Sugar Allyltin Compounds: Preparation and Application in Organic Synthesis

Sławomir Jarosz*[a] and Anna Gaweł[a]

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General methodology for the preparation of allyltin derivatives is reported, with special attention paid to sugar allyltins. Typical procedures affording such organometallics involve the conversion of partially protected hexoses or pentoses (Sug–CH_2OH) into homologated allylic alcohols (Sug–CH=CH–CH_2OH), which are further transformed into the primary or secondary sugar allyltin derivatives of the general formula Sug–CH=CH–CH_2SnR_3, (*E*)/(*Z*) ratio ≈ 5:1, or Sug–CH*(SnR_3)–CH=CH_2 (single isomer with the (*S*)-configuration at the newly created chiral center*). Controlled Lewis acid-induced fragmentation of these hexose-derived organometallics provides highly oxygenated dienoaldehydes with the (*E*) geometry across the internal double bond: CH_2=CH–CH=CH–[CH(OR)]$_3$–CHO. The (*Z*)-dienoaldehydes are also available by thermal fragmentation of the secondary sugar allyltins. Both these synthons ((*E*) and (*Z*)) can be further converted into highly functionalized derivatives of bicyclo[4.3.0]nonene and bicyclo[4.4.0]decene. Stereochemical aspects of reactions between sugar allyltins and sugar aldehydes (in the presence of Lewis acids or under high pressure) are also discussed.

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Sławomir Jarosz was born in Warsaw in 1952. In 1974 he accomplished the Warsaw University and obtained the M.Sc. in organic chemistry with Professor Jerzy T. Wróbel. In 1979 he obtained the Ph.D. (with Professor Aleksander Zamojski) working on the asymmetric Paterno-Büchi reaction. Then, he spent a year as a post-doc with Professor Bert Fraser-Reid (1980–1981) at the University of Waterloo (Canada) and University of Maryland (U.S.A.). In 1988–1989 he was a visiting Professor at Duke University (Durham NC, U.S.A.). In 1990 he defended habilitation (D.Sc.) and in 1999 was promoted to a full Professor. He is the head of a research group at the Institute of Organic Chemistry, Polish Academy of Sciences in Warsaw (since 1992) and currently the Research Director of the Institute. He is a co-author of about 110 papers, including two chapters in 'Glycoscience. Chemistry and Chemical Biology' (Springer-Verlag, 2001). His main interests include: carbohydrates, stereoselective synthesis, metalloorganic and radical chemistry.

Anna Gaweł was born in Rzeszów (Poland) in 1978. In 2002 she obtained the M.Sc. in organic chemistry at the Rzeszów University of Technology. Since 2003 she joined the Institute of Organic Chemistry PAS, where she was working in the group of Professor Mieczysław Mąkosza. Since November 2003 she is a Ph.D. student at the IOC PAS working with Professor Sławomir Jarosz. Her main interest includes: carbohydrates, and – besides the sugar organometallics – the chemistry of sucrose.

MICROREVIEWS: This feature introduces the readers to the authors' research through a concise overview of the selected topic. Reference to important work from others in the field is included.

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[a] Institute of Organic Chemistry, Polish Academy of Sciences, Kasprzaka 44, 01-224 Warszawa, Poland,
E-mail: sljar@icho.edu.pl

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1. Introduction

The history of organotin chemistry can be dated back to 1849, when Frankland synthesized the first organotin compound, diethyl diiodotin, by treatment of ethyl iodide with metallic tin.[1] Over fifty years later a number of simple and mixed tetraalkyltin derivatives were obtained by Pope and Peachey by treatment of Grignard reagents with $SnCl_4$; this reaction soon became a standard method for the preparation of alkyl- and aryltin derivatives.[1] The real interest in organotin chemistry started in the mid 1960s, however, when Kuivila discovered that trialkyltin hydrides reacted with alkyl halides through a radical-chain mechanism involving short-lived trialkyltin radicals.[2] Barton elaborated an elegant and convenient method based on this for radical deoxygenation of secondary alcohols.[3] Nowadays organotin derivatives are important synthetic intermediates, and their utility and synthesis are described in numerous monographs.[1,4–6] This review covers only syntheses of allyltin derivatives (and particularly sugar allyltins) and their application in stereocontrolled organic synthesis.

2. Properties of Allyltin Derivatives

The C–Sn bond is covalent (average length about 2.2 Å[7]), which makes organotin derivatives stable enough to be isolated in a pure form. Their stability is so high that activation of the Sn–C bond is required for introduction of some functional groups.[5] The tin atom is more electropositive than the carbon atom, so organostannanes show reactivity as carbanions (this polarity may be reversed, however, by replacing the stannyl group with a thalium moiety[8]) or as radicals. The strength of the C–Sn bond is dependent on the nature of the organic substituent and can be arranged in the following order: allyl ≈ benzyl < ethynyl < phenyl ≈ vinyl < alkyl.[9] Among allylstannanes the reactivity can be depicted as: $Ph_3SnAll < Me_3SnAll < All_4Sn < All_3SnCl$.[10] Since the Sn–allyl bond is weaker than the C–alkyl(aryl) bond, allylic stannanes are convenient sources of C_3 (allyl) fragments. The trisubstituted stannyl moiety can be readily replaced with lithium, which makes organotin derivatives stable precursors of the corresponding organolithium reagents.[11,12] The dissociation energy of the C–Sn bond in an allyltin is similar to that of the Sn–H bond; this linkage can be easily split into alkyl(aryl)tin and allyl radicals, allowing the allylation of organic compounds to be performed under radical conditions.[13]

Allylation with allylstannanes (these being much more reactive than allylsilanes[14]) has found wide application in organic synthesis since the beginning of the 1970s, because of its compatibility with the presence of various functional groups.[15] No wonder, therefore, that allyltin derivatives are one of the most useful classes of synthetic intermediates among organic stannanes.

Generally, two main classes of these derivatives may be considered: *i*) allyltins, in which the only heteroatom situated directly at the allylic system is the tin atom (compounds **1** and **1′**) and *ii*) alkoxy- (**2** and **2′**) and, to lesser extent, amino-allyltin compounds (Figure 1).

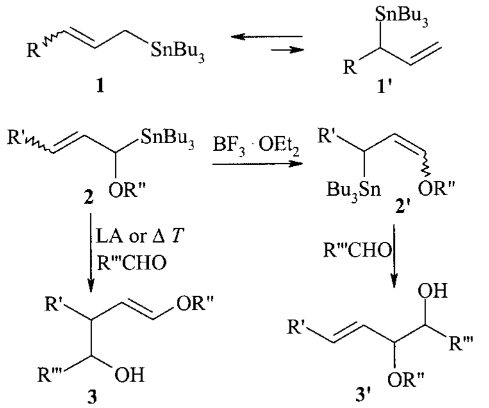


Figure 1. Examples of allyltin derivatives.

Primary allyltin derivatives **1** are more thermodynamically stable than the secondary forms. The latter (**1′**) are reasonably stable in nonpolar solvents, although they easily isomerize into **1** in methanol or in the presence of even mild Lewis acid.[16]

α-Alkoxyallyltins **2** isomerize to γ-alkoxy-derivatives **2′** on treatment with nonchelating strong Lewis acids (preferably boron trifluoride–diethyl ether);[17] this is one of the most useful methods for the preparation of such compounds. No such isomerization is observed, however, when a mixture of aldehyde and **2** is treated with a Lewis acid, with the corresponding product **3** being formed.[18] The same product (although with different relative stereochemistry) is formed on treatment of **2** with aldehyde at high temperature.[19] Regioisomers **2′** under the same conditions provide products **3′** (Figure 1).[20]

Only the syntheses and reactions of compounds of the general formula $Bu_3Sn–All'$ (All′ = substituted allyl group) are dealt with here. Moreover, this review preferentially describes the synthesis and reactivity of compounds of type **1** and **1′** and is limited to derivatives in which substituent R represents a sugar unit. Such sugar allyltins have great synthetic potential and can be used as chirons in stereoselective syntheses of highly oxygenated carbobicyclic derivatives (Section 5).

3. Synthesis of Allyltin Derivatives

3.1. Synthesis of (Nonsugar) Allyltin Compounds without Heteroatoms (other than Sn) at the Allylic System

Two general strategies are employed for the preparation of allyltin derivatives.

Addition of a C_2-Fragment Containing Tin to a C_1-Fragment (C_2 + C_1)

This methodology was described in the mid-1970s.[12,21] Treatment of tin-containing phosphoranes (C_2 fragment) with aldehydes or ketones (C_1 fragment) afforded the corresponding allyltins as mixtures of geometrical isomers (Figure 2).

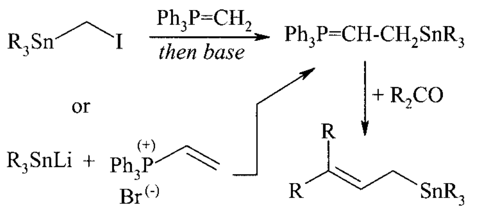


Figure 2. Synthesis of allyltins by Wittig reactions.

This method has found rather limited application, probably due to difficulties in the synthesis of more highly functionalized derivatives and serious problems with reproducibility of the results. Kishi, however, recently used this method for the preparation of (*Z*)-allyltin derivatives as key intermediates in the total synthesis of cytoblastin.[22]

Reaction of a R_3Sn-Fragment with an Allylic C_3-Derivative (C_0 + C_3)

Most allyltin derivatives are prepared by the 'C_0 + C_3' strategy, from the allylic C_3 fragment and a trialkyltin species ('C–C=C + R_3Sn'). Four general methods may be considered for their preparation:

a) *Reactions between allylic metallorganic compounds and tin electrophiles:* Bu_3SnCl[23] or $(Bu_3Sn)_2O$[24] (part a in Figure 3). This method is not compatible with functional groups such as C=O, CN.

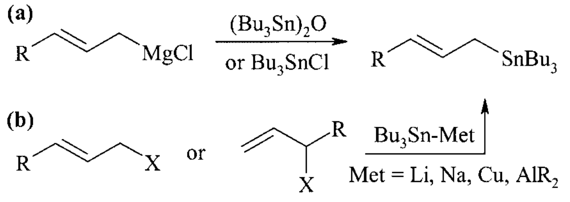


Figure 3. Synthesis of allyltin derivatives from (a) tin electrophiles and (b) tin nucleophiles.

b) *Reactions between allylic substrates and tin nucleophiles:* (R_3Sn–Met)[25] (part b in Figure 3). This may proceed according to the S_N2 or (to a lesser extent) the S_N2' mechanisms and usually provides the primary allyltins. A useful "one-pot" procedure for the synthesis of allyltins from allylic alcohols has been reported by Weigand and Bruckner,[26] whilst an elegant method for the synthesis of the primary allyltins (with a soft tin cuprate reagent[27]) by the S_N2' mechanism was proposed recently.[28] As already mentioned, the methods presented here usually provide the primary allyltin derivatives. There is a big problem with regioselective preparation of the secondary isomers, and generally there is no useful method to achieve this goal.[29]

c) *Generation of allylanions and trapping them with tin electrophiles:* Abstraction of a proton from the allylic system generates the allyl anion, which then reacts with stannyl electrophiles to produce the corresponding allyltin derivatives[30,31]

d) *Treatment of allylic substrates with stannyl radicals:* This method is based on the S_R2' mechanism (Figure 4). Sulfur derivatives (thiocarbonates,[32] sulfones,[33] aryl sulfides,[34] etc.) are usually applied as allyl components. One of the most convenient methods[32] consists of conversion of allylic alcohols into xanthates, followed by sigmatropic thermal [3,3] rearrangement into dithiocarbonates and subsequent reaction with Bu_3SnH, ultimately providing allyltins, usually as mixtures of geometrical isomers, with the (*E*) forms strongly predominating.

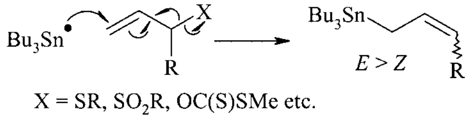


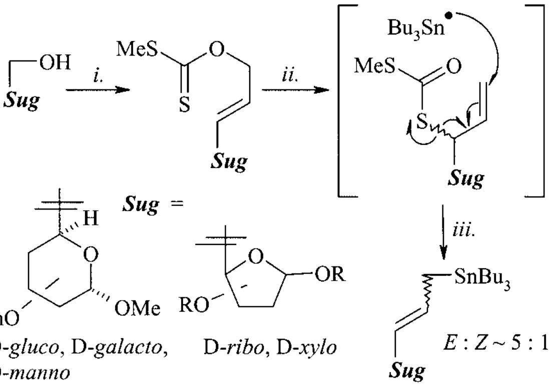
Figure 4. Synthesis of allyltins by radical methods.

e) *Other methods:* Less common methods are represented by hydrostannylation[35] or silylstannylation[36] of allenic substrates and hydrostannylation of dienes.[37] Electrochemical preparation of allylstannanes has also been reported.[38]

3.2. Synthesis of Sugar Allyltin Derivatives

As discussed in Section 3.1., a number of methods can be used for the preparation of allyltin derivatives,[1–5,32,39] but they are hardly applicable to sugars.[40] Most of the methods do not afford any sugar allyltins and quite often give rise to decomposition of sugar substrates.[40] The most reliable and reproducible methods allowing sugar allyltins to be obtained involve treatment of appropriate allylic derivatives with stannyl radicals. The 'xanthate' method proposed by Ueno and Okawara[32] was applied by Mortlock and Thomas[41] in the first synthesis of sugar allyltin derivative from 2,3-*O*-isopropylidene-D-glyceraldehyde.

