JOC The Journal of Organic Chemistry

ARTICLE

pubs.acs.org/joc

A Modular Approach to Aryl-*C*-ribonucleosides via the Allylic Substitution and Ring-Closing Metathesis Sequence. A Stereocontrolled Synthesis of All Four α-/β- and D-/L-*C*-Nucleoside Stereoisomers†

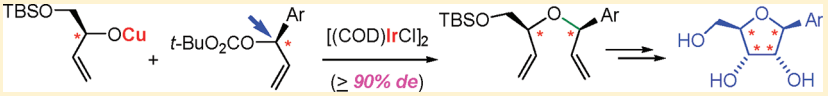
Jan Štambaský,[‡,¶] Vojtěch Kapras,[‡,§] Martin Štefko,[⊥] Ondřej Kysilka,[‡] Michal Hocek,*[,⊥] Andrei V. Malkov,*[,‡,▽] and Pavel Kočovský*[,‡]

[‡]Department of Chemistry, WestChem, University of Glasgow, Glasgow G12 8QQ, Scotland, U.K.

[⊥]Institute of Organic Chemistry and Biochemistry, Gilead Sciences & IOCB Research Center, Academy of Sciences of the Czech Republic, CZ-16610, Prague 6, Czech Republic

Supporting Information

ABSTRACT:



Iridium(I)-catalyzed allylation of the enantiopure monoprotected copper(I) alkoxide, generated from (*S*)-**5a**, with the enantiopure allylic carbonates (*R*)-**9a**,**b** has been developed as the key step in a new approach to *C*-nucleoside analogues. The anomeric center was thus constructed via a stereocontrolled formation of the C−O rather than C−C bond with retention of configuration. The resulting bisallyl ethers **15a**,**b** (≥90% de and >99% ee) were converted into *C*-ribosides **29a**,**b** via the Ru-catalyzed ring-closing metathesis, followed by a diastereoselective dihydroxylation catalyzed by OsO_4 or RuO_4 and deprotection. Variation of the absolute configuration of the starting segments **5a** and **9a**,**b** allowed a stereocontrolled synthesis of all four α/β-D/L-combinations.

INTRODUCTION

Aryl-*C*-nucleosides attract a great deal of attention as cornerstones in the pursuit of extension of the genetic alphabet.[1] These aromatic derivatives form pairs selectively with the same or other hydrophobic nucleobases in oligonucleotide duplexes as a result of an increased propensity to π-stacking and favorable desolvation energy (as compared to canonical hydrophilic nucleobases).[2] Triphosphates of some of the *C*-nucleosides have been efficiently incorporated into DNA by DNA polymerase.[3] Recently, an artificial base-pair, consisting of 2-methoxy-4-methylphenyl *C*-nucleoside and thioisocarbostyril base, has been reported[4] to be selectively replicated and the growing DNA chain was efficiently extended, which previously constituted a serious problem with the existing artificial base pairs. This new generation of base-pairs was recently successful even in the PCR amplification.[4c] Therefore, it would be highly desirable to build on these promising results and expand the portfolio of artificial base-pairs, from which new, efficient combinations can be expected to emerge. However, this program will require development of a robust modular methodology that would allow the synthesis of libraries of new *C*-nucleoside derivatives.

There are several synthetic approaches[5] to *C*-nucleosides: (1) addition of organometallics to a ribono- or 2-deoxyribonolactone;[3,6] (2) coupling of a halogenose with organometallics;[7] (3) electrophilic, Lewis acid-catalyzed substitution of electron-rich aromatics with a carbohydrate;[8] (4) Heck-type coupling of aryl iodides with a glycal;[9] and (5) opening of glycal-derived epoxides (anhydrosugars) with organometallics.[10] However, none of these methods is truly general, and many of them suffer from poor stereoselectivity, low yields, or lability of the starting materials. We are currently involved in the development of modular methodologies allowing a generation of a series of diverse derivatives. Thus, we have recently developed modular syntheses of substituted phenyl,[11] pyridyl and pyrimidyl,[12] and thienyl[13] *C*-nucleosides. This methodology was based on the preparation of halogenated aryl *C*-nucleoside intermediates and subsequent displacement of the halogen with alkyl, aryl, or amino substituents by cross-coupling reactions. However, even in this approach, the C-glycosidation step represents a bottleneck in the whole synthesis in terms of efficiency and anomeric selectivity. Therefore, our next goal was to develop a new general strategy for the construction of aryl-*C*-nucleosides in all stereochemical combinations at will (D and L series, as well as α- and β-anomers) by stereoselective and/or stereoconserved synthesis starting from simple chiral building blocks available in both enantiomeric forms. Herein, we report on a modular stereocontrolled synthesis of all four 1,4-stereoisomeric aryl-*C*-nucleosides via building-up the carbohydrate moiety by a stereospecific iridium-catalyzed allylic substitution reaction of the enantiopure arylpropenyl carbonates with

