Branched-Chain Carbohydrate Lactones from a Samarium(II) Iodide-Promoted Serial Deoxygenation–Carbonyl Addition Reaction

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A new deoxygenation–carbonyl addition reaction mediated by samarium(II) iodide (SmI_2) in THF/HMPA was examined with carbohydrate lactones and several substrates containing an α-alkoxy carboxylic ester. In a single reaction, these compounds were deoxygenated and subsequently coupled to several ketones by a carbonyl addition reaction. The first reactions studied simple ester and ketone adducts which were later elaborated to more complex optically active carbohydrate lactones appended to terpene ketones. Simple esters smoothly afforded β-hydroxy carbonyl products. Fully benzoate-protected 3-deoxycarbohydrate lactones were reacted with simple ketones to produce C_2-branched sugars. The attendant carbonyl addition to the least sterically hindered face of the aldonolactone provided the major products. Moderate diastereoselectivities (up to 5:1) were observed in the simple ketone products as determined by difference NOE studies. Finally, the terpene ketones, (−)-menthone or (+)-dihydrocarvone, were coupled to 3-deoxycarbohydrate lactones which gave C_2-branched sugars with very high diastereoselectivities (up to 99:1).

Introduction

Branched-chain carbohydrates have been found to be biologically important molecules, and they occur in a large number of natural products.[1] These substrates are an intensely investigated area of organic synthesis;[2] however, most classic synthetic technologies involve modifications of a carbonyl on the pyranose or furanose ring with the Wittig reaction,[3] CH_2N_2,[4] organometallic reagents,[5] and a variety of other protocols.[1,2] These methods have now been largely replaced by more modern free-radical approaches, such as the Giese reaction[2a,b] and 5-hexenyl-type one-electron cyclizations, to achieve pyranosidic and furanosidic homologations.[6,7] A totally different synthetic approach to branched-chain sugars would involve direct deoxygenation of a ring carbon followed by carbon–carbon bond formation; however, the protocol to accomplish this task must also be compatible with the wide variety of other oxygenated functions present and inherent stereochemical features of the carbohydrate.[8] Ideally, a single reagent would be highly desirable which could accomplish both synthetic tasks in one transformation and thereby reduce the number of steps needed in a particular synthetic sequence.

The synthetic development of the highly selective and mild reducing agent samarium diiodide (SmI_2) is one of the most significant advancements in organic chemistry over the last 12 years.[9] The seminal investigations of Kagan have been elegantly elaborated and extended by Molander, Inanaga, and Curran in a manner which has led to broad applications in synthetic organic chemistry.[9,10]

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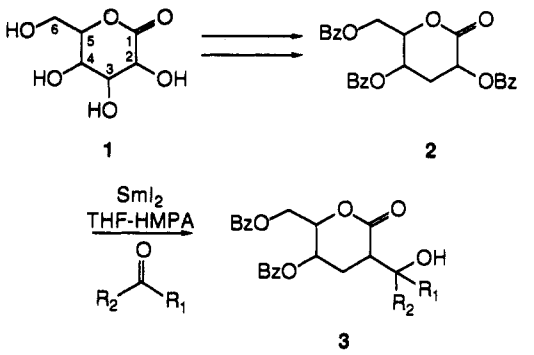
We have been interested in many facets of the utility of SmI_2, particularly with applications of SmI_2 to carbohydrate templates and other densely oxygenated substrates.[11] Carbohydrates especially serve as important vehicles to demonstrate a wide variation in the scope of SmI_2 reactions, not only because they are optically active but also because they are highly oxygenated and create the potential for chelation and deoxygenation reactions which have already become important reaction attributes of SmI_2.[9,10] The utilization of SmI_2 in transformation of complex, optically active compounds such as carbohydrates and terpenes is in direct contrast to nearly all current technology, which primarily involves simple achiral substrates as synthetic vehicles.[11,12]

For many years, esters and presumably lactones were considered inert to the reductive effects of SmI_2.[9] Kagan's early report on SmI_2 indicated that simple esters like methyl octanoate were unreactive.[13] Inanaga has since then demonstrated that solutions of SmI_2 in the presence of HMPA and other additives with THF can produce much stronger reducing media than SmI_2 alone in THF.[10g,14] Several beneficial effects of this major preparatory advance are seen in rate enhancements,[9,10] tandem cyclizations,[10c] and coupling reactions of unsaturated centers.[10g] One of the first uses of the SmI_2–HMPA reagent combination was in the α-deoxygenation of α,β-epoxy esters.[15] A similar α-deoxygenation reaction with a carefully selected proton source has also been examined with malic esters and carbohydrate lactones.[12a,16] With several activated ring oxygens on aldonolactones, SmI_2 promotes a deoxygenation of one or several sites[12a] producing unsaturated and saturated lactones in good yields in the presence of a proper proton source.[16c] A recent report demonstrated that only α-deoxygenation occurs when the β-hydroxyl is not activated (unprotected), and in some cases, HMPA appears to not be required in every deoxygenation reaction.[12a]

We wished to combine several important features of these reactions in a serial or tandem sequence, that is, the deoxygenation of α-oxygenated esters with a carbonyl coupling reaction, both of which can be promoted by SmI_2 in THF–HMPA on a carbohydrate template, as shown in Scheme I. The strong oxophilicity, stereoselectivity, and regiocontrol of the one-electron reductant SmI_2 should be worthy of investigation in this capacity. The C_3-deoxygenated aldonolactones such as **2** were examined and

Scheme I



utilized in these studies primarily due to their structural simplicity and brevity in preparation.[17] In this conversion, a new carbon–carbon bond is formed, a β-hydroxy ester **3** is afforded by an intermolecular carbonyl addition reaction, and the net synthetic modification can be viewed as an overall transformation of an α-hydroxy ester to a β-hydroxy ester.

This reaction is related to the SmI_2 Reformatsky and other dehalogenation–carbonyl coupling reactions.[9,18] Kagan reported the first studies of the condensation of ethyl α-bromopropionate with cyclohexanone which coupled in 51% yield.[13a] Since this report, highly diastereoselective 1,2-, 1,3-, and 1,4-intramolecular asymmetric inductions have been reported, with SmI_2 offering distinct advantages over the "classic Reformatsky" conditions with zinc and other metals.[19] Unfortunately, Reformatsky-type reactions promoted by lanthanide reagents generally provide modest diastereoselectivities at best (>3:1) with secondary α-halo ester precursors.[9]

Results and Discussion

Simple Esters and Ketones. Because the serial reductive deoxygenation and coupling reactions of α-oxygenated esters have not been studied prior to our work, we decided to initially examine simple achiral esters first and later extend these reactions to optically active ketones and carbohydrates.[11c,h] The transformations, tabulated in Table I, show several successful examples of the coupling of α-benzoate esters with various ketones.

We examined the reaction without HMPA; however, either no reaction or a very slow rate was observed and starting substrates could be recovered unchanged.[15,16] In several reactions with added HMPA, we attempted to add the ketone after the start of the reaction at several delayed time intervals, but only decomposition of the α-benzoate ester was observed. We reasoned that, after ejection of the benzoate, an electrophile such as a ketone must be present or immediate decomposition of the Sm(III) enolate begins. Carbonyl addition reactions with aldehydes, such as cyclohexanecarboxaldehyde, resulted only in their rapid dimerization (pinacol coupling) with concomitant decom-