We have adopted the same methodology for the preparation of more complex sugar allyltins.[42] Firstly, sugar derivatives with free terminal hydroxy groups were converted into the allylic alcohols by a sequence of standard reactions involving oxidation, C_2-Wittig homologation, and reduction of the resulting α,β-unsaturated esters. The alcohols obtained in this sequence were converted into xanthates and further subjected to sigmatropic [3,3] rearrangement to dithiocarbonates (this process was nonselective). Treatment of these with tri-*n*-butyltin hydride provided the desired sugar allyltins as mixtures of geometrical isomers in ca. 5:1 (*E*)/(*Z*) ratios, regardless of the geometry across the double bond in the starting allyl alcohol.[43] Derivatives of furanoses can be prepared in the same way[44] (Scheme 1).



Scheme 1. *i*) 1. Swern oxid. then $Ph_3P{=}CHCO_2Me$, 80%; 2. DIBAL-H, –23 °C, 80%; 3. NaH, CS_2, MeI. *ii*) toluene, 110 °C, 2 h. *iii*) Bu_3SnH, toluene,110 °C, 0.5 h.

Although the 'xanthate' method is highly reproducible and provides sugar allyltins in good yields, it has one main limitation. The allyltins obtained by this method are always mixtures of geometrical isomers, with the (*E*) forms strongly predominating. For many synthetic purposes (e.g., for reaction with aldehydes conducted under high pressure or at high temperature to afford homoallylic alcohols[39]) pure geometrical isomers are needed. The accessibility of (*Z*)-sugar allyltins by the 'xanthate' method, however, is very limited.

3.2.1. Preparation of Sugar Allyltin Compounds with Tributyltin Cuprate (Bu_3SnCu)

Pure geometrical isomers of sugar allyltins may be prepared by treatment of the corresponding allylic derivatives with tin nucleophiles, represented by tributyltin cuprate ('Bu_3SnCu'),[27] tributyltin lithium,[5] or tributyltin sodium (Bu_3SnNa).[45] These nucleophiles may react either in S_N2 or in S_N2' modes. All these reagents were tested in reaction with sugar allylic bromides (X = Br) and mesylates (X = OMs). Only tributyltin cuprate reacted satisfactorily with sugar allylic derivatives; the other two compounds either did not react at all or caused decomposition of the starting material.[46]

Tributyltin cuprate,[27] being a very soft nucleophile, will react preferentially with the soft end of the allylic system. Therefore, suitable activation of the sugar allylic moiety should direct the regioselectivity of the reaction.

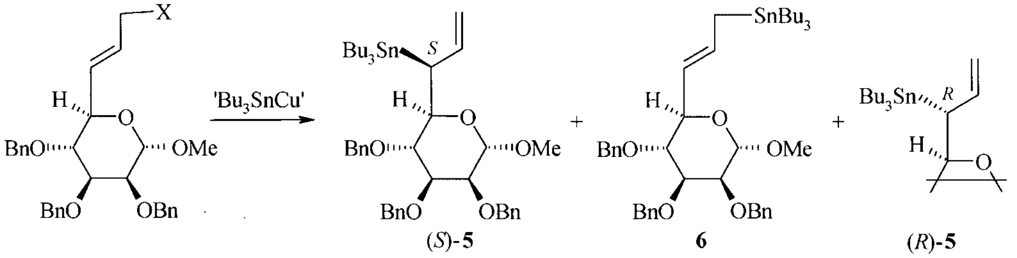
The S_N2 mode, affording primary allyltin derivatives, should be preferred for compounds with soft 'ends' (e.g., iodine), while the S_N2' process should dominate for hard allylic derivatives (e.g., X = OMs). This would allow either the primary allyltins (with preservation of the geometry across the double bond; (*Z*)-allyltins should be readily available by this method) or the secondary regioisomers to be obtained.

Indeed, treatment of Bu_3SnCu with derivatives of methyl α-D-*manno*-pyranoside (**4a**–**d**) fully confirmed our assumption (Figure 5). The highest yield of the secondary derivative **5** was obtained in the reaction of **4d**, with the 'hard end′. Moreover, only one stereoisomer of the secondary allyltin was formed, to which the (*S*) configuration at the newly created stereogenic center was assigned.[46]

Galactose derivatives represent a special case. The S_N2' process is unlikely because of the strong shielding of the *C*-6 center in **7** (Figure 6), and only primary isomers **8** are formed.[43] Situation is slightly different for diacetonogalactose derivatives. Mesylate (*E*)-**9** reacted with Bu_3SnCu to afford only the primary organometallic derivative (*E*)-**10**, while the (*Z*) isomer also furnished – besides the primary product (*Z*)-**10** – the secondary isomers **11** upon treatment with the same reagent, although in low yields. It is worth mentioning that these secondary sugar allyltins were formed in comparable amounts.[47]

Furanose derivatives of sugars also provided secondary allyltins on treatment with Bu_3SnCu (Figure 7). It is very interesting that the configuration of the regioisomer **14** formed in this process ***was not dependent*** on the geometry of the starting allylic mesylate; the same derivative **14**, with the (*S*) configuration at *C*-5, was obtained from both geometrical isomers (*E*)-**12** and (*Z*)-**12**.[46]

Another class of sugar allyltins (represented by **16** and **17** in Scheme 2) was prepared by Marshall and Elliott,[48] by the 1,4-addition of Bu_3SnCu to the α,β-unsaturated



	(*S*)-**5**	**6**	(*R*)-**5**
4a: X = Cl	50%	2%	0%
4b: X = Br	30	16	traces
4c: X = I	*18*	*20*	*0*
4d: X = OMs	***57.5***	***2.5***	***0***

Figure 5. Reactions between sugar allylic derivatives and metallated tributyltin reagents.

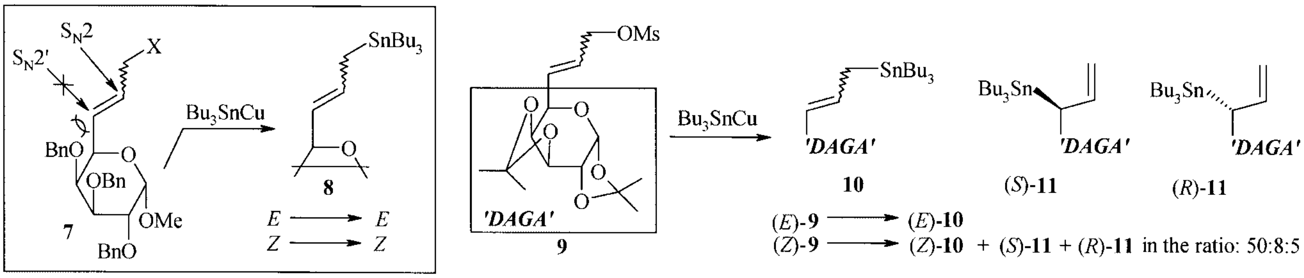
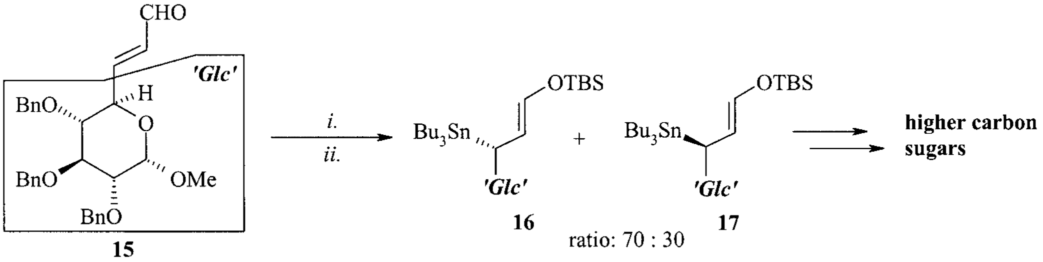


Figure 6. Reactions between allylic derivatives of galactose and Bu_3SnCu.



Scheme 2. *i*) Bu_3SnCu. *ii*) TBSCl (80%).

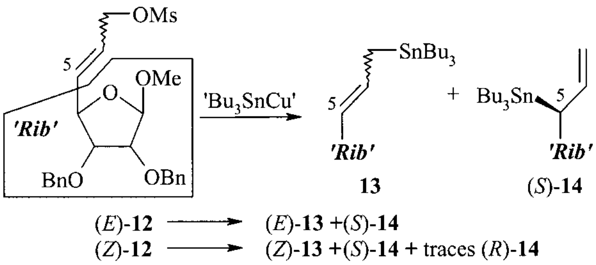


Figure 7. Reactions between furanose derivatives and Bu_3SnCu.

sugar aldehyde **15**, followed by trapping of the intermediate with silyl chloride. These organometallic derivatives were further used in the synthesis of higher-carbon sugars.

4. Reactions of Allyltin Derivatives

One of the most important reactions of allyltin derivatives is with aldehydes to provide homoallylic alcohols. In many cases stereocontrolled additions of allyltins to aldehydes are key steps in the preparation of complex natural products. Keck used the addition of Bu_3SnAll as a key step in the preparation of the C_1–C_9 fragment of rhizoxin.[49] Radical-mediated annulations with allyltins provide a convenient route to carbocyclic derivatives.[50] Oxidation of allyltin derivatives with *m*-chloroperbenzoic acid proceeds at the *C*-3 position to afford allylic alcohols. This can be the method of choice for the interconversion of primary allylic alcohols into secondary ones through a 1,3-shift of a hydroxy group.[32]

4.1. Synthesis of Homoallylic Alcohols. General Remarks

Allyltytin derivatives – being much more reactive than the corresponding silanes – are very useful donors of the allyl group. Reactions between allylstannanes and aldehydes for stereoselective synthesis of homoallylic alcohols have been designed specially.[4,39c,51] Depending on the nature of the starting organometallic compound, homoallylic alcohols (**18**, **19**, or **20**) are obtained through thermal or acid-catalyzed reactions between allyltins and aldehydes; this process proceeds with rearrangement of the allylic fragment (Figure 8). The uncatalyzed version proceeds through a six-membered cyclic transition state,[52] while with Lewis acid catalysis an open-chain transition state has been proposed.[39,53] Allyltributyltins can be conveniently transmetallated to form more reactive species.[54]

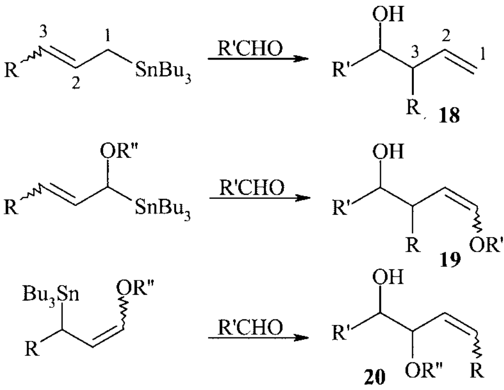


Figure 8. Reactions between allyltins and aldehydes.

The stereochemistry of the reaction between an allyltin and an aldehyde depends on the method of activation of the Sn–C bond. From the (*E*)-stannane (*E*)-**21** the *threo*-product **22** is formed predominantly (or exclusively) when the reaction is performed at high temperature[52] or under high pressure.[55] Alternatively, the (*Z*)-**21** isomer affords the *erythro* product **23**. Such selectivities are explained by the cyclic six-membered transition states in which the steric ef-

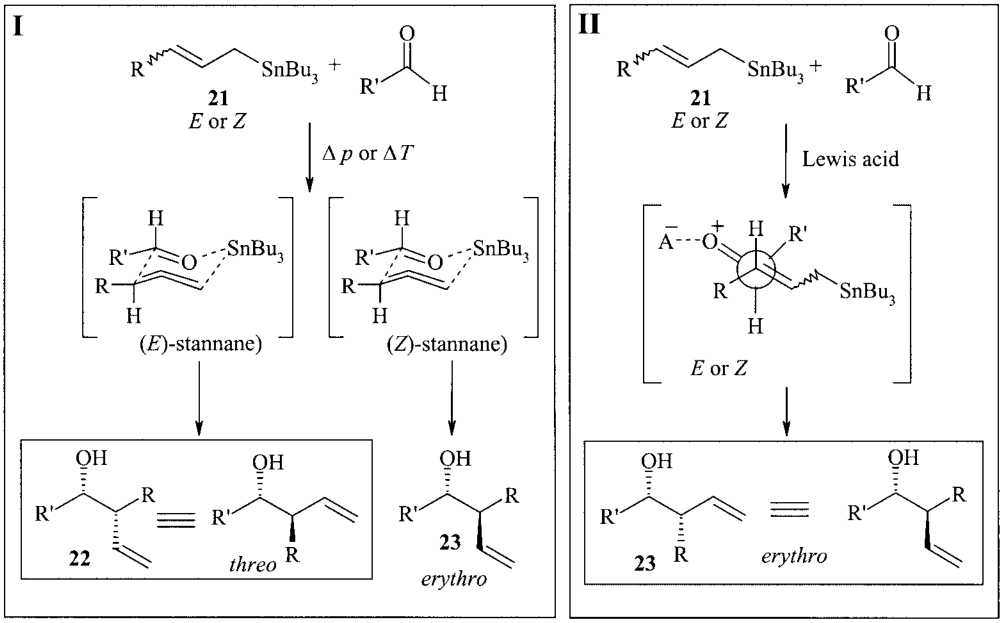


Figure 9. Stereochemical models for the reactions between allyltins and aldehydes under high pressure or at high temperature (**I**) or with catalysis by Lewis acids (**II**).

fects are minimized[39] (part I, Figure 9). Allylation of aldehydes with allylic organometallic reagents can provide homoallylic alcohols with impressive regio- and stereocontrol. Generally, reactions between aldehydes and (*E*)-but-2-enyl metal derivatives (Li, Mg, B, Zn, etc.) afford *threo* homoallylic alcohols, while the (*Z*)-organometallic reagents give *erythro* derivatives.[39] In contrast, but-2-enylstannanes provide the *erythro* adducts regardless of the geometry of the starting allyltin upon treatment with aldehydes.[56] This is the result of a very low acidity of the tetraorganotin derivative, which cannot compete with the Lewis acid catalyst (part II, Figure 9).