Received: June 3, 2011
Published: August 12, 2011

enantiopure allylic alcohols as O-nucleophiles, followed by ring-closing metathesis (RCM) and dihydroxylation.

RESULTS AND DISCUSSION

As discussed in the previous paragraph, the methodology available for the synthesis of *C*-nucleosides is generally confined to those approaches that rely on the construction of the C−C bond at the anomeric center of a suitable carbohydrate derivative (**A** in Chart 1).[5] We envisaged that a stereocontrolled formation of the endocyclic C−O bond (**B** or **C**) could serve as an attractive alternative that may eliminate some of the deficiencies in the existing synthetic arsenal and open a new avenue toward these important targets.

We reasoned that transition metal-catalyzed allylic substitution with an appropriate O-nucleophile could serve as a perfect tool for the stereo- and regiocontrolled construction of one of the C−O bonds (Scheme 1) to generate the bisallyl ether **G**. Subsequent cyclization of the latter intermediate via ring-closing metathesis would then provide the dihydrofuran derivative **H**, whose dihydroxylation would produce the desired *C*-riboside.

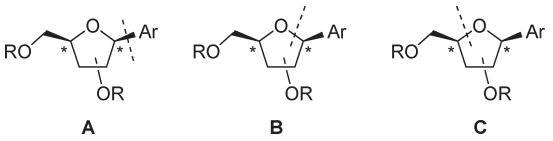
Four approaches to the key intermediate **G** can be considered: thus, alkoxide **D**, generated from the monoprotected enantiopure 3-butene-1,2-diol, can be expected to react with the nonchiral allylic substrate **E** (pathway a) or its enantiopure isomer **F** (pathway b). Alternatively, the enantiopure allylic alkoxide **J** could be utilized as a nucleophile in the reaction with the allylic substrate **I** or **K** (pathways c and d). In this scheme, pathways a and c would require the use of one enantiopure reactant each and a chiral catalyst, whereas pathways b and d would make use of two enantiopure reactants each and a nonchiral metal catalyst.

All the required types of starting materials are, a priori, readily available: thus, the enantiopure 3-butene-1,2-diol, as a precursor of the monoprotected alkoxide **D** and of carbonate **K**, is commercially available in both enantiomeric forms (from butadiene), whereas the nonchiral, monoprotected allylic substrate **I** can be obtained from the commercially available 2-butene-1,4-diol. The nonchiral cinnamyl-type substrates **E** are a textbook target for the Wittig-type methodology and can also be prepared by the methods recently developed by us that are based on either Suzuki−Miyaura coupling or cross-metathesis.[14] Finally, a very efficient synthesis of several enantiopure carbonates **F** and the corresponding alcohols (as precursors of alkoxides **J**), which hinges on an enzymatic resolution of the corresponding 1-arylprop-2-en-1-ols, has recently been developed by us.[15]