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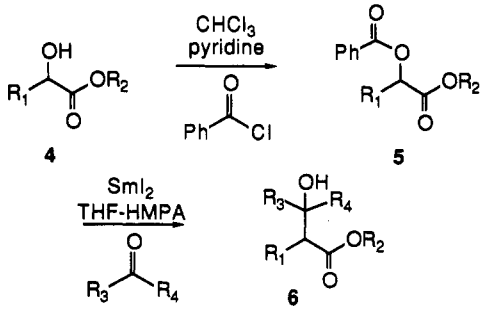
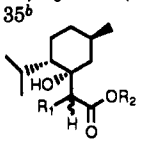
Table I. β-Hydroxy Esters from the Deoxygenation/Condensation of α-Hydroxy Esters



entry	ester	ketone	product and yield[a] (%)
1	**5a**, $R_1 = CH_3$, $R_2 = CH_2CH_3$ 75%	4-heptanone	**6a**, $R_3,R_4 = (CH_2)_2CH_3$ 66
2	**5a**	benzylacetone	**6b**, $R_3 = (CH_2)_2Ph$, $R_4 = CH_3$ 87[b]
3	**5a**	cyclohexanone	**6c**, $R_3,R_4 = (CH_2)_5$ 75
4	**5a**	2-methyl-3-heptanone	**6d**, $R_3 = CH(CH_3)_2$, $R_4 = (CH_2)_3CH_3$ 35[b]
5	**5b**, $R_1 = (CH_2)_3CH_3$, $R_2 = CH_2CH_3$ 87%	(−)-methone	 52[c]
6	**5b**	2-octanone	**6f**, $R_3 = (CH_2)_5CH_3$, $R_4 = CH_3$ 73

[a] Yields refer to isolated material. [b] *Ca.* 1:1 diastereomeric mixture. [c] Single diastereomer (>20:1) by 300-MHz ^{1}HNMR.

position of the α-alkoxy ester. Even with ketones, a small amount of pinacol dimer side product was observed in many reactions. Because ketones were generally successful, this is probably a reflection of the rates of dimerization of the aldehydes vs the ketones. Relative to ketones, the less hindered aldehydes undergo pinacol coupling faster than the deoxygenation/carbonyl coupling. Although α-hydroxy esters, such as **4**, are slowly deoxygenated by SmI_2,[16a] they could not be used directly in this reaction. Activation of the alcohol as a benzoate ester **5** was critical for success. The α-benzoate was ejected much faster than an α-alcohol by SmI_2, giving the ketone time to react prior to its pinacol coupling. Most of the success in these studies was probably due to an advantageous timing of the rates of the various events involved.

The yields for all but one of the ketones shown in Table I were generally good and not optimized in most cases. The lower yield in entry 4 can be attributed to increased steric crowding due to the adjacent methyl, which slowed reaction coupling and allowed for decomposition in the Sm(III) enolate and pinacol coupling of the ketone. Other addends such as alkyl halides, esters, and lactones did not function well in the reaction. Compounds **6b** and **6d** were obtained as almost 1:1 mixtures; however, (−)-menthone adduct **6e** was observed as a single diastereomeric product by ^{1}H NMR.[20]

Carbohydrate Lactones and Simple Ketones. Substantially more complex carbohydrate starting substrates were examined in the deoxygenation–carbonyl addition reaction promoted by SmI_2.[11h] The C_3-deoxygenated aldonolactones were selected as carbohydrate templates and ideal starting substrates for these studies for three reasons. First, aldonolactones have a built-in lactone carbonyl function, and many are readily accessible from commercial sources. Second, the C_3-deoxygenation completely limits the SmI_2-deoxygenation to the C_2-hydroxyl in these substrates. This was done because Sm(III) enolates would have likely eliminated the active C_3-alkoxy functions to afford α,β-unsaturated aldonolactones.[16b,c] Third, all the hydroxyls can be simultaneously protected/activated as benzoates, and the C_3-hydroxyl can be easily excised in each compound by the elegant two-step method of DeLederkremer.[17b,21] The original method involved the exhaustive acetylation of the lactone and a one-step elimination of the C_3-acetate to the α,β-unsaturated aldonolactone, followed by hydrogenation. The benzoate protecting-activating groups were used in this study because they had been very successful in the simple cases in Table I. Thus, the next series of reactions studied involved the transformation of 3-deoxycarbohydrate lactones in which the deoxygenation of a C_2-benzoate moiety is followed by the formation of a new carbon–carbon bond, shown in general form in Scheme I. If the simple ester cases could be elaborated to carbohydrates, the reaction should then afford a β-hydroxy lactone product **3**, as a C_2-branched chain sugar in a subsequent tandem reaction after the deoxygenation. Eventually, it is hoped that this general method would provide a new access to biologically important natural products.

The first substrate examined was commercially available L-gulonolactone (**7**) which was treated with benzoyl chloride to produce 2,3,5,6-tetra-*O*-benzoylgulono-γ-lactone (**8**)[21b] in 97% yield, shown in Scheme II. Next, Et_3N-promoted elimination of benzoic acid followed by hydro-

(20) The addition of organometallic reagents to the (−)-menthone carbonyl occurs trans to the isopropyl group: Johnson, C. R.; Stark, C. J., Jr. *Tetrahedron Lett.* **1979**, 4713 and references cited therein.

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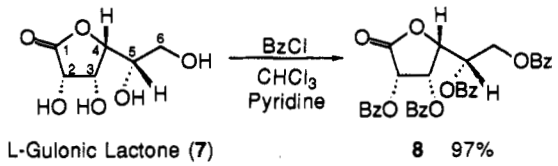
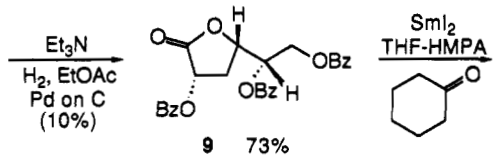
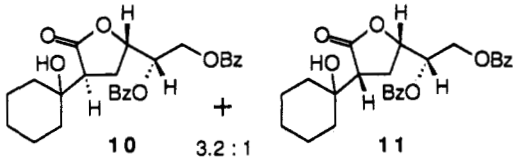
Scheme II



L-Gulonic Lactone (**7**) **8** 97%



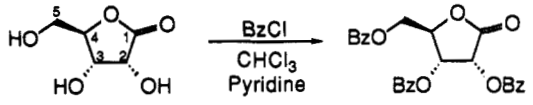
9 73%



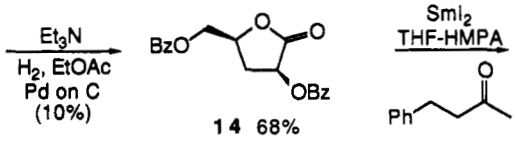
10 3.2 : 1 **11**

72%

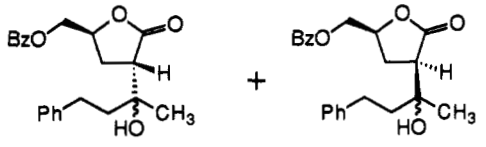
Scheme III



D-Ribonic Lactone (**12**) **13** 91%



14 68%



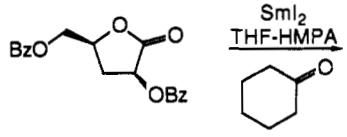
15a **15b** 5 : 5 : 1 : 1 **16a** **16b**

69%

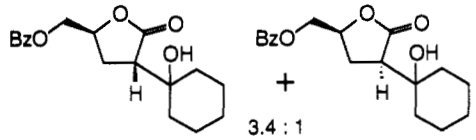
genation of the endocyclic olefin from the least hindered face of the furanose ring rendered 3-deoxy-2,5,6-tri-*O*-benzoylgulono-γ-lactone (**9**), isolated in highly crystalline form (mp 124–125 °C) in 73% yield. With key precursor **9** in hand, it was next treated with cyclohexanone and an intensely dark blue solution of SmI_2 (4 equiv) in THF/HMPA from −78 to +23 °C over 1 h. Two branched-chain carbohydrates, **10** and **11**, formed in a ratio of *ca.* 3.2:1, as determined by 300-MHz ^1H NMR, in 72% yield. The products were easily separated and major product, **10**, was crystallized as colorless needles (mp 143.5–144.5 °C). The minor product **11** could not be completely purified; however, it could be structurally confirmed as a minor stereoisomer by NMR. Difference NOE studies of **10** indicated that cyclohexanone had a preference to add to the least hindered face of the lactone ring, as expected.