For hydroxy- (alkoxy-) or aminoaldehydes, an additional effect due to complexation to –OR and –NR$_2$ groups also needs to be considered together with complexation of the Lewis acid to the C=O group. Some Lewis acids (ZnCl$_2$, TiCl$_4$, SnCl$_4$, etc.) may form chelates with such carbonyl compounds to afford five- (for α derivatives) or six-membered (β) cyclic intermediates.[57] The product expected from the 'chelation' model is therefore usually strongly preferred. The α-aminoaldehydes react similarly.[58] The selectivity is also dependent on the Lewis acid used[59] (Figure 10).

The δ-alkoxyallyltins (such as **24** in Scheme 3) represent a special case. At high temperature or under high pressure they react with aldehydes in a normal way [i.e., the products (**25**, **25′**) are the result of the attack of electrophile (aldehyde) on the γ-carbon atom]. However, the situation is changed when tin tetrachloride is used as activator in this process. Thomas studied the reactions between such substituted allyltin derivatives and aldehydes in a series of papers, and found that the attack of electrophile in the SnCl$_4$-catalyzed process occurred exclusively at the α-carbon atom.[60] The formation of such products may be explained in terms of transmetallation of **24** with SnCl$_4$ to afford **27** (an X-ray structure of such a type of oxastannane has been described in the literature[61]), which upon treatment with aldehyde gives compound **26** (Scheme 3). When boron trifluoride was used 1,4-elimination was observed and the yields of the desired coupling products were low. Aminoallyltins (OBn replaced with NBn$_2$) reacted similarly.[62]

When the alkoxy function is located at the ε-position another transmetallated intermediate (**28**; Scheme 4) is formed; the reaction between this derivative and aldehyde affords product with high selectivity.[63]

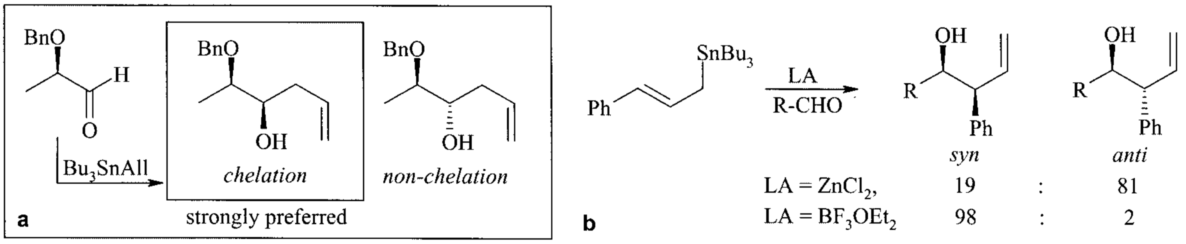
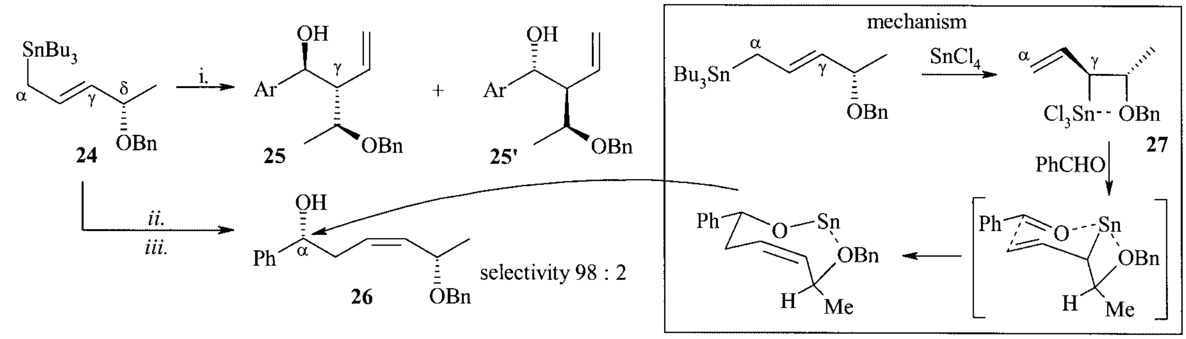
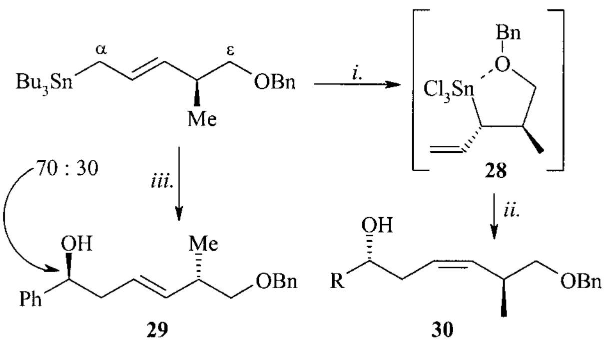


Figure 10. **a**) Reactions between allyltins and α-alkoxyaldehydes. **b**) Influence of the Lewis acid on stereoselectivity.



Scheme 3. *i*) ArCHO, 150 °C. *ii*) $SnCl_4$. *iii*) PhCHO.



Scheme 4. *i*) $SnCl_4$. *ii*) RCHO. *iii*) 1. $InCl_3$; 2. PhCHO.

The stereochemistry of this process is changed when $InCl_3$ or $BiCl_3$ are used as promoters[63] (Scheme 4). The five-membered intermediate **28** can be trapped by exchange of the chlorine atoms for phenyl groups (with PhLi).[64]

The concept of remote 1,5- and 1,7-asymmetric induction with allylmetals[65,66] can also be applied to 1,8-induction.[67] Application of remote asymmetric induction in $SnCl_4$-catalyzed reactions between β-aminoaldehydes and allyltins was presented by Thomas in the synthesis of the antifungal agent panamycin 607.[68]

Alkoxyallyltin derivatives react with imines in a similar way as with aldehydes.[69]

4.2. Synthesis of Higher-Carbon Sugars from Allyltin Compounds

Higher-carbon sugars are attractive targets and their synthesis has attracted considerable attention in the last two decades. A number of methods affording such complicated molecules have been developed.[70] Over recent years we have proposed a general methodology for the preparation of higher-carbon sugars by coupling of two sugar subunits.[71]

The precursor **33** is readily obtained from sugar phosphoranes[72] **31**, phosphonates[73] **32**, or vinyltin derivatives of monosaccharides[74] **34** (Figure 11).

Another class of higher sugar precursors – homoallylic alcohols flanked at both ends with sugar moieties (e.g., **37** in Figure 12) – was recently prepared by us in a boron trifluoride-catalyzed addition of sugar allyltins to sugar aldehydes.[75]

Only this catalyst ($BF_3{\cdot}OEt_2$) was suitable for such transformation, the pyranose derivatives (e.g., **6** or **35**) reacting readily with aldehydes to provide the products **37** in high yields and with very high diastereoselectivities. Use of other Lewis acids (e.g., $TiCl_4$, $ZnCl_2$) was associated with decomposition of sugar organometallics;[76] interestingly, this process can be controlled to provide useful chiral synthons in the form of (*E*)-dienoaldehydes[42] (e.g., **38**), starting materials in stereocontrolled synthesis of carbobicyclic derivatives[77,78] (see Section 5).

The boron $BF_3{\cdot}OEt_2$-catalyzed reaction between the sugar derivative **35** and the sugar aldehyde **36** afforded the higher sugar precursor **37** in ca 80% yield. The relative stereochemistry was *erythro*, as would be expected from the open-chain model, and the (6*R*,7*S*) absolute configuration was assigned to the product by chemical and spectral correlation.[75] The stereochemistry of this reaction can be explained in terms of the models shown in Figure 13.

Furanose allyltin derivatives, however, did not react with aldehydes in the same way as pyranoses; in the presence of

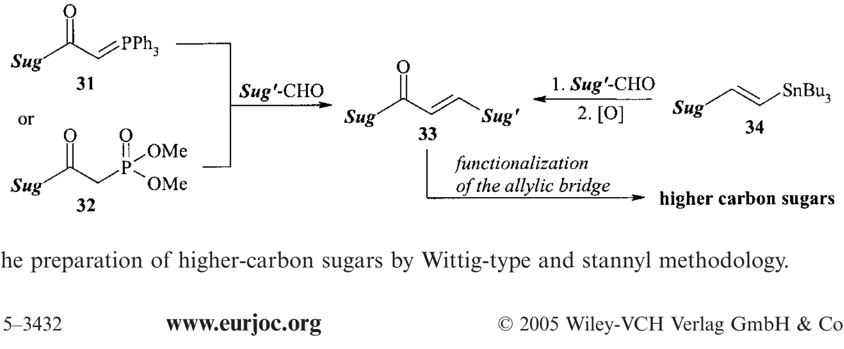


Figure 11. Methods for the preparation of higher-carbon sugars by Wittig-type and stannyl methodology.

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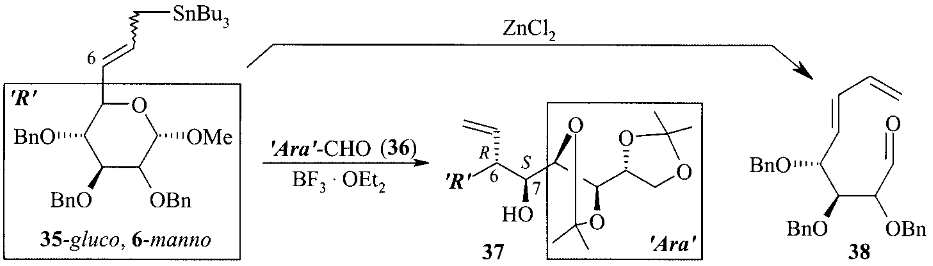


Figure 12. Behavior of sugar allyltins towards Lewis acids.

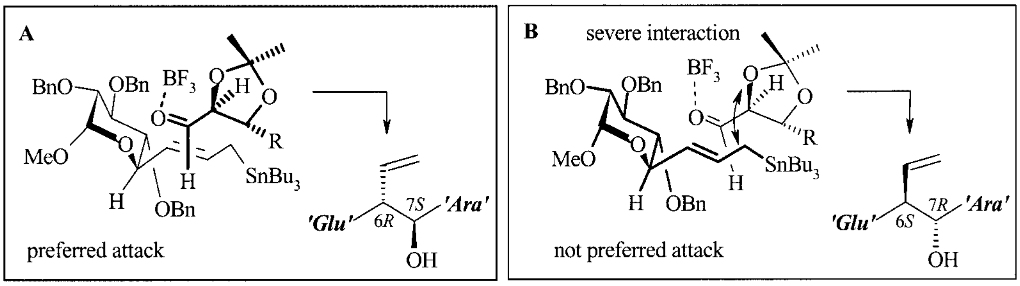
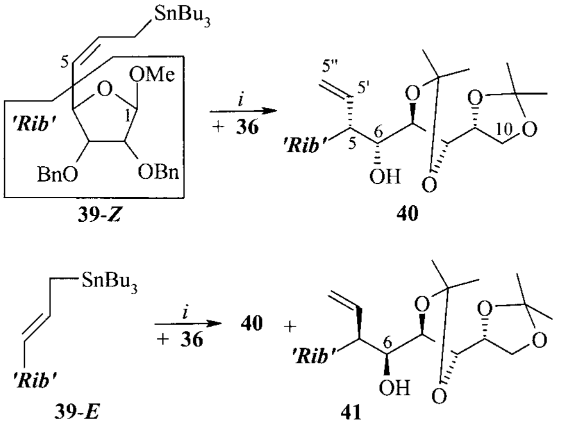


Figure 13. The preferred (**A**) and not preferred (**B**) transition states in the reaction between **35** and aldehyde **36**.

BF_3·OEt_2 they underwent decomposition ***prior to*** the reaction with aldehyde.[75] Use of acid catalysts in formation of compounds of type **40** (or **41** in Scheme 5) should therefore be avoided, and other conditions should be checked to achieve this transformation. The process affording homoallylic alcohols with preservation of the sugar skeleton of furanose was achieved under high pressure.



Scheme 5. i) 13 kbar, 57 °C, CH_2Cl_2, 7 days.

Thus, isomer (*Z*)-**39** reacted with aldehyde **36** under 13 kbar pressure to afford the *threo* derivative **40** as the only product, in 97% yield[79] (Scheme 5). However, the (*E*)-**13** isomer provided the same *threo* derivative **40** together with another *threo*-homoallylic alcohol **41**.[79]

Although the *threo* product(s) would be expected from the high-pressure reaction of the (*E*) isomers according to the cyclic mechanism of this process (Figure 9), it is hard to explain the formation of such product with the same relative stereochemistry from the (*Z*) isomer under these conditions, unless different mechanisms for the two reactions are considered. Formation of the *threo* adducts **40** and **41** from the (*E*)-organometallic (*E*)-**39** might be explained in terms of the cyclic model used for such a reaction as shown in Figure 9. Formation of the *threo adduct* **40** from the (*Z*) isomer is more difficult to explain, since according to this cyclic model, the (*Z*)-organometallics should provide the *erythro* products. The possibility that the (*Z*) isomer might undergo isomerization to (*E*)-***39 prior to*** reaction with aldehyde was excluded, since (*E*)-**39** gives *threo* adducts with low stereoselectivity in reaction with **36**, while the selectivity in the reaction of (*Z*)-**39** was very high (97% of only one stereoisomer).[79] The widely accepted cyclic model therefore has to be modified.

Although tetraorganostannanes are weak Lewis acids, their acidity increases at high pressures. The process studied by us may therefore be regarded as acid-catalyzed with *internal* Lewis acid (Sug-*Sn*Bu_3). However, in the open-chain, antiperiplanar model of the acid-catalyzed reaction, the adducts with the relative *erythro* configuration would be expected.[39] The *threo* product **40** or **41** could, possibly, result from other transition states **42-I** and **42-II** with antiperiplanar arrangements of the carbonyl and allylstannane groups, although it is very unlikely due to severe steric repulsions between the arabinose and ribose units (Figure 14).