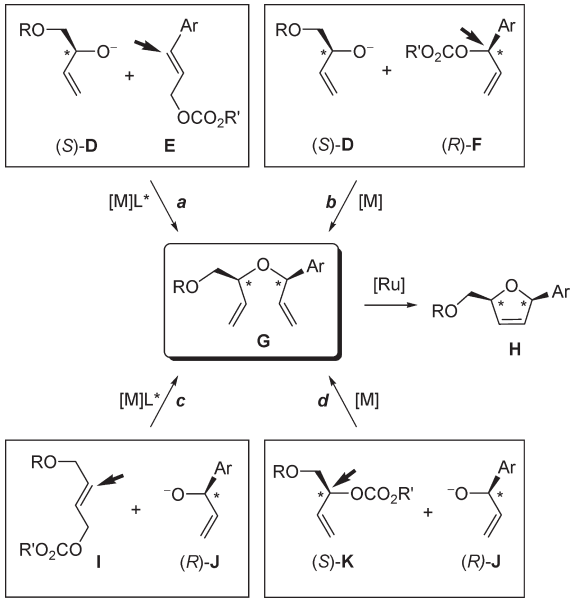
Transition metal-catalyzed allylic substitution (Scheme 2) is known to proceed via the corresponding π-allyl complexes in a stereo- and regiocontrolled manner.[16] Nonsymmetrically substituted complexes, such as **2**, which can be generated either from the linear esters **1** or from their branched isomers **3**,[17] are inherently chiral. Therefore, an enantioselective reaction starting with **1** requires the use of a chiral catalyst (with a chiral ligand L*),[18] whereas a nonchiral catalyst is sufficient when the enantiopure branched isomer **3** is used.[16,19−21] While both allylic esters and carbonates have been frequently employed as substrates, in some instances the *tert*-butyl carbonyl leaving group [R^2 = O(*t*-Bu)] is required for the catalytic substitution reaction to occur efficiently (vide infra).

Regioselectivity of the nucleophilic attack by nucleophiles at the nonsymmetrically substituted η^3-complexes is mainly governed by the nature of the metal. Thus, Pd complexes are preferentially attacked at the less substituted terminus,[16,17,22,23]

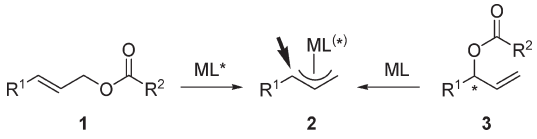
Chart 1. Strategic Bond Disconnection



Scheme 1. Retrosynthetic Analysis



Scheme 2. Transition Metal-Catalyzed Asymmetric Allylic Substitution

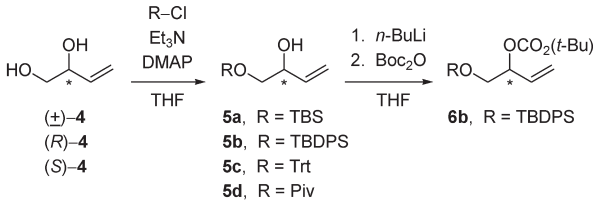


whereas Mo,[24] W,[25,26] Ru,[27] Rh,[28] and Ir[29−31] exhibit the opposite tendency, affording the branched isomer as the major product. However, in the Rh-catalyzed reactions with symmetrical substrates, the nucleophile enters at the site to which the leaving group was originally attached.[28b] Finally, Fe[32] complexes are preferentially attacked by nucleophiles at the leaving group site with retention of configuration. Of this portfolio of transition metal catalysts, Ir and Rh appear to be particularly suitable for the construction of the C−O (and C−N) bonds, whereas other metal catalysts have proven to be less successful here and are mainly used in the realm of C−C bond formation. Therefore, we focused on these two metals in the present study.

Synthesis of Protected Butenediols. One of the main advantages of our new strategy toward *C*-nucleosides is the opportunity to employ a common building block for the nucleophilic partner in the allylic substitution reaction. 3-Butene-1,2-diol (**4**), commercially available in both enantiomeric forms, was selected as a starting material (Scheme 3), bearing in mind that, if used as a

dx.doi.org/10.1021/jo201110z |*J. Org. Chem.* 2011, 76, 7781–7803

Scheme 3. Synthesis of the Protected Butenediols 5a−d



Yields: (±)-**5a** (81%); (±)-**5b** (95%); (±)-**5c** (88%); (±)-**5d** (53%); (*R*)-**5a** (80%); (*S*)-**5a** (80%); (*R*)-**5b** (88%); (*S*)-**5b** (86%)