A second study, shown in Scheme III, utilized the carbohydrate lactone D-ribonolactone (**12**) as a starting substrate which was exhaustively esterified and deoxygenated in the C_3 position by DeLederkremer[17b,21] elimination/hydrogenation of the furanose ring in 91% and 68% yields, respectively, in a manner similar to the previous glucono-γ-lactone example. The C_2-benzoate was inverted in this substrate because hydrogenation occurred on the back face of the α,β-unsaturated γ-aldonolactone ring. Crystalline 3-deoxy-2,5-di-*O*-benzoylthreo-γ-lactone

Scheme IV



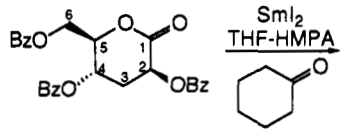
14



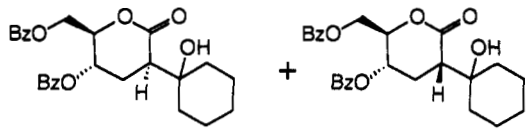
28a 3.4 : 1 **28b**

64%

Scheme V



2,4,6-Tri-O-Benzoyl-3-Deoxy
-D-Arabino-1,5-Lactone (**17**)



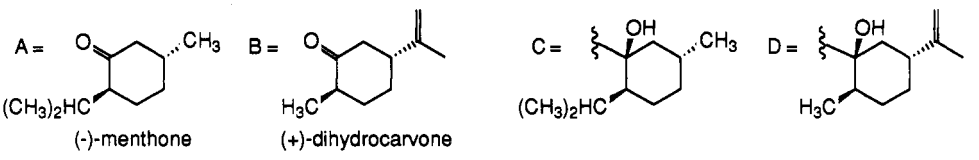
18a 2.3 : 1 **18b**

69%

(**14**) (mp 136–138 °C), produced from the two-step process, was then treated with SmI_2 and benzylacetone in THF/HMPA to afford stereoisomers **15a**:**15b**:**16a**:**16b** in a *ca.* 5:5:1:1 ratio, respectively, in 69% yield. The stereochemistry here also reflects a preference for the carbonyl addition reaction of benzylacetone to the least hindered face of the furanose ring via the Sm(III) enolate. Avoidance of the C_4 methylene benzoate appendage favored the formation of diastereoisomers **15a** and **15b**. It was disappointing to observe no asymmetric induction (1:1) of the adjacent alcohol center on the appendage. This may indicate a lack of chelation with the Sm(III) and the incoming ketone in the transition state of the carbonyl addition to the ester enolate, which might control facial selectivity of the benzyl acetone. The stereochemistry of the major products were confirmed by difference NOE studies for the two major isomers **15a** and **15b**. The stereochemistry of the alcohol center in **15a** and **15b** could not be confirmed unequivocally in these structures even though these two compounds were separable by chromatography. As above, the minor products **16a** and **16b** could not be purified sufficiently for characterization, but ^1H NMR clearly indicated they were indeed isomeric with **15a** and **15b**. A similar coupling of **14** with cyclohexanone produced a inseparable 3.4:1 mixture of products **28a** and **28b** with a preference for addition to the least sterically hindered face of the γ-lactone ring, shown in Scheme IV.

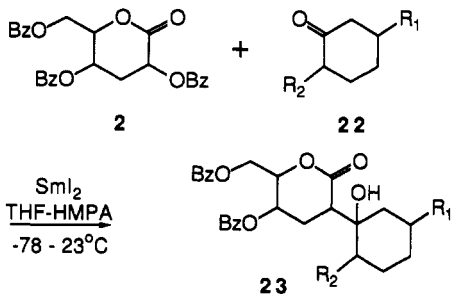
In a third study, shown in Scheme V, 2,4,6-tri-*O*-benzoyl-3-deoxy-D-arabino-1,5-lactone (**17**), previously prepared by DeLederkremer in a elimination/hydrogenation reaction from δ-gluconolactone,[17b] was treated with SmI_2 and cyclohexanone in THF–HMPA. Products **18a** and **18b** were observed in a 2.3:1 ratio, respectively. In this example, the approach of the ketone to the β-face of the pyranose ring is favored for stereoelectronic reasons because axial

Table II. Coupled Carbohydrate Lactones and Terpene Ketones



entry	aldonolactone	ketone	product	R	yield (%)	ratio
1	14	A	**19a**	C	46	35:1
2	14	B	**19b**	D	58	50:1
3	9	A	**20a**	C	53	14:1
4	9	B	**20b**	D	59	99:1
5	17	A	**21a**	C	45	35:1
6	17	B	**21b**	D	57	30:1

Scheme VI



approach to the Sm(III) enolate is preferred.[22] Difference NOE studies strongly support the stereochemistry of **18a** as the major product in the reaction.

Carbohydrate Lactones and Terpene Ketones. A study of the deoxygenation–carbonyl addition reaction with terpene ketones mediated by SmI_2 was also examined. This synthetic construction, shown in Scheme VI, represents a general methodology to afford a terpene and carbohydrate coupling. The overall approach permits the assembly of naturally occurring compounds which contain hydroxylated tetrahydropyran or furan moieties coupled to isoprenoid-type segments in a wide array of acyclic and annulated forms.[2d] These include a variety of diverse compounds, such as the loganins,[23a] goldinodox,[23b,c] ambruticin,[23d,e] pseudomonic acids,[23f,h] and tirandimycin.[23i,k]

We were pleased to observe high diastereoselectivities in the products, shown in Table II, with both new carbon centers formed in the reaction with excellent stereocontrol. The ratios were as high as 99:1, as determined by capillary GC, for compound **20b** in entry 4, and all were 30:1 or higher except entry 3.[24] The diastereomeric ratios produced from the terpene ketones gave much improved ratios compared to the simple ketones which produced only modest (up to 5:1) ratios. The use of sterically bulky chiral ketones supports an earlier observation with the (–)-menthone adduct **6e** in Table I, where it appears that the structural features of the ketone have a greater effect on the diastereoselectivity of the reaction than the ester/lactone component.

The stereochemistry of the new C_2 stereocenter on the carbohydrate lactone was confirmed by analogy to the difference NOE studies discussed above and X-ray crystal structures of two examples. In those examples, the previous cyclohexanone adducts **10** and **28a** provided a reliable precedent for entries 1–4, where the least hindered face of the γ-lactone ring of the sugar was favored in the carbonyl addition reaction. The δ-lactones in entries 5 and 6 appear to have a preference for attack on the β-face of the carbohydrate ring which is a stereoelectronic result of preferred axial approach of the ketone to the samarium(III) enolate as observed before with compound **18a** in Scheme V. The stereochemistry of the terpene alcohol center in products **19a**, **20a**, and **21a** from (–)-mentone was a result of a known preference for addition to the π-face of the cyclohexanone carbonyl opposite the isopropyl group.[20] Compounds **19b**, **20b**, and **21b** result from an analogous addition to the carbonyl of (+)-dihydrocarvone opposite the methyl substituent. Single-crystal X-ray studies of compounds **20a** and **20b** readily confirmed the preference for addition of each of the terpene ketones on the least hindered face of each cyclohexanone ring; avoidance of the face with the steric bias adjacent to the ketone carbonyl was observed.[25]

Mechanistic Rationale. Among several possible mechanistic arguments, one of two possible pathways explains the course of events which render the products. The precise nature of the effects of HMPA in SmI_2 reactions remains unresolved; however, in our reactions it was indispensible. One possible mechanistic pathway involves a sequence of two one-electron transfers from SmI_2 through

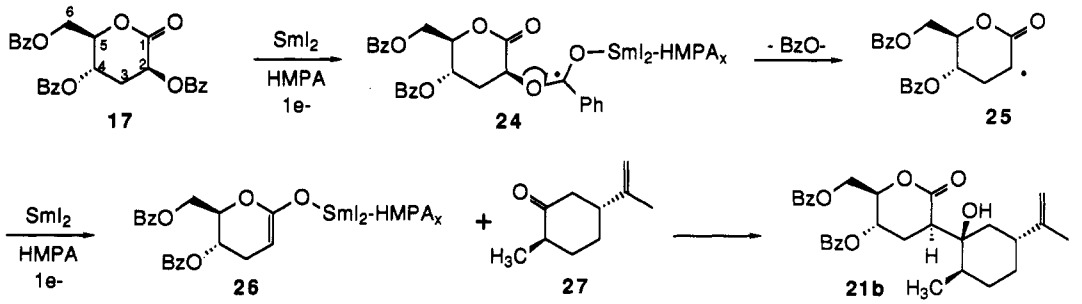
(22) Deslonchamps, P. *Stereoelectronic Effects in Organic Chemistry*; Pergamon Press: New York, 1983; pp 274–284.