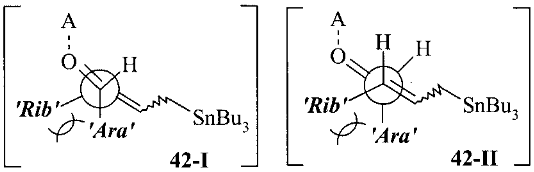


Figure 14. Stereochemical open-chain models in the reaction between **39** and **36**, affording *threo* adducts **40** and **41**.

Exclusive formation of the *threo*-homoallylic alcohols in the high-pressure reactions of isomeric sugar allyltins (*Z*)-

and (*E*)-**39** with aldehyde 3**6** may be explained in terms of an open-chain synclinal model, as proposed recently by Nishigaichi and Takuwa.[80] This model postulates that the carbonyl and olefinic fragments of both reacting molecules are synclinal to each other; in Nishigaichi and Takuwa's original model this transition state is stabilized by external Lewis acid (e.g., $TiCl_4$).[80]

We propose that the synclinal transition state is stabilized by tributyltin moiety as part of one reacting partner. Such a transition state is cyclic, but the conformation of this six-membered ring is highly distorted from the chair form. According to this model we can propose transition states **43a** and **43b** for the reaction between (*E*)-**39** and **36**, and **44a** and **44b** for the reaction of (*Z*)-**39** (Figure 15); all of these would produce the *threo* adducts **40** or **41**. The steric interactions in **43a** or **43b** are comparable, so the stereoselectivity in the reaction between the (*E*) isomer **39-*E*** and **36** should be low. The situation is better in the reaction of the (*Z*) isomer of **39**. Transition state **44b** should be so highly favored over the alternative **44a** that only one stereoisomeric *threo*-homoallylic alcohol **40** should be formed, in very high yield[79] (Figure 15).

Allyltin derivatives have been applied as useful synthons in directed synthesis of higher-carbon sugars (one example reported by Marshal has already been shown in Section 3.2.). The key step in these preparations consists of the highly stereoselective boron trifluoride–diethyl ether-catalyzed addition of organometallic derivative **45** to the respective aldehydes,[81–83] followed by *cis*-hydroxylation of the double bond(s) in the resulting homoallylic alcohols with OsO_4 in accordance with Kishi's rule[84] (Figure 16).

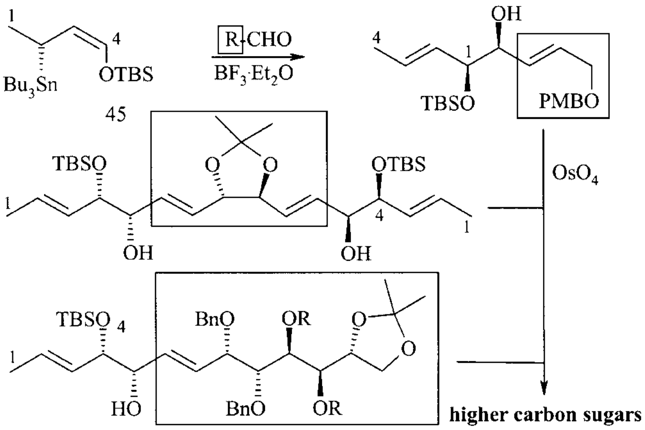


Figure 16. Stereoselective synthesis of higher-carbon sugars from allyltin derivatives.

The key step in the preparation of higher aminosugars also involved a BF_3-catalyzed addition of a γ-alkoxyallyltin to a linear *C*-6 sugar aldehyde.[85] The synthesis of *C*-allylglycosides by treatment of *S*-phenylglycosides with allyltin compounds under radical conditions was reported by Keck.[86]

4.3. Controlled Fragmentation of Sugar Allyltin Derivatives

During the work on higher-carbon sugars we prepared the allyltin **35** (Figure 17), a derivative of D-glucose, and used it in reaction with a sugar aldehyde.[76]

The target compound – homoallylic alcohol **46** – was formed in rather small amounts, and the major product

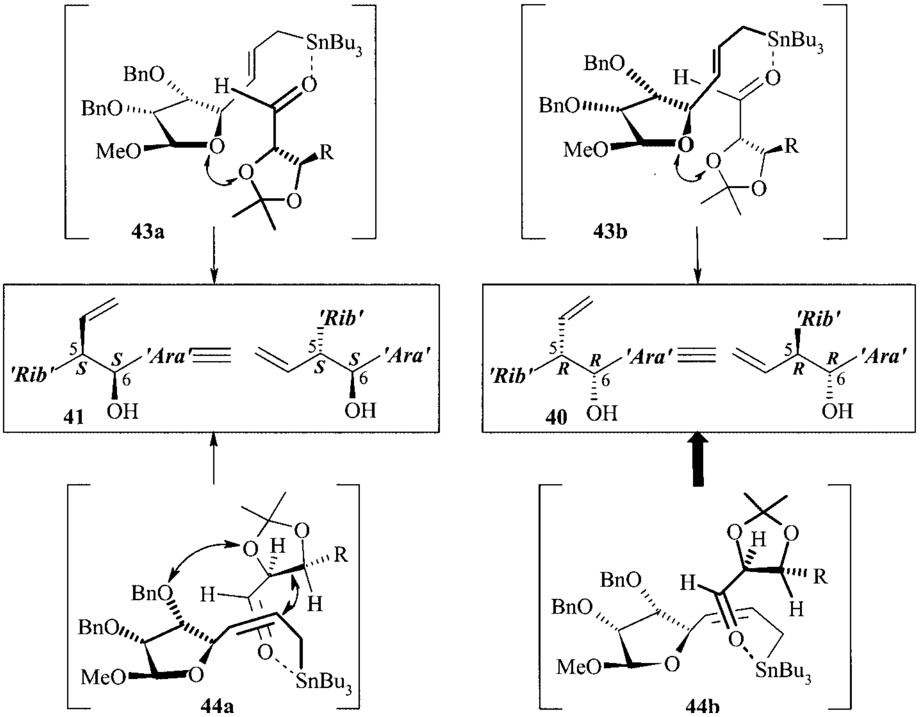


Figure 15. Stereochemical models for high-pressure reactions between isomeric allylstannanes (*Z*)-**39** and (*E*)-**39** and aldehyde **36**.

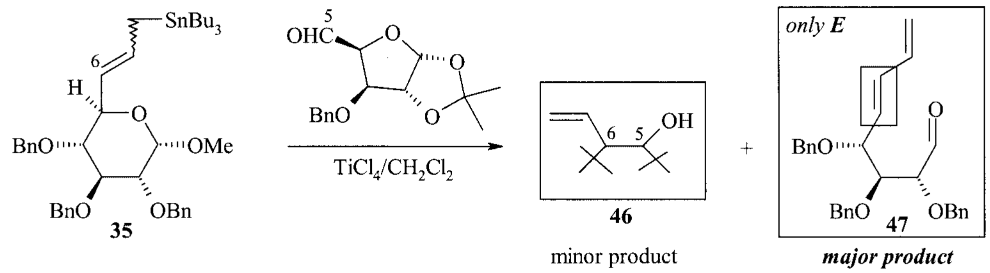


Figure 17. $TiCl_4$-catalyzed reaction between the sugar allyltin **35** and an aldehyde.

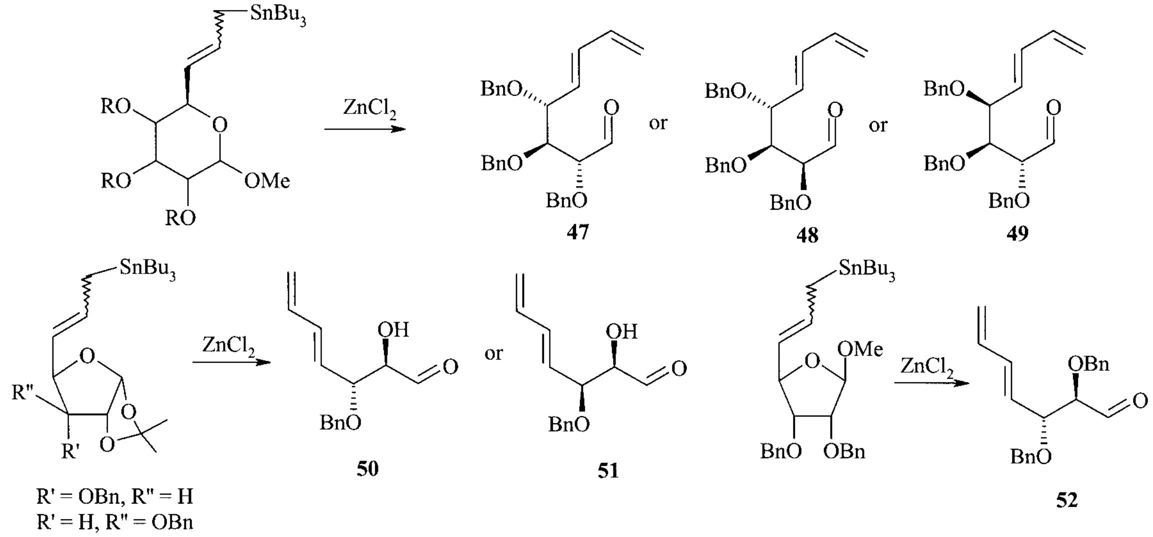


Figure 18. Preparation of different dienoaldehydes by controlled decomposition of sugar allyltin species.

turned to be the dienoaldehyde **47** resulting from the fragmentation of the sugar allyltin (Figure 17). (A similar fragmentation was observed by McNeill and Thomas[60] when a δ-alkoxyallyltin species was treated with BF_3.)

This rather unusual rearrangement soon became the standard method in our laboratory for the preparation of highly oxygenated dienoaldehydes with (*E*) geometry across the internal double bond[42,44] (Figure 18).

Several dienoaldehydes **47**–**49** were prepared conveniently by controlled fragmentation of the corresponding sugar allyltins (derived from D-glucose, D-mannose, and D-galactose, respectively).[42] Similarly, the dienes **50**–**52** were obtained in good yields by this simple method by fragmentation of furanose derivatives[44] (Figure 18).

4.3.1. Thermal Stability of Sugar Allyltin Compounds

The behavior of sugar allyltins at high temperature is interesting. While the primary isomers are stable up to 214 °C (boiling trichlorobenzene), secondary derivatives undergo fragmentation in boiling xylene (140 °C) with elimination of the stannyl moiety to provide products identified as dienoaldehydes, but with (*Z*) geometry across the internal double bonds.[46] This observation opened a new, very interesting opportunity in stereocontrolled organic syntheses of highly oxygenated carbobicyclic derivatives in enantiomerically pure form (described in Section 5). While fragmentation of the primary isomers with Lewis acids provided the (*E*)-dienes as the only products,[46,87] thermal decomposition of the secondary ones gave the (*Z*)-dienes. Both geometrical isomers, (*E*) or (*Z*), of dienoaldehydes are therefore easily available in pure form, either by treatment of the primary sugar allyltin with zinc chloride (→ (*E*) regardless of the geometry of the starting allyltin), or by a controlled thermal fragmentation of secondary organometallics (only one stereoisomer formed in reaction of sugar

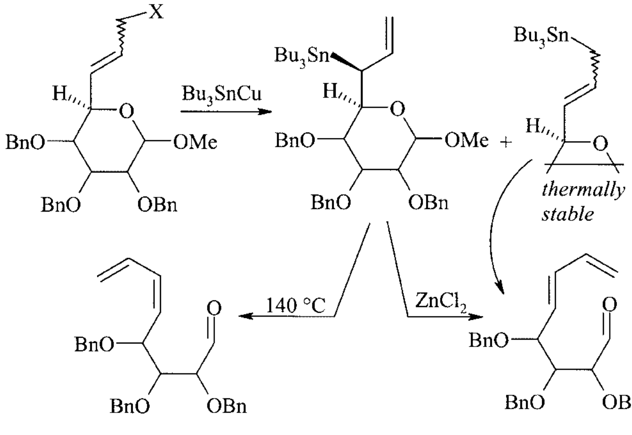


Figure 19. Preparation of secondary sugar allyltins and their behavior at high temperature and in the presence of $ZnCl_2$.

allylic mesylates with Bu_3SnCu). Interestingly, this secondary isomer decomposed to the (*E*)-diene upon treatment with $ZnCl_2$.[46] The basic idea of this methodology is presented in Figure 19. Several (*Z*)-dienoaldehydes were prepared from secondary sugar allyltins – the exclusive (or major) products of the reaction of sugar allylic mesylates with BuSnCu.[46]

This very interesting and useful behavior of sugar allyltins needs explanation. We do not yet know the mechanism of fragmentation induced with a Lewis acid to afford the (*E*)-dienes regardless of the configuration of starting allyltin, but highly stereoselective thermal fragmentation of the secondary isomers can be explained if a concerted process is assumed for the elimination of the stannyl moiety.