nucleophile (pathways a and b in Scheme 1), (*S*)-**4** would produce the natural D-*C*-nucleosides, whereas (*R*)-**4** would give rise to their non-natural L-enantiomers. The chemistry to be involved required protection of the latter diol at the primary hydroxyl, leaving free the secondary hydroxyl function. Various protecting groups were investigated,[33] and racemic diol **4** was first employed to optimize the protecting group and reaction conditions. The protecting groups were selected with a view of attaining the highest selectivity toward the primary hydroxyl, also bearing in mind their behavior in the subsequent reactions. Four protecting groups were explored, namely *tert*-butyldimethylsilyl (TBS), *tert*-butyldiphenylsilyl (TBDPS), triphenylmethyl (Trt), and pivaloyl (Piv). Diol **4** was treated with the respective derivatizing agent R-Cl (neat, or 2 M solution in the case of solids) in the presence of Et_3N (4−5 equiv) and 4-(dimethylamino)pyridine (DMAP, 10 mol %) in an appropriate solvent at room temperature for 24 h: THF was used for the alkylchlorosilanes, whereas dichloromethane was found to be the solvent of choice for the trityl and pivaloyl chlorides. The isolated yields of the monoprotected products, shown in Scheme 3, reflect the selectivity of the individual reactions. Later, during the course of the investigation of the metal-catalyzed allylic substitution and the subsequent transformations, the *tert*-butyldimethylsilyl and, to some extent, *tert*-butyldiphenylsilyl group, were identified as an optimum (vide infra). Protection of the enantiopure diol (*R*)-**4** and (*S*)-**4** (both ≥99% ee) proceeded in a similar way without any loss of enantiopurity. The monoprotected diols (±)-**5b** and (*R*)-**5b** were converted into the corresponding *tert*-butyl carbonates (±)-**6b** (94%) and (*R*)-**6b** (95%, ≥99% ee) by using our protocol,[14,15] involving deprotonation of the free hydroxyl with *n*-BuLi at 0 °C, followed by treatment with Boc anhydride at room temperature. Under these conditions, the possible migration of the protecting group from the primary to the secondary hydroxyl was minimized.

Synthesis of Cinnamyl- and Isocinnamyl-Type *tert*-Butyl Carbonates. Hartwig has found allylic carbonates, in particular *tert*-butyl carbonates, to be superior to esters as substrates for the Ir-catalyzed allylic substitution.[29] The synthesis of a series of cinnamyl-type carbonates was reported by us in another paper,[14] in which we compared three approaches: (1) the Wittig−Horner-Emmons olefination of aldehydes ArCHO to produce the corresponding α,β-unsaturated esters $ArCH{=}CHCO_2Et$, followed by reduction with DIBAL-H and conversion of the resulting allylic alcohols $ArCH{=}CHCH_2OH$ into the desired carbonates upon reaction with *n*-BuLi and Boc_2O; (2) Suzuki−Miyaura coupling of aryl iodides ArI with *trans*-vinyl pinacolboronate $(RO)_2BCH{=}CHCH_2OCO_2(t\text{-Bu})$, which in turn was obtained by hydroboration of propargyl carbonate $HC{\equiv}CCH_2OCO_2(t\text{-Bu})$ with pinacolborane; (3) cross metathesis of vinyl aromatics $ArCH{=}CH_2$ with the Boc-protected allyl alcohol $CH_2{=}CHCH_2OCO_2(t\text{-Bu})$, catalyzed by the Grubbs second-generation complex.[14] Of this series, only the phenyl derivative **7** was used as a model compound in the present investigation (Chart 2).

Chart 2. Allylic Derivatives

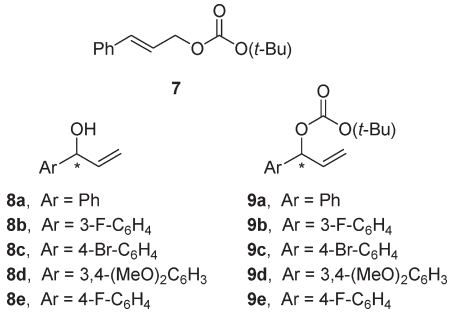
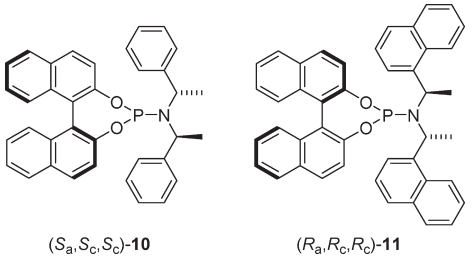