(23) (a) Thomas, A. F. In The Synthesis of Monoterpenes. In *The Total Synthesis of Natural Products*; ApSimon, J., Ed.; J. Wiley & Sons: New York, 1973. (b) Maehr, H.; Leach, M.; Blount, J. F.; Stempel, A. *J. Am. Chem. Soc.* **1974**, *96*, 4034. (c) Vos, C.; Vermiel, P. E. J. *Tetrahedron Lett.* **1973**, 5173. (d) Connor, D. T.; Greenough, R. C.; von Strandtmann, M. *J. Org. Chem.* **1977**, *42*, 3664. (e) Just, G.; Potvin, P. *Can. J. Chem.* **1980**, *58*, 2173. (f) Clayton, J. P.; O'Hanlon, P. J.; Rogers, N. H. *Tetrahedron Lett.* **1980**, 881. (g) Keck, G. E.; Kachensky, D. F.; Enholm, E. J. *J. Org. Chem.* **1985**, *50*, 4317. (h) Keck, G. E.; Kachensky, D. F.; Enholm, E. J. *J. Org. Chem.* **1984**, *49*, 1462. (i) Duchamp, D. J.; Branfman, A. R.; Button, A. C.; Rinehart, K. L., Jr. *J. Am. Chem. Soc.* **1973**, *95*, 4077. (j) Ireland, R. E.; Wuts, P. G. M.; Ernst, B. *J. Am. Chem. Soc.* **1981**, *103*, 3205. (k) Boeckman, R. K., Jr.; Starrett, J. E., Jr.; Nickell, D. G.; Sum, P.-E. *J. Am. Chem. Soc.* **1986**, *108*, 5549.

(24) Although the ratios observed were high in many cases, it has not been determined whether they reflect consonant or dissonant double stereodifferentiation in the starting components.

(25) (a) Abboud, K. A.; Jiang, S.; Enholm, E. J. *Acta Crystallogr. C*, in press. (b) Abboud, K. A.; Jiang, S.; Enholm, E. J. *Acta Crystallogr. C*, in press.

Scheme VII



a chelated structure. This has been recently proposed by Inanaga for deoxygenations of α-alkoxy esters with SmI_2 and HMPA.[16] In this scenario, monodentate HMPA molecules, coordinated via their oxygen atoms to SmI_2 present in the reaction mixture, are insufficient to preclude the strong bidentate chelation of SmI_2. This explanation seems a possibility when one considers the stoichiometry (1.75 mmol of HMPA:4.00 mmol of SmI_2:1.00 mmol of aldonolactone) used in these reactions may result in incompletely complexed SmI_2 in the reaction mixture. A recent hypothesis suggests that SmI_2 may hold up to six HMPA molecules in its coordination sphere.[10g] Because simple, unsubstituted esters are unreactive toward SmI_2,[13] the presence of oxygenated functions adjacent to the ester, which provide a tighter bidentate chelation for the oxophillic samarium species, may predominate.[16a]

Another, perhaps more likely, explanation argues against the chelate altogether, in which deaggregation of the SmI_2 largely predominates, and the HMPA oxygen donor ligands increase the Sm(II)/Sm(III) cell emf.[10g] In this scenario, the increased reducing strength of the SmI_2 complexed to HMPA is sufficient to initiate the benzoate elimination. A modification of this process, with entry 6 from Table V serving as a generalized example, is proposed in Scheme VII. During the first stages of the reductive coupling, the SmI_2 molecule, coordinated to an unknown number of HMPA molecules, reduces the benzoate ester carbonyl to produce **24** via a one-electron transfer process. It is worth noting that the initiatory reduction of either the lactone carbonyl or the benzoate ester carbonyl can lead to product. The reduction of the benzoate carbonyl produces the benzylic stabilized radical species **24**, which is likely formed more rapidly and, therefore, favored in the initial reduction of the two ester carbonyls. This is supported by SmI_2 reductions of aromatic ketones which usually take place much more rapidly than simple ketones.[13] Expulsion of the benzoate produces a resonance-stabilized radical species **25**. A second equivalent of SmI_2 then reduces the radical to a samarium(III) enolate.[26] The enolate **26** appears to be of reduced reactivity because it does not displace or condense with any benzoate functions. Subsequent carbonyl addition with (+)-dihydrocarvone affords the highly modified C_2-branched sugar **21b**.

Conclusion. In summary, a synthetic method was examined for the preparation of C_2 branched-chain carbohydrates by a deoxygenation and carbonyl addition reaction with ketones; it is a useful adaptation of SmI_2 technology. The reaction of simple ketones with 3-deoxy aldonolactones in the presence of SmI_2/HMPA produced modest diastereoselectivities (up to 5:1) in the products with the stereochemistry determined by difference NOE studies. The terpene ketones, (−)-menthone or (+)-dihydrocarvone, were coupled to 3-deoxycarbohydrate lactones and gave C_2-branched sugars with very high diastereoselectivities (up to 99:1). After ejection of the C_2-benzoate, the approach of the ketone to the lactone ring in the major product is controlled by the steric and stereoelectronic effects. The overall synthetic technology shown herein allows the construction of C_2-branched sugars with excellent future potential for coupling stereochemically sophisticated carbonyl components.

Experimental Section

General. All reactions were run under an inert atmosphere of argon using flame-dried apparatus.[27] All yields reported refer to isolated material judged to be homogeneous by thin-layer chromatography and NMR spectroscopy. Temperatures below ambient temperature refer to bath temperatures unless otherwise stated. Solvents and anhydrous reagents were purified according to established procedures[28] by distillation under N_2 from an appropriate drying agent: ether and THF from benzophenone ketyl; chloroform, ethyl acetate from CaH_2.

Analytical TLC was performed with precoated silica gel plates (0.25 mm) using phosphomolybdic acid in ethanol as an indicator. Melting points are uncorrected. Column chromatography was performed using (230–400 mesh) silica gel by standard flash chromatographic techniques.[29] HMPA was distilled from Na at 1 mmHg and stored under argon. Samarium metal was purchased from Rhone-Poulenc Inc., Phoenix, AZ, and stored under Ar. CH_2I_2 was distilled prior to use.

Typical Procedure To Prepare Benzoate Esters 5a and 5b. Benzoyl chloride (10 mL), pyridine (10 mL), and chloroform (20 mL) were cooled in an ice–salt bath. The α-hydroxy ester **4** (5.0 g) was added dropwise, via syringe, over 10 min with stirring. After 1 h, **4** was consumed by TLC, and the reaction was quenched with water (30 mL) and extracted with chloroform (3 × 50 mL). The chloroform layers were dried over Na_2SO_4, evaporated, and distilled or recrystallized (if solid) to obtain the pure product.

Typical Procedure To Prepare β-Hydroxy Esters 6a–6e. Samarium metal (5 mmol) was placed in a 50-mL flame-dried flask under Ar atmosphere, and THF (0.5 M in ester) was added. Diiodomethane (4 mmol) and HMPA (300 μL) were added, and the color of the reaction mixture turned blue-purple. After 1.5 h, the solution was cooled to −78 °C, the α-benzoate ester (1 mmol) and the ketone (2 mmol) were added in THF (ca. 1 mL), via syringe, and the reaction mixture was warmed to room temperature. When the reaction was complete by TLC analysis, several drops of $NaHCO_3$ (aqueous saturated) and ether were added and stirring continued for 0.5 h to extract the product. After suction filtration through Celite and evaporation of the solvents, the product was isolated by flash column chromatography.