4.3.2. Mechanism of Thermal Fragmentation of Secondary Sugar Allyltin Compounds and Determination of Absolute Configurations

Three different mechanisms of controlled fragmentation of secondary sugar allyltins merit consideration: the radical process (involving cleavage of the carbon–oxygen bond under the radical conditions; such a process, although not common, is known[88]) or two concerted ones: *anti* (E-2) or *syn* elimination. To check whether radicals were involved in the fragmentation of secondary sugar allyltin derivatives, compound **5** was heated at 140 °C in the presence of Bu_3SnH and in a separate experiment with $(Bu_3Sn)_2$. ***No formation*** either of a reduced product **54** or a primary (*Z*)- or (*E*)-allylstannane **6** (stable up to at least 214 °C) was noted, which reasonably excluded the radical mechanism of fragmentation (Figure 20).[87]

Two other possible mechanisms of such elimination (concerted: *anti* or *syn*) were therefore analyzed. Were the process of controlled fragmentation of secondary sugar allyltins to proceed according to one of these, diastereoisomeric organometallics differing in their configuration at the stereogenic center bearing the stannyl group should decompose to dienoaldehydes with ***opposite*** geometries across their internal double bonds. Although single stereoisomers (*S*)-**5** were formed with very high diastereoselectivity in reactions between the sugar allylic mesylates and Bu_3SnCu, we were also able to isolate traces of the opposite (*R*)-**5** isomers.[46] This isomer underwent similar fragmentation to that of (*S*)-**5** to provide the diene, but with the (*E*) configuration across the internal double bond. This result unequivocally pointed to a concerted mechanism of thermal fragmentation of secondary sugar allyltin derivatives, the question, however, being which one: *syn* or *anti*. This problem is very important, since knowledge of the mechanism would allow the configuration at the stereogenic center bearing the stannyl moiety to be determined. Determination of the configurations of tin derivatives is not trivial, but their structures may often be deduced from the products of their controlled fragmentation[89] if the mechanisms of such processes are known.

We suggested that the *anti*-(E-2) elimination mechanism as shown in Figure 21 was more likely, and would be consis-

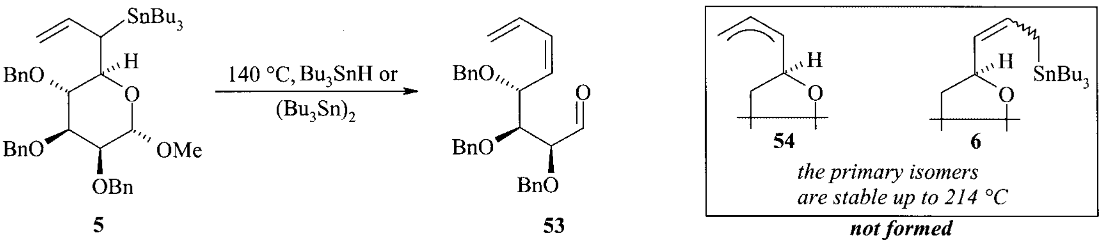


Figure 20. The (excluded) radical mechanism of decomposition of **5**.

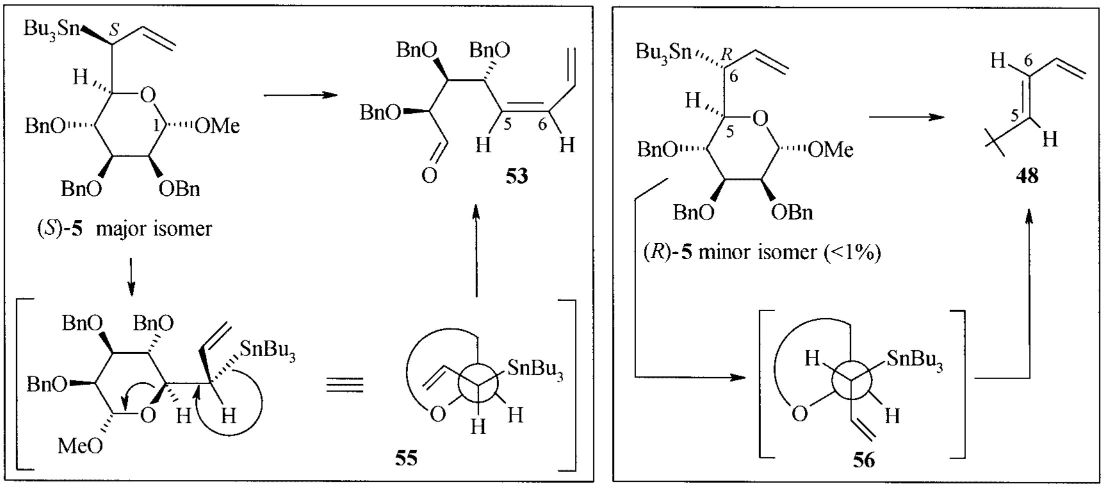


Figure 21. Stereochemical models for the controlled decomposition of secondary sugar allyltins.

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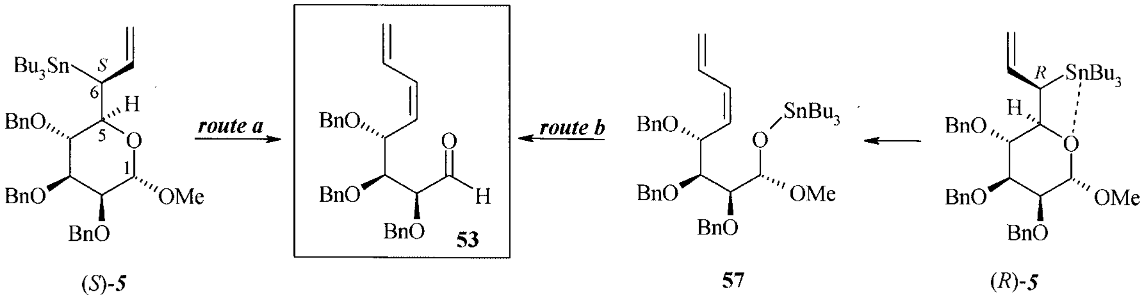


Figure 22. Possible mechanisms of decomposition of secondary allylstannanes to afford the (*Z*)-dienoaldehydes.

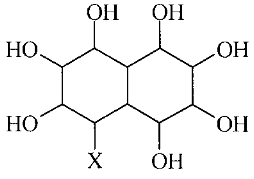
tent with literature data[90] proposed for thermal fragmentation of β-stannyl alcohols and β-stannyl esters. In this case the configuration at the *C*-6 center would be (*S*) (route a in Figure 22). However, if we assume the *syn* elimination mechanism (route b) the configuration would be (6*R*). ^{117}Sn NMR spectroscopy was applied to solve this problem.

According to the stoichiometry of the rearrangement, tributyltin methoxide is eliminated. This derivative is rather unstable and even traces of moisture induce its decomposition to tri-*n*-butyltin oxide.[1,91] It should be formed as a primary product by the *anti* mechanism and a secondary product in the *syn* mode, via the intermediate mixed acetal **57**. Such mixed acetals are known, but most of them are very sensitive to moisture and readily undergo hydrolysis. Although it is claimed that the adducts of aldehydes with Bu_3SnOMe (mixed acetals of type **57**) are stable to hydrolysis '*only if the carbonyl compound is a powerful acceptor (e.g., chloral)*'[92] we have been able to detect such mixed acetals by ^{117}Sn NMR spectroscopy.[79]

To distinguish between these two possibilities, the *syn* or *anti* mode, we thus applied ^{117}Sn NMR spectroscopy. Tributyltin methoxide was detected, but no signal for the mixed acetal **57** was visible in the spectrum of the crude mixture obtained by thermal degradation of **5**,[79] which, we believe, supports the E-2 mechanism of the fragmentation.

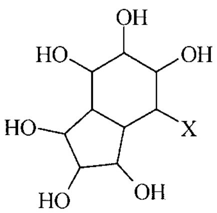
5. Synthesis of Highly Oxygenated Carbobicyclic Derivatives from Sugar Allyltin Compounds

Monocyclic analogues of simple sugars such as cyclitols,[93] and carbasugars[94] play important roles in biological processes. Much less is known about bicyclic analogues, their synthesis and biological activity, though it has been reported that certain highly oxygenated, although racemic, derivatives of bicyclo[4.4.0]decane **58** and bicyclo[4.3.0]nonane **59** showed potent and selective α-glucosidase inhibition at μM concentrations against α- and β-glucosidases.[95]



58

racemic



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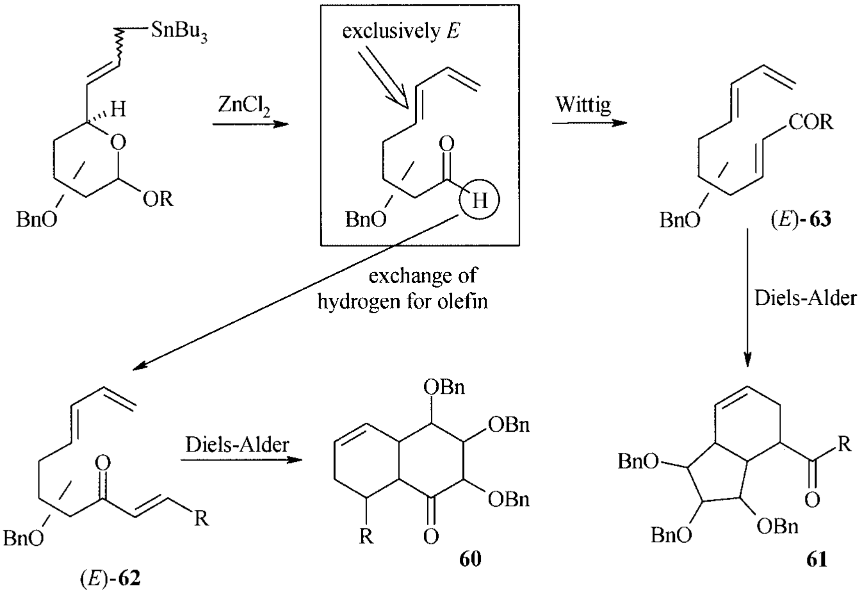


Figure 23. Synthesis of highly oxygenated perhydroindane and decaline precursors from sugar allyltins.

We decided to prepare such derivatives (or rather their convenient precursors) in optically pure form. One of the most convenient methods for the synthesis of enantiomerically pure compounds is undoubtedly the '*chiron approach*':[96] the use of readily available optically pure natural products such as sugars, aminoacids, terpenes, etc. as starting materials. Retrosynthetic analysis as shown in Figure 23 indicated that the bicyclic derivatives **60** and **61** might be suitable direct precursors of (optically pure) compounds **58** and **59**, respectively.

Such precursors might be obtained from the trienes **62** and **63**, and these trienes should be available from dienoaldehydes of defined geometry. As shown in Section 4.3., such synthons are readily available from the corresponding sugar allyltin derivatives. Moreover, both the (*E*)- and the (*Z*)-dienes are available in pure form through appropriate choice of reagents. Such dienoaldehydes can be converted into the trienes **62** and/or **63**, and highly stereoselective and predictable cyclization[97] of these should provide precursors **60** and **61**. (In the late 1980s Herczegh[98] reported on the synthesis of carbobicyclic compounds from sugar chirons by standard methodology. The preparation of geometrically pure dienoaldehydes represented a serious problem, however.)

5.1. Synthesis of Monocarbocyclic Derivatives from Sugar-Derived Dienoaldehydes

A review on the synthesis of carbocyclic derivatives based on transition metal-catalyzed cyclization of organostannanes appeared recently.[99]

The dienoaldehydes obtained by us from sugar allyltins, can serve as precursors of both monocyclic and bicyclic highly oxygenated derivatives. Since the chemistry of monocyclic analogues is very well explored[93,94,100] we tested only one type of reaction for the preparation of cyclopenanes as shown in Scheme 6.

Aldehyde **47**, obtained by a controlled fragmentation of the corresponding D-*gluco* configured allyltin (c.f. Section 4.3.), was treated with tributyltin hydride under radical conditions to afford cyclopentane **66** as a single stereoisomer, although in moderate yield.[101] Alternatively, conversion of the aldehyde **47** into the xanthate **65** followed by radical cyclization gave compound **64**.[101]

5.2. Synthesis of Carbobicyclic Derivatives from Sugar-Derived Dienoaldehydes

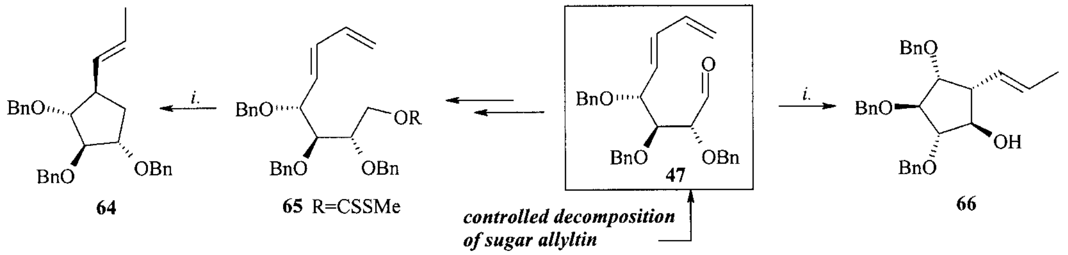
This section presents an approach to highly oxygenated bicyclo[4.3.0]nonene and bicyclo[4.4.0]decene derivatives from sugar allyltins. The general idea was depicted in Figure 23.

