_4CH{=}CHCOR$ form (*E* isomers; X = H, Me, MeO, Cl; R = Me, Et, *n*-Pr, *i*-Pr, *n*-Bu, *t*-Bu, *n*-Pe, Ph) was carried out by using a rhodium catalyst supported at 1 wt % on $AlPO_4$ in methanol solvent under low hydrogen pressure (0.55 MPa) at room temperature (298 K). The reactions were found to be highly selective toward the formation of the conjugate reduction product (p-$XC_6H_4CH_2CH_2COR$). In no cases could any appreciable amount of allylic or saturated alcohol be detected, although a small amount of benzyl ketone is obtained in the *p*-chlorobenzylidene ketones due to the hydrogenolysis of the C–Cl bond. The influence of the substituents on the reaction rate is analyzed, and both resonance and steric effects of the COR and R groups, respectively, seem to simultaneously influence the reaction process.

Introduction

Chemoselective hydrogenation of activated double bonds, such as α,β-unsaturated carbonyl functions, has been a long-desired synthetic transformation, since this problem is frequently encountered in synthetic schemes. So, the selective reduction of either the double bond or the carbonyl group of α-enones has been investigated by several workers using different catalytic systems.[1-8] However, some of these methods have not always afforded satisfactory results because of a lack of consistent regiospecificity and the fact that some hydride reagents are quite difficult to prepare.

Rhodium catalysts have attracted much attention from the viewpoint of synthetic organic, as well as from that of industrial chemistry, due to their high catalytic activity and easy preparation and reduction.

In this paper the $Rh/AlPO_4$ system[9,10] is described as a new heterogeneous hydrogenation catalyst for the selective liquid-phase reduction, at room temperature, of the carbon–carbon double bond of α-enones of different types and structures. This catalyst is easily prepared and stable on long storage.

The study of the influence of ketone structure on reactivity shows that the functional groups on the carbon–carbon double bond affect the hydrogenation activity by electronic and steric effects, specially the first one.

From the present study seventeen new ketones of the type p-$XC_6H_4CH_2CH_2COR$ are reported. Although a search of the literature revealed that five of these ketones are known, they were reported without physical and spectroscopic properties.

Results and Discussion

Diffusion Control, Reaction Kinetics, and Solvent Effect. Several hydrogenation runs, performed at various agitation regimes and with different amounts of catalyst, showed that the initial rates of hydrogenation were directly

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