(26) Other examples of carbonyl additions to samarium enolates include: (a) Molander, G. A.; Etter, J. B.; Harring, L. S.; Thorel, P.-J. *J. Am. Chem. Soc.* **1991**, *113*, 8036 and references cited therein. (b) Curran, D. P.; Wolin, R. L. *Synlett* **1991**, 317. (c) Girard, P.; Namy, J. L.; Kagan, H. B. *J. Am. Chem. Soc.* **1980**, *102*, 2693.

(27) Brown, H. C. *Organic Synthesis via Boranes*; Wiley Interscience: New York, 1975.

(28) Perrin, D. D.; Armarego, W. L. F.; Perrin, D. R. *Purification of Laboratory Chemicals*; Pergamon Press: New York, 1980.

(29) Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923.

Typical Procedure for the Preparation of Benzoylated Aldonolactones 8 and 13. The well-documented procedure of DeLederkremer was adapted to prepare these compounds.[17,21] Benzoyl chloride (32 mL), pyridine (40 mL), and chloroform (32 mL) were cooled in an ice bath, and the lactone 7 or 12 (5.0 g) was slowly added in small portions with stirring. After 1 h, the lactone was consumed by TLC analysis and the reaction mixture was diluted with chloroform (100 mL), washed with saturated solution of sodium hydrogen carbonate (3 × 20 mL), and with water (3 × 20 mL). The organic layers were dried over sodium sulfate and evaporated under reduced pressure with the addition of toluene (3 × 50 mL) to azeotropically remove the pyridine. The residue was initially crystallized from ether and recrystallized from ethanol to obtain 8 or 13.

Typical Procedure for the Preparation of 3-Deoxybenzoylated Aldonolactones 9 and 14. Benzoylated aldonolactone 8 or 13 (3 g) was placed in a 100-mL round-bottom flask, and ethyl acetate (20 mL) was added. Heating was used to aid in dissolution. Triethylamine (2 mL) was added after cooling to room temperature, and then the solution was hydrogenated over 10% palladium on actived carbon (200 mg) with hydrogen in a balloon (1 atm) for 4 h. The reaction mixture was diluted with ethyl acetate (30 mL), filtered through a plug of Celite, washed with sodium hydrogen carbonate (10 mL) once and then with 4 M HCl (10 mL) once and with water (10 mL) once, and then evaporated under reduced pressure to obtain a syrup which crystallized from ethanol and was recrystallized from ethanol/acetone (5:3).

Typical Procedure for the Aldonolactone Coupled Products. Samarium metal (5 mmol) was stirred with THF (0.1 M in aldonolactone) under Ar atmosphere. Diiodomethane (4 mmol) and HMPA (300 μL) were added, and the color of the reaction mixture turned blue-purple. After 1.5 h, the solution was cooled to −78 °C, the lactone 3-deoxycarbohydrate (1 mmol) and the terpene ketone (2 mmol) were added in THF (ca. 1 mL), via syringe, and the reaction mixture was warmed to room temperature. When the carbohydrate was consumed by TLC analysis, several drops of $NaHCO_3$ (aqueous saturated) and ethyl acetate (15 mL) were added, and stirring was continued for 0.5 h to extract the product. After suction filtration through Celite and evaporation of the solvents, the product was isolated by flash column chromatography.

Ethyl (*S*)-(−)-lactate, benzoyl ester (5a): R_f = 0.45 (20% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.10 (m, 2H), 7.57 (m, 1H), 7.44 (m, 2H), 5.31 (q, 1H, J = 7.2 Hz), 4.23 (q, 2H, J = 7.2 Hz), 1.62 (d, 3H, J = 7.2 Hz), 1.26 (t, 3H, J = 7.2 Hz); 75-MHz ^{13}C NMR ($CDCl_3$) δ 170.73, 165.86, 133.23, 129.79, 129.50, 128.35, 69.16, 61.31, 17.01, 14.06; IR (neat oil) 2988, 1726, 1602, 1451, 1273, 1201, 1113, 714 cm^{-1}; mass spectrum (EI), 222 (17.3), 177 (20.1), 149 (20.6), 105 (100), 77 (69.8), 51 (40.6). Anal. Calcd: C, 64.85; H, 6.35. Found: C, 64.97; H, 6.32.

Ethyl *dl*-2-hydroxycaproate, benzoyl ester (5b): R_f = 0.44 (10% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.00 (m, 2H), 7.49 (m, 1H), 7.35 (m, 2H), 5.12 (t, 1H, J = 6.3 Hz), 4.12 (q, 2H, J = 7.1 Hz), 1.90 (m, 2H), 1.35 (m, 4H), 1.19 (t, 3H, J = 7.1 Hz), 0.85 (t, 3H, J = 7.2 Hz); 75-MHz ^{13}C NMR ($CDCl_3$) δ 170.30, 166.07, 133.21, 129.78, 129.59, 128.36, 72.87, 61.22, 30.94, 27.33, 22.26, 14.11, 13.83; IR (neat oil) 2959, 2873, 1724, 1602, 1452, 1271, 1197, 1111, 1027, 857, 712 cm^{-1}; mass spectrum (EI), 265 (32.4) (M + 1, self CI), 219 (25.6), 142 (34.2), 105 (100), 77 (62.3), 51 (21.8). Anal. Calcd: C, 68.16; H, 7.63. Found: C, 68.09; H, 7.64.

1-[2-[(Ethyloxy)carbonyl]propyl]cyclohexanol (6c): R_f = 0.45 (20% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 4.18 (q, 2H, J = 7.2 Hz), 3.06 (s, 1H), 2.50 (q, 1H, J = 6.9 Hz), 1.86–1.38 (m, 10H), 1.30 (t, 3H, J = 7.2 Hz), 1.20 (d, 3H, J = 6.9 Hz); 75-MHz ^{13}C NMR ($CDCl_3$) δ 176.97, 71.28, 60.43, 47.84, 37.01, 33.80, 25.67, 21.90, 21.59, 14.15, 11.48; IR (neat oil) 3515, 2935, 2861, 1712, 1448, 1372, 1334, 1259, 1182, 1049, 960, 850 cm^{-1}; mass spectrum (CI), 201 (16.9), 183 (100), 155 (13.7), 131 (13.3), 109 (26.8), 105 (14.7); exact mass (CI) for $C_{11}H_{21}O_3$ (M + 1) calcd 201.1491, found 201.1523.

Ethyl 3-hydroxy-2-methyl-3-propylhexanoate (6a): R_f = 0.52 (20% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 4.19 (d of q, 2H, J_q = 6.9 Hz, J_d = 3.6 Hz), 3.29 (s, 1H), 2.55 (q, 1H, J = 7.2 Hz), 1.52–1.33 (m, 8H), 1.29 (t, 3H, J = 7.2 Hz), 1.17 (d, 3H, J = 7.2 Hz), 0.92 (t, 6H, J = 6.9 Hz); 75-MHz ^{13}C NMR ($CDCl_3$) δ 177.18, 74.37, 60.49, 45.69, 40.38, 37.16, 16.72, 16.46, 14.58, 14.12, 11.77; IR (neat oil) 3516, 2960, 2874, 1712, 1459, 1337, 1187, 1097, 1024, 983, 910, 860 cm^{-1}; mass spectrum (CI), 217 (17.9), 200 (12.2), 199 (100); exact mass (CI) for $C_{12}H_{25}O_3$ (M + 1) calcd 217.1803, found 217.1786. Anal. Calcd: C, 66.63; H, 11.18. Found: C, 66.77; H, 11.14.