5.2.1. Synthesis of Bicyclo[4.3.0]nonenes

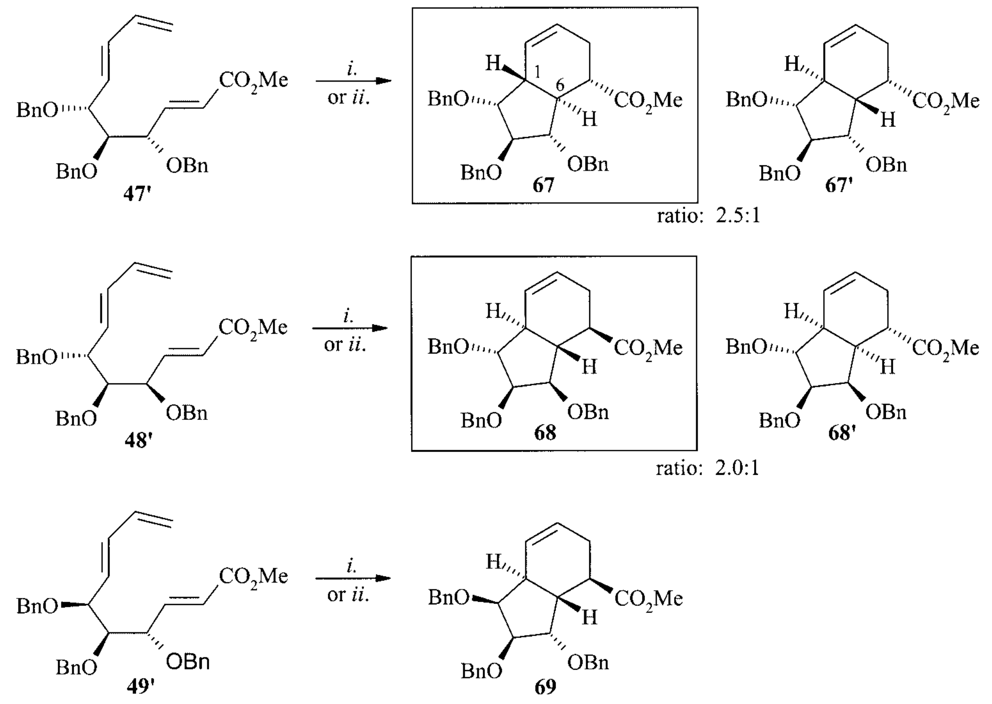
The first synthesis of these bicyclic derivatives was performed by us in 1997.[77] The corresponding dienoaldehydes **47**–**49** (see Figure 18) were treated with the simplest stabilized Wittig reagent ($Ph_3P=CHCO_2Me$) to afford the trienes **47′**–**49′** (Scheme 7). Cyclization of these precursors was induced by use either of aluminium trichloride or of high pressure. The reaction under high pressure performed on a small scale (10 mg) was highly stereoselective and provided single stereoisomers (**67**–**69**), while in an acid-catalyzed process a mixture of isomers were obtained from the D-*xylo*- (**47′**) and D-*lyxo*- (**48′**) trienes. The junctions between the rings were *trans*, the result of the *endo* transition state in this intramolecular Diels–Alder reaction. When the high pressure reaction was performed on a preparative scale (1.2 g) significant amounts of the alternative *endo* adduct **67′** were formed in the cyclization of **47′**.[102]

Could the absolute configuration at the ring junction (i.e., at C-1 and C-6) be changed? To test this possibility we treated the trienes not with achiral Wittig reagent, but with chiral phosphonates. The syntheses of such sugar-derived Wittig-type reagents are presented in Scheme 8. The corresponding methyl esters (derived either from D-mannose or D-glyceraldehyde) afforded the phosphonates **70** with (*S*) configuration at the neighboring center and **71** with (*R*) configuration in high yield[77b] upon treatment with the dimethyl methylphosphonate anion (Scheme 8).

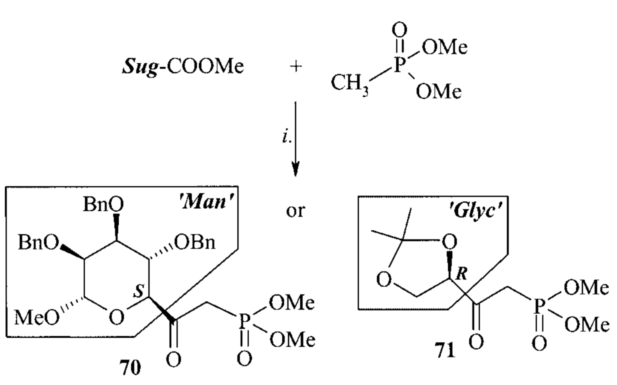
Treatment of D-*xylo*-dienoaldehyde **47** with the phosphonate **70** gave compound **72** with the (1*R*,6*S*) configuration (Scheme 9), while subjection of the phosphonate **71** to the same process gave the bicycle **73** with the opposite configurations at these two stereogenic centers. The same tendency was observed for dienoaldehydes **48** and **49**.[77b] The configuration of these two centers can be changed, although the relative geometry is still *trans* (Scheme 8).[77b] Thus, the desired bicyclo[4.3.0]nonene system is available by judicious choice of the reagents.



Scheme 6. *i*) $Bu_3SnH/AIBN$.



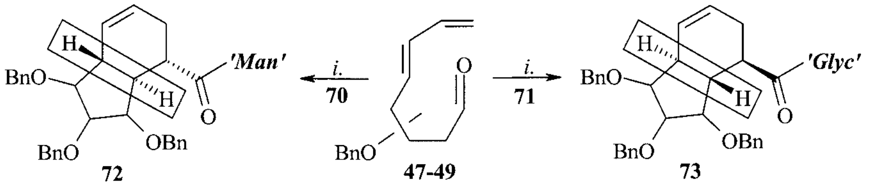
Scheme 7. *i*) $AlCl_3$ (78–85%). *ii*) 15 kbar (ca. 80% yield in each case).



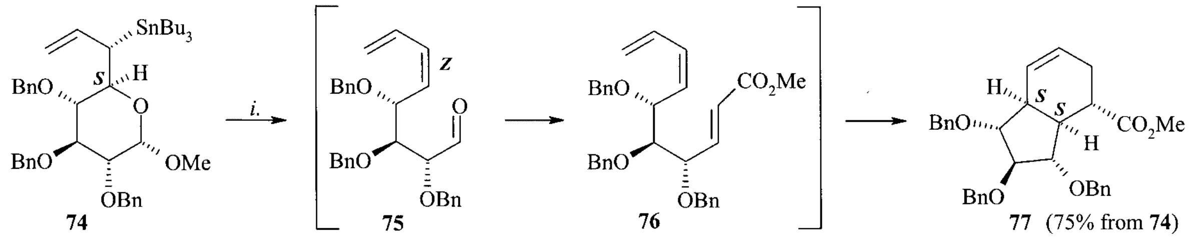
Scheme 8. *i*) BuLi, THF, –78 °C, 80–90%.

The *trans* junction between the rings is the result of the preferred *endo* transition state of the IMDA process. Having the (*Z*)-dienoaldehydes also to hand, we applied these for the preparation of bicycles with relative *cis* configurations between the six- and five-membered rings (Scheme 10).[103]

When secondary D-*gluco*-configured sugar allyltin **74** was thermally decomposed in the presence of the simplest stabilized phosphorane ($Ph_3P{=}CHCO_2Me$), the (*Z*)-dienoaldehyde **75** was formed and converted in situ into the triene **76**, which underwent spontaneous IMDA reaction to form the *cis*-bicycle **77**.[103]



Scheme 9. *i*) Toluene, K_2CO_3, 18-crown-6, room temp.

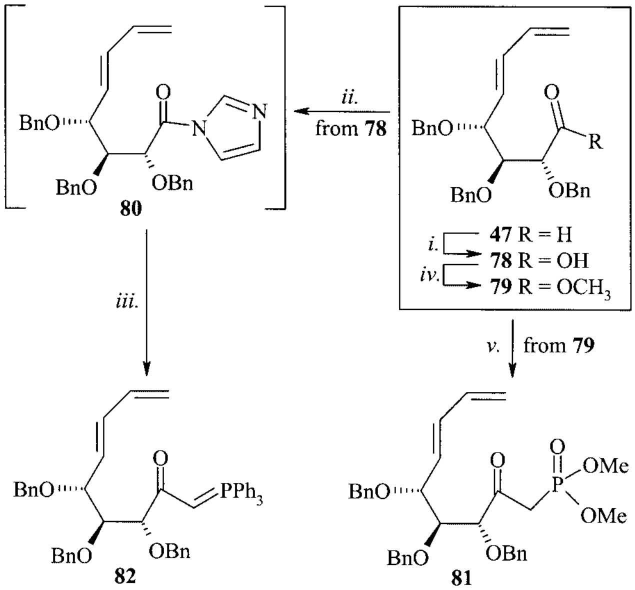


Scheme 10. *i*) Boiling xylene (140 °C), $Ph_3P{=}CHCO_2Me$, 2 h.

5.2.2. Synthesis of Bicyclo[4.4.0]decenes

During the synthesis of higher-carbon sugars we developed the methodology of coupling of two sugar subunits by a Wittig-type methodology. Simple sugars can easily be converted into sugar phosphoranes[72,104] or phosphonates,[73,104] which can be used as olefinating agents to provide the α,β-unsaturated enones in good yields (c.f. Figure 11, Section 4.2).

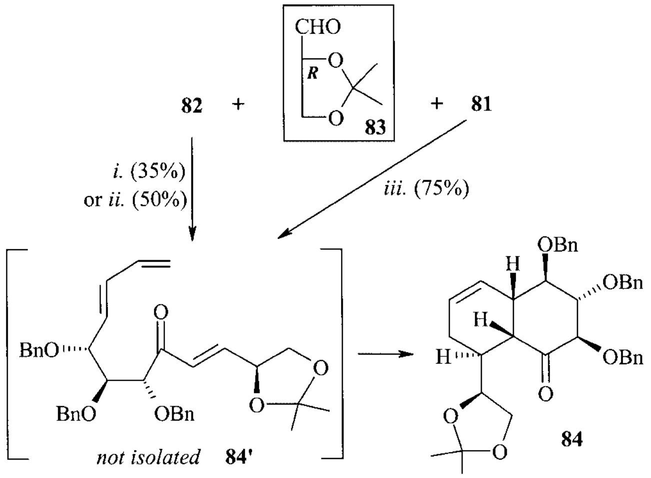
This methodology was applied for conversion of the dienoaldehydes into the corresponding trienes and is presented in Scheme 11 (exemplified by the synthesis of the Wittig-type reagents with the D-*xylo*-configuration from the aldehyde **47**). Aldehyde **47** was oxidized to the acid **78**, which was further transformed into the methyl ester **79**. The synthesis of the Wittig reagent **82** was achieved by conversion of the acid **78** into the imidazolide **80** and its subsequent reaction with 3 equiv. of $Ph_3P{=}CH_2$.[78a] The phosphonate **81** was prepared in much higher yield (86% vs. 55% of the phosphorane) by treatment of the methyl ester **79** with dimethyl methylphosphonate anion.[78b]



Scheme 11. *i*) Jones' oxidation. *ii*) Im$_2$CO, benzene, room temp. 15 min. *iii*) $Ph_3P{=}CH_2$, (3 equiv.), benzene, room temp. 2 h. 55% from **47**. *iv*) CH_2N_2. *v*) MeP(O)(OMe)$_2$, BuLi, THF, 15 min., 86%.

Both Wittig-type reagents were used for the synthesis of the sugar-derived trienes; a model reaction with D-glyceraldehyde derivative **83** is shown in Scheme 12. Ylide **82** was very unreactive, and the process could be conducted only at high temperature (boiling xylene) or under high pressure (10 kbar). The triene **84′** formed under these conditions cyclized in situ to provide the bicyclic derivative **84** as single stereoisomer.[78a]

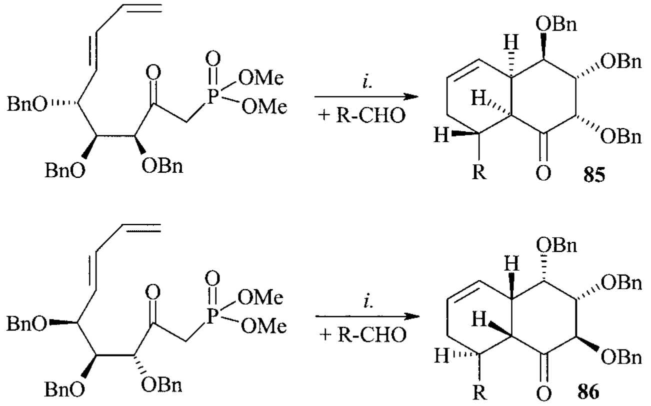
The yield of this tandem reaction was not very impressive, however, varying from 35% (at 140 °C) to 50% (10 kbar). If the rather low yield in the synthesis of phosphorane **82** (55% yield from **47**) is also taken into account, the overall yield of **84** is very low. Much more efficient was the reaction between the phosphonate **81** and aldehyde **83** performed under mild phase-transfer conditions (K_2CO_3/toluene/18-crown-6, room temp.), which afforded the same bicycle **84** in 75% yield (65% overall, calculated on **47**).[78b]



Scheme 12. *i*) Xylene, reflux. *ii*) Toluene, 10 kbar. *iii*) K_2CO_3, 18-crown-6, toluene, room temp.

We also performed a model study on functionalization of the precursor **84**. Stereoselective reduction of the carbonyl group followed by oxidation (epoxidation or *cis*-hydroxylation) of the double bond allowed a number of highly oxygenated derivatives of decalin, also containing nitrogen functionalities in the molecule, to be obtained.[105]

Treatment of the phosphonates (derived from sugar allyltins with the D-*manno* and D-*galacto* configurations) with aldehyde **83** under mild phase-transfer conditions also provided trienes that underwent spontaneous, highly stereoselective cyclization to the corresponding bicyclic derivatives **85** and **86** (Scheme 13).[78b]



Scheme 13. *i*) K_2CO_3, 18-crown-6, toluene, room temp.

The high stereoselectivity of these processes may be explained in terms of the *endo* transition state of the IMDA process, exemplified by the cyclization of the triene **87**[78b] (Figure 24).