Chart 3. Phosphoramidite Ligands



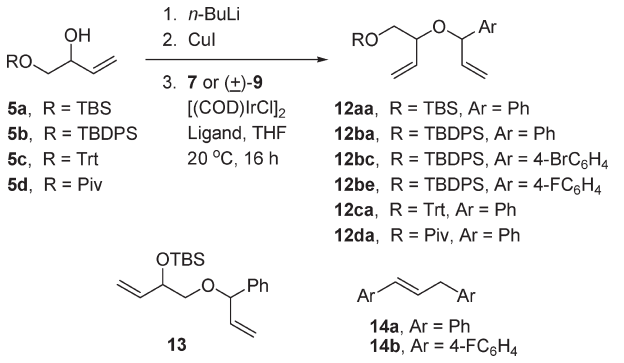
Racemic isocinnamyl-type alcohols **8a−e** (Chart 2) were prepared via addition of vinylmagnesium bromide to the corresponding aldehydes ArCHO.[15] Their optimized resolution by using an enantioselective acetylation with isopropenyl acetate, catalyzed by Novozyme 435, afforded both enantiomeric series in ≥99% ee.[15] Conversion of the latter alcohols into the Boc derivatives **9a−e** was carried out under optimized conditions, involving deprotonation with *n*-BuLi in THF, followed by treatment with Boc anhydride at room temperature for 3 h;[15,34,35] this protocol was found to minimize side reactions, in particular the allylic rearrangement.[15]

Iridium-Catalyzed Allylic Substitution with Oxygen Nucleophiles. Rhodium- and iridium-catalyzed allylic nucleophilic substitution of the cinnamyl-type carbonates **1** and **3** with MeOH, $PhCH_2OH$, and other simple alcohols has been shown by Evans,[28] Hartwig,[29] and Helmchen[30q] to require the use of the corresponding Cu(I) alkoxide as the O-nucleophile, which in turn can be generated from the respective alcohol by deprotonation with *n*-BuLi, followed by transmetalation with CuI. Both isomeric carbonates **1** and **3** give predominantly the branched product, irrespective of the alcoholate nucleophile.[28−30] Reactions of the chiral allylic substrates **3**, catalyzed by both Rh and Ir, are known to proceed with overall retention of configuration with C-, N-, and O-nucleophiles.[28−31] Furthermore, Helmchen has demonstrated a double inversion mechanism for stabilized C-nucleophiles, such as $NaCH(CO_2Me)_2$;[30i] in this, Ir parallels the stereochemical behavior of Pd[16,19,36] but differs from that of Mo, where a double retention pathway is followed.[20,21,37]

Iridium-Catalyzed Reaction of Cinnamyl Carbonate 7 with Monoprotected Diols 5. In the reactions of allylic carbonates with simple copper(I) alkoxides, catalyzed by either rhodium or

dx.doi.org/10.1021/jo201110z |*J. Org. Chem.* 2011, 76, 7781–7803

Scheme 4. Allylic Substitution Employing Racemic Substrates[a]



[a] TBS = (*t*-Bu)Me_2Si, TBDPS = (*t*-Bu)Ph_2Si, Trt = Ph_3C, Piv = *t*-BuCO.

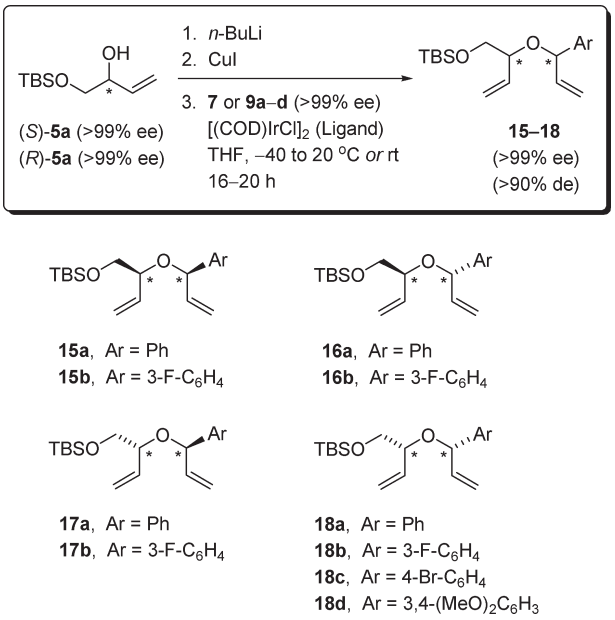
iridium, various chiral ligands, in particular Feringa−Alexakis phosphoramidites (Chart 3),[28c,29,30] have been reported to induce high enantioselectivity. According to the original procedure developed by Hartwig for the iridium-catalyzed intermolecular allylic etherification with simple alcohols,[29l] solid aliphatic lithium alkoxide and copper(I) iodide are mixed, followed by addition of a solvent at 0 °C; a solution of a mixture of the precatalyst and the ligand is then added at 0 °C, followed by addition of the allyl carbonate at 0 °C.