Ethyl 3-Hydroxy-2-methyl-3-isopropylheptanoate (6d). Physical data for 1:1 mixture of diastereoisomers: R_f = 0.51 (20% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 4.17 (q, 4H, J = 7.2 Hz), 3.61 (s, 1H), 3.55 (s, 1H), 2.72 (q, 1H, J = 7.2 Hz), 2.71 (q, 1H, J = 7.2 Hz), 1.91 (septet, 1H, J = 6.9 Hz), 1.79 (septet, 1H, J = 6.9 Hz), 1.75–1.22 (m, 18H), 1.21 (d, 3H, J = 7.2 Hz), 1.20 (d, 3H, J = 7.2 Hz), 1.00–0.84 (m, 18H); 75-MHz ^{13}C NMR ($CDCl_3$) δ 177.63, 177.48, 76.12, 75.88, 60.57, 44.48, 44.17, 36.04, 35.68, 34.25, 34.00, 26.43, 26.13; 23.64, 17.62, 17.43, 16.96, 14.02, 13.94, 12.75, 12.13; IR (neat oil) 3510, 2959, 1712, 1466, 1376, 1338, 1260, 1182, 1096, 1024 cm^{-1}; mass spectrum (EI), no M$^+$ observed, 213 (4.9), 187 (30.8), 173 (28.7), 141 (21.7), 129 (20.4), 127 (16.7), 102 (28.8), 85 (100), 71 (57.0), 57 (51.1), 43 (90.4); exact mass (CI) for $C_{13}H_{26}O_3$ (M + 1) calcd 213.1960, found 231.1975.

Ethyl 3-Hydroxy-2,3-dimethyl-5-phenylpentanoate (6b). Physical data for 1:1 mixture of diastereoisomers: R_f = 0.38 (20% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 7.31–7.12 (m, 10H), 4.18 (q, 4H, J = 7.2 Hz), 3.44 (s, 1H), 3.34 (s, 1H), 2.75 (m, 4H), 2.60 (m, 2H), 1.77 (m, 4H), 1.25 (m, 18H); 75-MHz ^{13}C NMR ($CDCl_3$) δ 176.55, 142.40, 142.36, 128.40, 128.32, 125.78, 72.81, 72.55, 60.71, 60.66, 48.03, 47.47, 43.50, 40.47, 30.19, 29.93, 25.54, 22.99, 14.18, 12.42, 12.07; IR (neat oil) 3510, 2980, 1712, 1600, 1455, 1375, 1339, 1184, 1066, 946, 752, 700 cm^{-1}; mass spectrum (EI) 251 (M + 1, self CI) (1.8), 232 (25.33), 158 (12.5), 145 (22.8), 131 (100), 91 (87.5), 74 (24.2). Anal. Calcd: C, 71.97; H, 8.86. Found: C, 72.03; H, 8.82.

Alcohol 6e. Physical data for single isomer: R_f = 0.50 (10% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 4.19 (q, 2H, J = 7.2 Hz), 2.80 (s, 0.5H), 2.76 (s, 0.5H), 2.41 (s, 1H), 1.92 (septet, 1H, J = 6.9 Hz), 1.85–1.45 (m, 6H), 1.45–1.10 (m, 6H), 1.28 (t, 3H, J = 7.2 Hz), 1.05–0.75 (m, 14H); 75-MHz ^{13}C NMR ($CDCl_3$) δ 174.81, 76.34, 60.44, 53.61, 46.76, 42.87, 35.05, 30.82, 27.70, 26.51, 25.64, 23.33, 22.68, 22.41, 20.50, 17.96, 14.27, 13.87; IR (neat oil) 3571, 2955, 1732, 1457, 1368, 1232, 1181, 1024, 946 cm^{-1}; mass spectrum (EI) 298 (4.5), 281 (100), 213 (55.5), 167 (19.4), 155 (35.9), 144 (45.1), 137 (44.1), 101 (64.7), 95 (32.9), 81 (47.2), 73 (22.1), 69 (76.2), 55 (59.6). Anal. Calcd: C, 72.44; H, 11.48. Found: C, 72.51; H, 11.45.

Ethyl 2-Butyl-3-hydroxy-3-methylnonanoate (6f). Physical data for 1:1 mixture of diastereoisomers: R_f = 0.41 (10% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 4.19 (q, 4H, J = 7.2 Hz), 2.94 (s, 1H), 2.87 (s, 1H), 2.40 (m, 2H), 1.90–1.20 (m, 40H), 1.17 (d, 4H, J = 6.3 Hz), 0.89 (t, 12H, J = 7.2 Hz); 75-MHz ^{13}C NMR ($CDCl_3$) δ 176.31, 176.19, 73.11, 72.78, 60.27, 53.95, 53.86, 42.27, 39.23, 31.72, 30.15, 30.04, 29.76, 27.01, 26.53, 23.77, 23.53, 23.38, 23.35, 22.55, 14.23, 13.98, 13.83; IR (neat oil) 3519, 2957, 2860, 1712, 1467, 1376, 1180, 1026, 938 cm^{-1}; mass spectrum (EI) 273 (M + 1, self CI) (43.4), 255 (100), 187 (45.3), 144 (37.4), 141 (27.0), 115 (16.4), 101 (67.8), 73 (27.7), 69 (22.9), 55 (27.4). Anal. Calcd: C, 70.52; H, 11.84. Found: C, 70.60; H, 11.82.

2,5,6-Tri-*O*-benzoyl-3-deoxygulono-γ-lactone (9): R_f = 0.25 (70% ether–hexanes); mp 124–125 °C; 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.15–7.30 (m, 15H), 5.79 (t, 1H, J = 9.6 Hz,), 5.70 (m, 1H), 5.02 (m, 1H), 4.76 (d of d, 1H, J = 4.8, 11.7 Hz), 4.67 (d of d, 1H, J = 6.6, 11.7 Hz), 3.01 (m, 1H), 2.30 (m, 1H); 75-MHz ^{13}C NMR ($CDCl_3$) δ 171.38, 165.94, 165.63, 165.30, 133.70, 133.38, 130.04, 129.94, 129.83, 129.70, 129.61, 129.25, 128.87, 128.61, 128.46, 128.38, 74.81, 71.19, 68.13, 62.67, 30.65; IR (KBr disk) 3066, 2978, 1770, 1729, 1600, 1452, 1274, 1212, 1111, 1024, 706 cm^{-1}; mass spectrum (EI) 475 (M + 1, self CI) (0.59), 106 (22.2), 105 (100), 77 (50.0), 54 (14.7). Anal. Calcd: C, 68.35; H, 4.67. Found: C, 68.03; H, 4.64.

2,5-Di-*O*-benzoyl-3-deoxythreo-γ-lactone (14): R_f = 0.31 (35% THF–hexanes); mp 135.5–137.5 °C; 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.05 (m, 4H), 7.58 (m, 2H), 7.42 (m, 4H), 5.77 (t, 1H, J = 9.6 Hz), 4.90 (m, 1H), 4.65 (d of d, 1H, J = 2.7, 12.3 Hz), 4.50 (d of d, 1H, J = 5.7, 12.3 Hz), 2.99 (m, 1H), 2.30 (m, 1H); 75-MHz ^{13}C NMR ($CDCl_3$) δ 171.63, 166.03, 165.33, 133.80, 133.47, 129.99,

129.79, 129.62, 129.56, 129.21, 128.53, 74.39, 68.62, 64.91, 30.93; IR (KBr disk) 3059, 2977, 1784, 1727, 1602, 1450, 1282, 1197, 1120, 1064, 1028, 978, 919, 803, 708 cm^{-1}; mass spectrum (EI) 341 (M + 1, self CI) (17.4), 218 (10.8), 105 (100). Anal. Calcd: C, 67.05; H, 4.74. Found: C, 67.44; H, 4.81.

2,4,6-Tri-*O*-benzoyl-3-deoxy-D-arabino-δ-lactone (17):[17b] R_f = 0.45 (35% THF–hexanes); mp 156–158 °C (lit.[17b] mp 158–160 °C); 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.07 (m, 6H), 7.60 (m, 3H), 7.45 (m, 6H), 6.00 (d of d, 1H, J = 4.8, 12.3 Hz), 5.62 (m, 1H), 5.05 (m, 1H), 4.75 (d of d, 1H, J = 3.9, 12.9 Hz), 4.65 (d of d, 1H, J = 4.8, 12.3 Hz), 2.78 (m, 1H), 2.67 (m, 1H); 75-MHz ^{13}C NMR ($CDCl_3$) δ 167.28, 165.89, 165.26, 133.89, 133.72, 133.47, 130.03, 129.83, 129.13, 128.79, 128.74, 128.68, 128.52, 77.75, 66.77, 64.70, 63.46, 30.90; IR (KBr disk) 3420, 3062, 1767, 1722, 1601, 1450, 1266, 1097, 706 cm^{-1}; mass spectrum (CI) 475 (18.8), 351 (17.0), 264 (10.1), 131 (23.2), 105 (100); exact mass (CI) for $C_{27}H_{23}O_8$ (M + 1) calcd 475.1392, found 475.1385. Anal. Calcd: C, 68.35; H, 4.76. Found: C, 68.55; H, 4.64.