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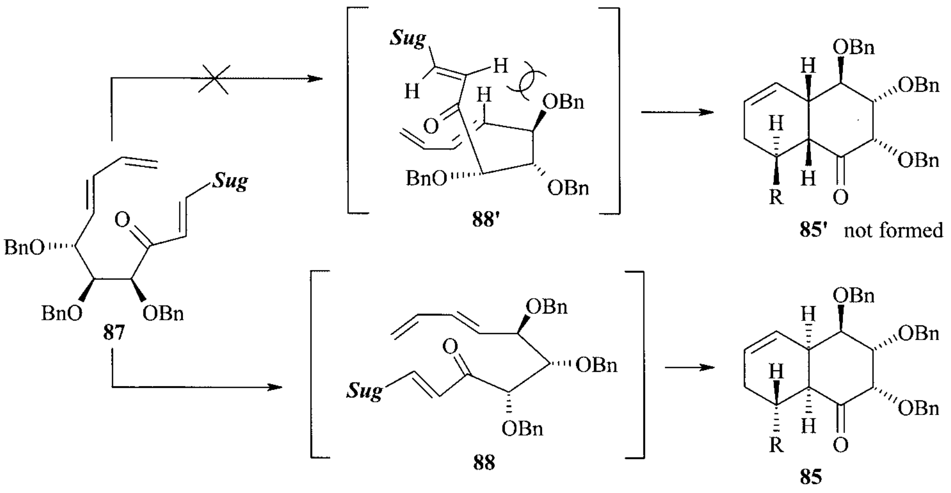

Figure 24. Stereochemical models of cyclization of triene **87**.

6. Conclusion and Perspectives

Sugar allyltins can easily be prepared from simple sugars either by a xanthate methodology or by treatment of appropriately activated sugar allylic derivatives (e.g., mesylates) with tributyltin cuprate. Such sugar organometallics are easily transformed into the dienoaldehydes of defined (*E*) or (*Z*) geometry across the internal double bond. These synthons are further converted – in a highly stereoselective manner – into derivatives of bicyclo [4.3.0]nonene and bicyclo[4.4.0]decene by simple methods (Figure 25).

Such highly functionalized derivatives are useful precursors of fully hydroxylated, enantiomerically pure perhydroindanes and decalins. Alternatively, they may be used for the preparation of monocyclic derivatives such as cyclohexanes and cyclopentanes with various functionalities (see Figure 25). Further work in this field is in progress.

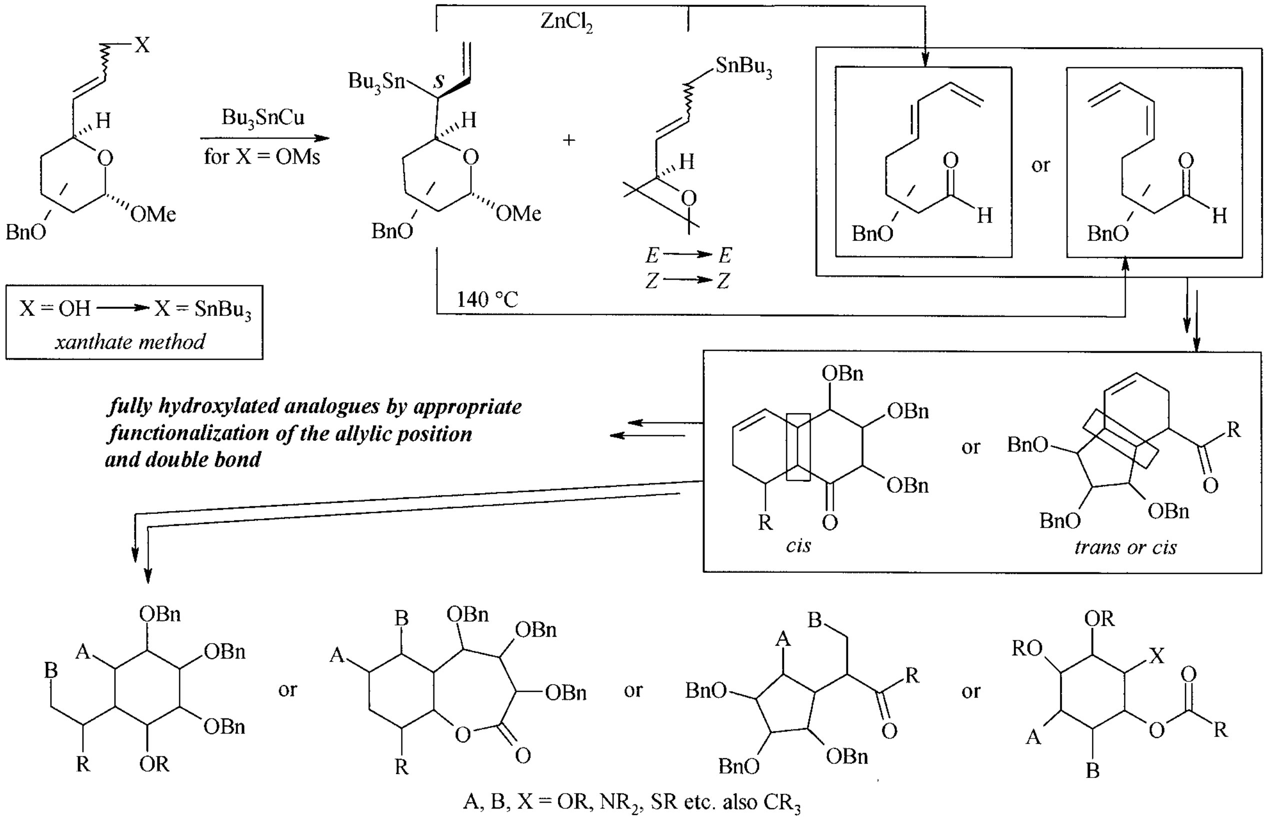

Figure 25. A concise approach to highly oxygenated carbocyclic derivatives from sugar allyltins.

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[1] A. L. Davies, "*Organotin Chemistry*", Wiley-VCH, Weinheim, New York, 2nd completely revised and updated edition, **2004**.

[2] a) H. G. Kuivila, L. W. Menapace, C. R. Warner, *J. Am. Chem. Soc.* **1962**, *84*, 3584–3586; b) H. G. Kuivila, *Adv. Organomet. Chem.* **1964**, *1*, 47.

[3] a) D. H. R. Barton, S. W. McCombie, *J. Chem. Soc., Perkin Trans. 1* **1975**, 1574–1585; b) D. H. R. Barton, W. B. Motherwell, in: *Organic Synthesis Today and Tomorrow* (Eds.: B. M. Trost, C. R. Hutchinson), Pergamon, Oxford, **1981**.

[4] a) M.Pereyre, J.-P. Quintard, A. Rahm, "*Tin in Organic Synthesis*", Butterworth: London, **1987**; b) E. J. Thomas, in: *Houben-Weyl, Methods in Organic Chemistry*, vol. E21, p. 1508.

[5] T. Sato, *Synthesis* **1990**, 259–270.

[6] S. Jarosz, A. Zamojski, *Curr. Org. Chem.* **2003**, *7*, 13–33.

[7] M. Sugawara, J.-i. Yoshida, *J. Org. Chem.* **2000**, *65*, 3135–3142.

[8] a) M. Ochiai, E. Fujita, M. Arimoto, H. Yamaguchi, *Chem. Pharm. Bull.* **1983**, *31*, 86–96; b) M. Ochiai, E. Fujita, M. Arimoto, H. Yamaguchi, *Chem. Pharm. Bull.* **1985**, *33*, 41–47.

[9] M. Gielen, *Acc. Chem. Res.* **1973**, *6*, 198–202.

[10] W. A. Nugent, B. E. Smart, *J. Organomet. Chem.* **1983**, *256*, C9–C11.

[11] a) D. Seyferth, M. A. Weiner, *J. Org. Chem.* **1959**, *24*, 1395–1396; b) D. Seyferth, M. A. Weiner, *J. Org. Chem.* **1961**, *26*, 4797–4800; c) D. Seyferth, T. F. Jula, *J. Organomet. Chem.* **1974**, *66*, 195–207; d) D. Seyferth, R. E. Mammarella, *J. Organomet. Chem.* **1979**, *177*, 53–65.

[12] D. Seyferth, K. R. Wursthorn, R. E. Mammarella, *J. Org. Chem.* **1977**, *42*, 3104–3106.

[13] a) E. J. Enholm, K. M. Moran, P. E. Whitley, *Tetrahedron Lett.* **1998**, *39*, 971–974; b) T. Toru, Y. Yamada, T. Ueno, E. Maekawa, Y. Ueno, *J. Am. Chem. Soc.* **1988**, *110*, 4815–4817 and references cited therein; c) A. Sutherland, J. F. Caplan, J. C. Vederas, *Chem. Commun.* **1999**, 555–556; d) M. P. Sibi, H. Hasegawa, *Org. Lett.* **2002**, *4*, 3347–3349.

[14] L. Chabaud, P. James, Y. Landais, *Eur. J. Org. Chem.* **2004**, 3173–3199 and references cited therein.

[15] a) M. Kosugi, K. Kurino, K. Takayama, T. Migita, *J. Organomet. Chem.* **1973**, *56*, C11–C16; b) G. E. Keck, J. B. Yates, *J. Am. Chem. Soc.* **1982**, *104*, 5829–5831; c) T. Migita, K. Nagai, M. Kosugi, *Bull. Chem. Soc. Jpn.* **1983**, *56*, 2480–2484.

[16] a) J. A. Verdone, J. A. Mangravite, N. M. Scarpa, H. G. Kuivila, *J. Am. Chem. Soc.* **1975**, *97*, 843; b) B. M. Trost, E. Keinan, *Tetrahedron Lett.* **1980**, *21*, 2595; c) V. J. Jephcote, E. J. Thomas, *Tetrahedron Lett.* **1985**, *26*, 5327; d) I. Fleming, M. Rowley, *J. Chem. Soc., Perkin Trans. 1* **1987**, 2259–2264.

[17] a) J. P. Quintard, B. Elissondo, M. Pereyre, *J. Org. Chem.* **1983**, *48*, 1559–1560; b) Y. Naruta, K. Maruyama, *J. Chem. Soc., Chem. Commun.* **1983**, 1264–1265.

[18] J. A. Marshall, D. V. Yashunsky, *J. Org. Chem.* **1991**, *56*, 5493–5495.

[19] a) A. J. Pratt, E. J. Thomas, *J. Chem. Soc., Chem. Commun.* **1982**, 1115–1117; b) A. J. Pratt, E. J. Thomas, *J. Chem. Soc., Perkin Trans. 1* **1989**, 1521–1527.

[20] a) J. A. Marshall, W. Y. Gung, *Tetrahedron* **1989**, *45*, 1043; b) B. W. Gung, A. J. Peat, B. M. Snook, D. T. Smith, *Tetrahedron Lett.* **1991**, *32*, 453; c) B. W. Gung, *Tetrahedron Lett.* **1991**, *32*, 2861.

[21] S. J. Hannon, T. G. Traylor, *J. Chem. Soc., Chem. Commun.* **1975**, 630–631.

[22] O. A. Moreno, Y. Kishi, *Bioorg. Med. Chem.* **1998**, *6*, 1243–1254.

[23] E. W. Abel, R. J. Rowley, *J. Organomet. Chem.* **1975**, *84*, 199–229.

[24] J. Grignon, C. Servens, M. Pereyre, *J. Organomet. Chem.* **1975**, *96*, 225–235.

[25] a) E. Matarasso-Tchiroukhine, P. Cadiot, *J. Organomet. Chem.* **1976**, *121*, 155–168; b) G. Duumartin, J. P. Quintard, M. Pereyre, *J. Organomet. Chem.* **1980**, *185*, C34–C36; c) G. E. Keck, S. D. Tonnies, *Tetrahedron Lett.* **1993**, *29*, 4607–4610; d) M. Koreeda, Y. Tanaka, *Chem. Lett.* **1982**, 1297–1298.

[26] S. Weigand, R. Bruckner, *Synthesis* **1996**, 475–482.

[27] B. H. Lipshutz, E. L. Ellsworth, S. H. Dimock, D. C. Reuter, *Tetrahedron Lett.* **1989**, *30*, 2065.

[28] J. M. Cuerva, E. Gomez-Bengoa, M. Mendez, A. M. Echavarren, *J. Org. Chem.* **1997**, *62*, 7540–7541.

[29] a) B. M. Trost, J. W. Herndon, *J. Am. Chem. Soc.* **1984**, *106*, 6835–6839; b) T. Tabuchi, J. Inanaga, M. Yamaguchi, *Tetrahedron Lett.* **1987**, *28*, 215; c) S. Matsubara, K. Wakamatsu, J. Marizawa, N. Tsuboniwa, K. Oshima, H. Nozaki, *Bull. Chem. Soc. Jpn.* **1985**, *58*, 1196; d) E. Winter, R. Bruckner, *Synlett* **1994**, 1049–1053; e) G. Naruta, K. Maruyama, *Chem. Lett.* **1979**, 881.

[30] a) M. Andrianome, K. Häberle, D. Delmond, *Tetrahedron* **1989**, *45*, 1079–1088; b) M. Gruttadauria, E. J. Thomas, *J. Chem. Soc., Perkin Trans. 1* **1995**, 1469–1471; c) Y. Yamamoto, K. Kobayashi, H. Okano, I. Kadota, *J. Org. Chem.* **1992**, *57*, 7003–7005.

[31] a) I. Kadota, A. Ohno, Y. Matsukawa, Y. Yamamoto, *Tetrahedron Lett.* **1998**, *39*, 6373–6396; b) I. Kadota, C. Kadowaki, N. Yoshida, Y. Yamamoto, *Tetrahedron Lett.* **1998**, *39*, 6369–6372.

[32] a) Y. Ueno, M. Okawara, *J. Am. Chem. Soc.* **1979**, *101*, 1893; b) Y. Ueno, H. Sano, M. Okawara, *Synthesis* **1980**, 1011.

[33] a) Y. Ueno, M. Ohta, M. Okawara, *J. Organomet. Chem.* **1980**, *197*, C1–C4; b) J. E. Baldwin, R. M. Adlington, D. J. Birch, J. A. Crawford, J. B. Sweeney, *J. Chem. Soc., Chem. Commun.* **1986**, 1339–1340.