(2*S)-2-(1-Hydroxycyclohexyl)-5,6-di-*O*-benzoyl-3-deoxygulono-γ-lactone (10)**: R_f = 0.12 (70% ether–hexanes); mp 143.5–144.5 °C; 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.00 (m, 4H), 7.50 (m, 6H), 5.68 (m, 1H), 4.95 (1H), 4.70 (d of d, 1H, J = 5.1, 11.7 Hz), 4.62 (d of d, 1H, J = 7.5, 11.7 Hz), 2.73 (t, 1H, J = 9.6 Hz), 2.63 (s, 1H), 2.48 (m, 1H), 2.20 (m, 1H), 1.81–1.04 (m, 10H); 75-MHz ^{13}C NMR ($CDCl_3$) δ 177.39, 165.98, 165.57, 133.80, 133.27, 129.84, 129.68, 129.38, 128.82, 128.74, 128.42, 75.98, 72.61, 72.17, 62.97, 48.51, 35.34, 33.71, 26.28, 25.28, 21.48, 21.42; IR (KBr disk) 3550, 2928, 1764, 1724, 1711, 1560, 1451, 1291, 1268, 1161, 1119, 1069, 955, 916, 706 cm^{-1}; mass spectrum (EI) 452 (1.1), 435 (2.6), 106 (10.2), 105 (100), 77 (22.9). Anal. Calcd: C, 69.01; H, 6.24. Found: C, 68.44; H, 6.10.

(2*S)-2-(1-Hydroxycyclohexyl)-5-*O*-benzoyl-3-deoxyerythro-γ-lactone (28a)**: R_f = 0.37 (35% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.02 (m, 2H), 7.59 (m, 1H), 7.45 (m, 2H), 4.92–4.65 (m, 1H), 4.65–4.35 (m, 2H), 2.85 (m, 1H), 2.75 (s, 1H), 2.40 (m, 1H), 2.20 (m, 1H), 2.52–1.98 (m, 2H), 1.95–1.00 (m, 10H); 75-MHz ^{13}C NMR ($CDCl_3$) δ 177.58, 166.12, 133.43, 129.64, 129.27, 128.55, 75.57, 72.18, 71.38, 65.89, 48.98, 35.41, 33.74, 26.22, 25.36, 21.45, 21.35; IR (KBr disk) 3445, 2932, 2850, 1734, 1716, 1602, 1451, 1272, 1176, 1123, 1067, 971, 707 cm^{-1}; mass spectrum (EI) 318 (4.9), 301 (1.3), 284 (91.4), 269 (70.1), 192 (100), 115 (28.9), 105 (87.8); exact mass (EI) for $C_{18}H_{22}O_5$ calcd 318.1467, found 318.1466.

(2*S)-2-(1-Hydroxy-1-methyl-3-phenylpropyl)-5-*O*-benzoyl-3-deoxyerythro-γ-lactone (15a).** Isomer 1: R_f = 0.37 (35% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.02 (m, 2H), 7.59 (m, 1H), 7.45 (m, 2H), 7.22 (m, 5H), 4.86 (m, 1H), 4.45 (m, 2H), 3.62 (bs, 1H), 3.00 (t, 1H, J = 12.0 Hz), 2.70 (m, 2H), 2.24 (m, 2H), 1.85 (m, 2H), 1.30 (s, 3H); 75-MHz ^{13}C NMR ($CDCl_3$) δ 178.43, 166.08, 141.90, 133.55, 129.69, 129.65, 128.62, 128.46, 128.38, 125.93, 75.42, 72.87, 65.75, 47.74, 42.18, 29.65, 26.91, 23.50; IR (neat oil) 3508, 2938, 1760, 1723, 1602, 1496, 1453, 1381, 1272, 1176, 1118, 1070, 1026, 960, 712 cm^{-1}; mass spectrum (EI) 368 (0.12), 351 (2.7), 350 (12.1) 228 (11.8), 188 (11.6), 143 (22.4), 131 (27.1), 105 (100); exact mass (EI) for $C_{22}H_{24}O_5$ calcd 368.1624, found 368.1629.

(2*S)-2-(1-Hydroxy-1-methyl-3-phenylpropyl)-5-*O*-benzoyl-3-deoxyerythro-γ-lactone (15b).** Isomer 2: R_f = 0.31 (35% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.02 (m, 2H), 7.59 (m, 1H), 7.45 (m, 2H), 7.22 (m, 5H), 4.85 (m, 1H), 4.45 (m, 2H), 3.01 (bs, 1H), 2.93 (t, 1H, J = 12.0 Hz), 2.65 (m, 2H), 2.42 (m, 1H), 2.27 (m, 1H), 1.85 (m, 2H), 1.40 (s, 3H); 75-MHz ^{13}C NMR ($CDCl_3$) δ 177.64, 166.10, 141.78, 133.50, 129.65, 129.18, 128.58, 128.49, 128.46, 125.99, 75.40, 73.04, 65.76, 49.27, 40.44, 29.83, 26.50, 24.65; IR (neat oil) 3450, 2950, 1769, 1723, 1602, 1495, 1452, 1364, 1273, 1176, 1118, 1070, 1026, 945, 713 cm^{-1}; mass spectrum (EI) 368 (0.19), 351 (1.7), 350 (8.1), 143 (14.7), 131 (20.4), 105 (100); exact mass (EI) for $C_{22}H_{24}O_5$ calcd 368.1624, found 368.1617.

(2*R)-2-(1-Hydroxycyclohexyl)-4,6-di-*O*-benzoyl-3-deoxy-D-arabino-δ-lactone (18a)**: R_f = 0.61 (35% THF–hexanes); mp 138.5–140.5 °C; 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.05 (m, 4H), 7.60 (m, 2H), 7.45 (m, 4H), 5.48 (m, 1H), 4.90 (m, 1H), 4.68 (d of d, 1H, J = 4.2, 12.3 Hz), 4.60 (d of d, 1H, J = 7.2, 12.0 Hz), 3.66 (bs, 1H), 2.90 (d of t, 1H, J = 11.7, 4.2 Hz), 2.34 (m, 2H), 1.85–0.80 (m, 10H); IR (KBr disk) 3533, 2926, 2856, 1723, 1712, 1602, 1451, 1396, 1279, 1198, 1119, 969, 711 cm^{-1}; mass spectrum (CI) 453 (10.5), 435 (3.1); exact mass (CI) for $C_{28}H_{29}O_7$ (M + 1) calcd 453.1913, found 453.1932.

5,6-Di-*O*-benzoyl-3-deoxygulono-γ-lactone and menthone adduct 20a: R_f = 0.53 (35% THF–hexanes); mp 141–143 °C; 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.02 (m, 4H), 7.50 (m, 6H), 5.72 (m, 1H), 4.94 (m, 1H), 4.74 (d of d, 1H, J = 5.1, 11.7 Hz), 4.64 (d of d, 1H, J = 7.2, 11.7 Hz), 3.36 (s, 1H), 3.15 (t, 1H, J = 10.5 Hz), 2.20 (m, 2H), 2.00–0.90 (m, 9 H), 0.86 (d, 3H, J = 6.6 Hz), 0.72 (d, 3H, J = 6.9 Hz), 0.60 (d, 3H, J = 6.6 Hz); 75-MHz ^{13}C NMR ($CDCl_3$) δ 179.74, 165.97, 165.64, 133.93, 133.31, 129.77, 129.68, 129.31, 128.81, 128.60, 128.44, 76.03, 75.59, 72.66, 62.77, 47.61, 46.49, 41.64, 35.05, 27.31, 26.58, 26.45, 23.24, 22.25, 19.61, 17.33; IR (KBr disk) 3500, 2963, 1746, 1715, 1601, 1452, 1384, 1321, 1264, 1183, 1110, 1069, 1028, 714 cm^{-1}; mass spectrum (CI), 509 (3.8), 492 (30.7), 491 (100); exact mass (CI) for $C_{30}H_{37}O_7$ (M + 1) calcd 509.2539, found 509.2555. Anal. Calcd: C, 70.85; H, 7.13. Found: C, 70.95; H, 7.15.