[34] a) G. E. Keck, A. Palani, S. F. McHardy, *J. Org. Chem.* **1994**, *59*, 3113–3122; b) G. E. Keck, E. N. K. Cressman, E. J. Enholm, *J. Org. Chem.* **1989**, *54*, 4345–4349; c) Y. Ueno, H. Sano, S. Aoki, M. Okawara, *Tetrahedron Lett.* **1981**, *22*, 2675–2678; d) G. E. Keck, E. J. Enholm, *Tetrahedron Lett.* **1985**, *26*, 331–334.

[35] a) Y. Ichinose, K. Oshima, K. Utimoto, *Bull. Chem. Soc. Jpn.* **1988**, *61*, 2693; b) A. Barbero, P. Cuadrado, I. Fleming, A. M. Gonzales, F. J. Pulido, *J. Chem. Soc., Perkin Trans. 1* **1992**, 327–331; c) V. Gevorgyan, J. X. Liu, Y. Yamamoto, *J. Org. Chem.* **1997**, *62*, 2963–2967.

[36] M. Jeganmohan, M. Shanmugasundaram, K. J. Chang, C. H. Cheng, *Chem. Commun.* **2002**, 2552–2553.

[37] H. Miyake, K. Yamamura, *Chemistry Lett.* **1992**, 507–508.

[38] J. I. Yoshida, H. Funahashi, H. Iwasaki, N. Kawabata, *Tetrahedron Lett.* **1986**, *27*, 4409–4412.

[39] a) Y. Yamamoto, H. Yatagi, Y. Ishihara, N. Maeda, K. Maruyama, *Tetrahedron* **1984**, *40*, 2239; b) Y. Yamamoto, *Acc. Chem. Res.* **1987**, *20*, 243–249; c) Y. Yamamoto, N. Asao, *Chem. Rev.* **1993**, *93*, 2207–2293; d) S.-i. Sumida, M. Ohga, J. Mitani, J. Nokami, *J. Am. Chem. Soc.* **2000**, *122*, 1310–1313.

[40] S. Jarosz, E. Kozłowska, *Polish J. Chem.* **1998**, *72*, 815–831.

[41] S. V. Mortlock, E. J. Thomas, *Tetrahedron Lett.* **1988**, *29*, 2479.

[42] E. Kozłowska, S. Jarosz, *J. Carbohydr. Chem.* **1994**, *13*, 889–890.

[43] S. Jarosz, *Tetrahedron* **1997**, *53*, 10765–10774.

[44] S. Jarosz, S. Skóra, K. Szewczyk, *Tetrahedron: Asymmetry* **2000**, *11*, 1997–2006.

[45] C. H. W. Jones, R. G. Jones, P. Parington, R. M. G. Roberts, *J. Organomet. Chem.* **1971**, *32*, 201–212.

[46] S. Jarosz, K. Szewczyk, A. Zawisza, *Tetrahedron: Asymmetry* **2003**, *14*, 1715–1723.

[47] S. Jarosz, K. Szewczyk, A. Zawisza, *Polish J. Chem.* **2003**, *77*, 985–994.

[48] J. A. Marshall, L. M. Elliott, *J. Org. Chem.* **1996**, *61*, 4611–4616.

[49] G. E. Keck, M. Park, D. Krishnamurthy, *J. Org. Chem.* **1993**, *58*, 3787–3788.

[50] M. K. Sibi, J. Chen, T. R. Rheault, *Org. Lett.* **2001**, *3*, 3679–3681.

[51] a) W. R. Roush, in: C*omprehensive Organic Synthesis*, vol. 2 (Ed.: C. H. Heathcock), Pergamon, **1991**, p. 1.

[52] C. Servens, M. Pereyre, *J. Organomet. Chem.* **1972**, *35*, C20–C22.

[53] S. E. Denmark, E. J. Weber, T. M. Wilson, T. Wilson, *Tetrahedron* **1989**, *45*, 1053.

[54] a) G. E. Keck, M. B. Andrus, S. J. Castellino, *J. Am. Chem. Soc.* **1989**, *111*, 8136–8141; b) S. E. Denmark, T. Wilson, T. M. Wilson, *J. Am. Chem. Soc.* **1988**, *110*, 984–986; c) G. E. Keck, D. E. Abbott, E. P. Boden, E. J. Enholm, *Tetrahedron Lett.* **1984**, *25*, 3927; d) A. Boaretto, D. Marton, G. Tagliavini, *J. Organomet. Chem.* **1987**, *321*, 199–207.

[55] Y. Yamamoto, K. Maruyama, K. Matsumoto, *J. Chem. Soc., Chem. Commun.* **1983**, 489–490.

[56] Y. Yamamoto, H. Yatagai, Y. Naruta, K. Maruyama, *J. Am. Chem. Soc.* **1980**, *102*, 7107–7109.

[57] a) I. Suzuki, Y. Yamamoto, *J. Org. Chem.* **1993**, *58*, 4783–4784; b) G. E. Keck, E. P. Boden, *Tetrahedron Lett.* **1984**, *25*, 265.

[58] S.-i. Kiyooka, K. Suzuki, M. Shirouchi, Y. Kaneko, S. Tanimori, *Tetrahedron Lett.* **1993**, *34*, 5729–5732.

[59] Y. Nishigaichi, A. Takuwa, *Chem. Lett.* **1994**, 1429–1432.

[60] A. H. McNeill, E. J. Thomas, *Synthesis* **1994**, 322–334 and references cited therein.

[61] T. Kawashima, N. Iwama, R. Okazaki, *J. Am. Chem. Soc.* **1993**, *115*, 2507–2508.

[62] S. S. Stanway, E. J. Thomas, *J. Chem. Soc., Chem. Commun.* **1994**, 285–286.

[63] S. Donnelly, E. J. Thomas, E. A. Arnott, *Chem. Commun.* **2003**, 1460–1461.

[64] a) R. Beddoes, L. A. Hobson, E. Thomas, *Chem. Commun.* **1997**, 1929–1930; b) L. A. Hobson, M. A. Vincent, E. J. Thomas, I. A. Hiller, *Chem. Commun.* **1998**, 899–900.

[65] E. J. Thomas, *Chem. Commun.* **1997**, 411–417.

[66] E. M. Moffat, E. J. Thomas, *Tetrahedron* **1999**, *55*, 3723–3734 and references cited therein.

[67] K. E. Dorling, E. J. Thomas, *Tetrahedron Lett.* **1999**, *40*, 471–474.

[68] O. Germany, N. Kumar, E. J. Thomas, *Tetrahedron Lett.* **2001**, *42*, 4969–4974.

[69] D. J. Hallet, E. J. Thomas, *J. Chem. Soc., Chem. Commun.* **1995**, 657–658.

[70] a) Z. Gyorgydeak, I. Pelyvas, *Monosaccharide sugars: chemical synthesis by chain elongation, degradation and epimerization*, Academic Press, **1998** ; this book covers the literature up to **1997**; b) M. Joergensen, E. H. Iversen, R. Madsen, *J. Org. Chem.* **2001**, *66*, 4625–4629; c) G. V. M. Sharma, P. R. Krishna, *Curr. Org. Chem.* **2004**, *8*, 1187–1209 and references cited therein.

[71] S. Jarosz, *J. Carbohydr. Chem.* **2001**, *20*, 93–107 and references cited therein.

[72] a) S. Jarosz, D. R. Mootoo, B. Fraser-Reid, *Carbohydr. Res.* **1986**, *147*, 59–68; b) S. Jarosz, *Carbohydr. Res.* **1987**, *167*, 211–217; c) S. Jarosz, *Carbohydr. Res.* **1988**, *183*, 201–207; d) S. Jarosz, *Carbohydr. Res.* **1992**, *224*, 73–81; e) S. Jarosz, *J. Carbohydr. Chem.* **1993**, *12*, 1149–1160.

[73] a) S. Jarosz, P. Sałański, M. Mach, *Tetrahedron* **1998**, *54*, 2583–2594; b) S. Jarosz, M. Mach, *J. Chem. Soc., Perkin Trans. 1* **1998**, 3943–3948 and references cited therein.

[74] S. Jarosz, *Tetrahedron Lett.* **1988**, *29*, 1193–1197.

[75] S. Jarosz, S. Skóra, K. Szewczyk, Z. Ciunik, *Tetrahedron: Asymmetry* **2001**, *12*, 1895–1905.

[76] S. Jarosz, B. Fraser-Reid, *J. Org. Chem.* **1989**, *54*, 4011–4013.

[77] a) S. Jarosz, E. Kozłowska, A. Jeżewski, *Tetrahedron* **1997**, *53*, 10775–10782; b) S. Jarosz, S. Skóra, *Tetrahedron: Asymmetry* **2000**, *11*, 1425–1432.

[78] a) S. Jarosz, *J. Chem. Soc., Perkin Trans. 1* **1997**, 3579–3580; b) S. Jarosz, S. Skóra, *Tetrahedron: Asymmetry* **2000**, *11*, 1433–1448.

[79] S. Jarosz, K. Szewczyk, J. Sitkowski, A. Gaweł, *Tetrahedron: Asymmetry* **2004**, *15*, 2653–2656.

[80] a) Y. Nishigaichi, A. Takuwa, *Tetrahedron Lett.* **2002**, *43*, 3045–3047; b) Y. Nishigaichi, A. Takuwa, *Tetrahedron Lett.* **2003**, *44*, 1405–1408.

[81] a) S. Saito, Y. Morikawa, T. Moriwake, *J. Org. Chem.* **1990**, *55*, 5424–5426; b) B. W. Gung, J. P. Melnick, M. A. Wolf, J. A. Marshall, S. Beaudoin, *J. Org. Chem.* **1994**, *59*, 5609–5613.

[82] J. A. Marshall, *Chem. Rev.* **1996**, *96*, 31–48.

[83] N. Ikemoto, S. L. Schreiber, *J. Am. Chem. Soc.* **1992**, *114*, 2524–2536.

[84] J. K. Cha, W. J. Christ, Y. Kishi, *Tetrahedron* **1984**, *40*, 2247.

[85] K. Burgess, D. A. Chaplin, *Tetrahedron Lett.* **1992**, *33*, 6077–6080.

[86] G. E. Keck, E. J. Enholm, D. F. Kachensky, *Tetrahedron Lett.* **1984**, *25*, 1867.

[87] S. Jarosz, K. Szewczyk, *Tetrahedron Lett.* **2001**, *42*, 3021–3024.

[88] a) B. P. Roberts, T. M. Smits, *Tetrahedron Lett.* **2001**, *42*, 137–140; b) E. S. Huyser, Z. Garcia, *J. Org. Chem.* **1962**, *27*, 2716–2719.

[89] A. Krief, L. Provins, W. Dumont, *Angew. Chem. Int. Ed.* **1999**, *38*, 1946–1948.

[90] a) B. Jousseaume, N. Noiret, M. Pereyre, J. M. Frances, *J. Chem. Soc., Chem. Commun.* **1992**, 739–740; b) B. Ousseaume, N. Noiret, M. Pereyre, *Organometallics* **1992**, *11*, 3910–3914.

[91] J. M. Brown, B. C. Chapman, R. Harper, D. J. Mowthorpe, A. G. Davies, P. J. Smith, *J. Chem. Soc., Dalton Trans.* **1972**, 338.

[92] A. G. Davies, W. R. Symes, W. Ramsay, R. Foster, *J. Chem. Soc., C* **1967**, 1009–1016.

[93] L. E. Brammer, T. Hudlicky, *Tetrahedron: Asymmetry* **1998**, *9*, 2011–2014 and references cited therein.

[94] T. Suami, S. Ogawa, *Adv. Carbohydr. Chem. Biochem.* **1990**, *48*, 22.

[95] a) G. Mehta, S. S. Ramesh, *Chem. Commun.* **2000**, 2429–2430; b) G. Mehta, S. S. Ramesh, *Tetrahedron Lett.* **2001**, *42*, 1987–1990.

[96] a) S. Hanessian, *Total Synthesis of Natural Products: The Chiron Approach*, Pergamon Press, New York, **1983**; b) B. Fraser-Reid, *Acc. Chem. Res.* **1996**, *29*, 57–66 and references cited therein.

[97] a) U. Pindur, G. Lutz, C. Otto, *Chem. Rev.* **1993**, *93*, 741–761; b) W. R. Roush, K. Koyama, M. L. Curtin, K. J. Moriarty, *J. Am. Chem. Soc.* **1996**, *118*, 7502–7512; c) J. Shiina, S. Nishiyama, *Tetrahedron* **2003**, *59*, 6039–6044.

[98] P. Herczegh, M. Zsely, L. Szilagyi, I. Bajza, A. Kovacs, G. Batta, R. Bognar, *Cycloaddition Reactions in Organic Chemistry* 112–130 (ACS Symposium Series *494*, R. M. Guiliano, Edition **1992**) and references cited therein.

[99] M. Mendez, A. M. Echevarren, *Eur. J. Org. Chem.* **2002**, 15–28.

[100] A. M. Gomez, G. O. Danelon, S. Valverde, J. C. Lopez, *J. Org. Chem.* **1998**, *63*, 9626–9627 and references cited therein.

[101] M. Mach, S. Jarosz, *Polish J. Chem.* **1997**, *71*, 936–940.

[102] S. Jarosz, B. Boryczko, P. Cmoch, A. M. Gomez, C. Lopez, *Tetrahedron: Asymmetry* **2005**, *16*, 513–518.

[103] S. Jarosz, K. Szewczyk, A. Zawisza, *Tetrahedron: Asymmetry* **2003**, *14*, 1709–1713.

[104] S. Jarosz, *Tetrahedron Lett.* **1994**, *35*, 7655–7658.

[105] S. Jarosz, S. Skóra, *Tetrahedron: Asymmetry* **2001**, *12*, 1651–1656.

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