5,6-Di-*O*-benzoyl-3-deoxygulono-γ-lactone and dihydrocarvone adduct 20b: R_f = 0.63 (40% THF–hexanes); mp 145–146 °C; 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.01 (m, 4H), 7.49 (m, 6H), 5.69 (m, 1H), 4.95 (m, 1H), 4.67 (m, 4H), 3.51 (s, 1H), 3.03 (t, 1H, J = 10.5 Hz), 2.40 (m, 1H), 2.25 (m, 2H), 1.70 (s, 3H), 1.65–1.05 (m, 7H), 0.65 (d, 3H, J = 6.6 Hz); 75-MHz ^{13}C NMR ($CDCl_3$) δ 179.44, 165.95, 165.65, 149.72, 133.94, 133.30, 129.81, 129.68, 129.32, 128.80, 128.58, 128.44, 108.61, 76.03, 74.03, 72.70, 62.76, 46.24, 39.18, 37.25, 36.94, 31.30, 29.58, 26.25, 21.15, 14.43; IR (KBr disk) 3502, 2937, 1733, 1716, 1642, 1603, 1452, 1298, 1263, 1106, 1026, 978, 897, 711 cm^{-1}; mass spectrum (EI) 506 (0.78), 489 (2.9), 488 (9.1), 181 (38.2), 169 (28.4), 131 (51.0), 119 (38.1), 105 (100), 77 (22.8), 69 (141.9); exact mass (EI) for $C_{30}H_{34}O_7$ calcd 506.2305, found 506.2285. Anal. Calcd: C, 71.13; H, 6.76. Found: C, 70.91; H, 6.70.

5-*O*-Benzoyl-3-deoxyerythro-γ-lactone and dihydrocarvone adduct 19b: R_f = 0.58 (35% THF–hexanes); mp 85–87 °C; 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.02 (m, 2H), 7.60 (m, 1H), 7.47 (m, 2H), 4.86 (m, 1H), 4.70 (m, 2H), 4.50 (m, 2H), 3.59 (s, 1H), 3.19 (t, 1H, J = 10.2 Hz), 2.44 (m, 1H), 2.25 (m, 2H), 1.70 (s, 3H), 1.85–0.92 (m, 7H), 0.90 (d, 3H, J = 6.9 Hz); 75-MHz ^{13}C NMR ($CDCl_3$) δ 179.53, 166.09, 149.72, 133.53, 129.63, 129.13, 128.60, 108.62, 75.54, 74.09, 65.86, 46.49, 39.22, 37.32, 37.09, 31.32, 29.66, 26.02, 21.16, 14.73; IR (neat oil) 3516, 2932, 2857, 1756, 1725, 1643, 1602, 1452, 1375, 1272, 1178, 1117, 1070, 1026, 983, 890, 803, 712 cm^{-1}; mass spectrum (CI) 373 (8.4), 356 (18.0), 355 (100); exact mass (CI) for $C_{22}H_{29}O_5$ (M + 1) calcd 373.2015, found 373.2012.

5-*O*-Benzoyl-3-deoxyerythro-γ-lactone and menthone adduct 19a: R_f = 0.61 (35% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.02 (m, 2H), 7.60 (m, 1H), 7.47 (m, 2H), 4.86 (m, 1H), 4.52 (m, 2H), 3.44 (s, 1H), 3.30 (t, 1H, J = 10.2 Hz), 2.22 (m, 2H), 2.01–1.40 (m, 6H), 1.01 (m, 3H), 0.87 (m, 9H); 75-MHz ^{13}C NMR ($CDCl_3$) δ 179.83, 166.07, 133.51, 129.58, 129.10, 128.57, 75.72, 75.49, 65.98, 47.67, 46.82, 41.75, 35.07, 27.32, 26.66, 26.20, 23.36, 22.24, 19.69, 17.63; IR (neat oil) 3517, 2954, 1753, 1726, 1602, 1453, 1366, 1271, 1178, 1116, 1070, 1026, 94, 712, 656 cm^{-1}; mass spectrum (EI) 374 (11.3), 219 (16.2), 131 (53.5), 119 (43.7), 105 (100); exact mass (EI) for $C_{22}H_{30}O_5$ calcd 374.2093, found 374.2098.

4,6-Di-*O*-benzoyl-3-deoxy-D-arabino-δ-lactone and menthone adduct 21a: R_f = 0.58 (35% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.02 (m, 4H), 7.59 (m, 2H), 7.45 (m, 4H), 5.44 (m, 1H), 4.83 (m, 1H), 4.66 (d of d, 1H, J = 3.0, 12.3 Hz), 4.55 (d of d, 1H, J = 4.2, 12.3 Hz), 4.32 (s, 1H), 3.24 (m, 1H), 2.35 (m, 2H), 2.07–1.02 (m, 9H), 0.98 (d, 3H, J = 9.6 Hz), 0.90 (m, 3H, J = 6.9 Hz), 0.85 (m, 3H, J = 6.6 Hz); 75-MHz ^{13}C NMR ($CDCl_3$) δ 173.25, 165.95, 165.09, 133.74, 133.36, 129.74, 129.70, 129.16, 128.83, 128.55, 128.44, 78.99, 76.82, 66.23, 63.09, 46.44, 46.11, 42.19, 35.10, 27.49, 27.46, 26.14, 23.42, 22.29, 20.27, 17.99; IR (neat oil) 3490, 2952, 1726, 1602, 1452, 1266, 1178, 1095, 1026, 911, 711 cm^{-1}; mass spectrum (EI) 508 (2.1), 264 (26.9), 110 (13.1), 105 (100), 77 (17.2); exact mass (EI) for $C_{30}H_{36}O_7$ calcd 508.2461, found 508.2468.

4,6-Di-*O*-benzoyl-3-deoxy-D-arabino-δ-lactone and dihydrocarvone adduct 21b: R_f = 0.53 (35% THF–hexanes); 300-MHz ^{1}H NMR ($CDCl_3$) δ 8.02 (m, 4H), 7.59 (m, 2H), 7.45 (m, 4H), 5.43 (m, 1H), 4.84 (m, 1H), 4.69 (m, 2H), 4.66 (m, 1H), 4.55 (d of d, 1H, J = 5.6, 12.3 Hz), 4.46 (s, 1H), 3.12 (m, 1H), 2.46 (m,

2H), 1.72 (s, 3H), 1.96–1.02 (m, 8H), 0.95 (d, 3H, J = 6.3 Hz); 75-MHz ^{13}C NMR ($CDCl_3$) δ 172.90, 165.95, 165.14, 149.89, 133.78, 129.72, 129.14, 128.77, 128.58, 128.44, 108.53, 79.06, 74.91, 66.25, 63.03, 46.07, 39.34, 37.54, 36.04, 31.31, 29.71, 27.31, 21.19, 14.52; IR (neat oil) 3491, 3072, 2933, 1732, 1644, 1602, 1453, 1376, 1267, 1207, 1113, 1026, 980, 910, 711 cm^{-1}; mass spectrum (EI) 506 (0.13), 489 (0.6), 488 (3.3), 105 (100), 77 (17.3); exact mass (EI) for $C_{30}H_{34}O_7$ calcd 506.2305, found 506.2305.

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Supplementary Material Available: ^{1}H NMR and selected ^{13}C NMR spectra of compounds **6c**, **6d**, **28a**, **15a**, **15b**, **18a**, **19a**, **19b**, **21a**, and **21b** in the Experimental Section and tables of difference NOE data on compounds **10**, **18a**, **15a**, and **15b** (14 pages). 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.