Our reaction system required further development and optimization owing to the steric bulk of alcohol **5b**, which was utilized as the first model compound. This endeavor included finding the right conditions for the deprotonation of the alcohol (to avoid the migration of the protecting group from the primary to secondary hydroxyl), optimization of the copper source for the alkoxide formation, the time required for full conversion, the reaction temperature profile, and assessment of the influence of the ligand, additives, and the nature of the precatalyst and its loading.

Various methods for the formation of the alkoxide from (±)-**5b** were investigated, namely deprotonation with *n*-butyllithium, vinylmagnesium bromide, phenylmagnesium bromide, and phenylzinc bromide in THF (Scheme 4). A solution of the alkoxide thus generated was then directly transferred to a suspension of CuI or CuBr·Me_2S in THF at 0 °C or at 20 °C. For the formation of the alkoxide from (±)-**5b**, the protocol using *n*-BuLi at 0 °C for 10 min, followed by transmetalation with CuI at 20 °C for 30 min, proved to be optimal. The appearance of a bright yellow solution of the corresponding copper alkoxide was indicative of a successful transmetalation. The quality of the CuI proved to be of key importance; the optimal procedure for its preparation included rigorous drying of a perfectly ground CuI in the reaction flask at 140 °C overnight and until the reaction was set up. No difference was noticed when nondegassed solvent was used.

With a successful procedure for the copper alkoxide formation in hand, we endeavored to work out the conditions for the reaction of **5b** with the cinnamyl derivative **7** (Scheme 4). In the initial experiments, racemic (±)-**5b** was employed as a precursor of the required nucleophile (vide supra). However, an attempted reaction of the copper(I) alkoxide generated from (±)-**5b** or (*R*)-**5b** with the cinnamyl carbonate **7** in the presence of $[(COD)IrCl]_2$ (3 mol %) failed. On the other hand, when the catalyst was prepared (in situ) from the latter Ir(I) complex (2 mol % based on the metal) and the chiral ligand **10** (2 mol %), the reaction of (±)-**5b** (1 equiv) with **7** (0.55 equiv) did proceed

Scheme 5. Allylic Substitution Employing Enantiopure Substrates[a]



[a] TBS = (*t*-Bu)Me_2Si; COD = 1,5-cyclooctadiene.

(to 73% conversion, based on **7**) with high selectivity for the branched product **12ba** but required higher temperature (20 °C) than that originally recommended by Hartwig,[29l] presumably owing to the increased steric bulk of the protecting group in alcohol **5b**. The latter success clearly demonstrated the key role of the phosphoramidite ligand. However, no stereochemical preference was observed, and the bisallyl ether **12ba** was isolated as a ∼1:1 mixture of two diastereoisomers. With the catalyst generated from ligand **11** (2 mol %), the reaction of (±)-**5b** (1 equiv) with **7** (0.55 equiv) reached 95% conversion at 20 °C over 16 h and afforded **12ba** as a 65:35 mixture of diastereoisomers in which the anti-isomer (i.e., *S*,*S*/*R*,*R*) dominated over its syn-counterpart (i.e., *S*,*R*/*R*,*S*).[38] Substrates **5c** and **5d** were found to be less suitable than **5b** as the conversions to **12ca**/**12da** were substantially lower (25% and 12%, respectively).[39] The reaction of (±)-**5a** (1 equiv) with **7** (0.55 equiv), catalyzed by $[(COD)IrCl]_2$ (2 mol %), in the presence of the phosphoramidite ligand **10** (2 mol %) furnished **12aa** as a ∼1:1 mixture of diastereoisomers in a rather lower yield (38%). Interestingly, in the case of **5a**, partial migration of the protecting group was observed in some cases, giving rise to the isomer **13** as a minor contaminant along with the main product **12aa** (see the following paragraph).[40]

The latter experiments defined the reaction conditions and demonstrated the difference in reactivity of the individual enantiomers of racemic **5b**−**d** when ligand **11** was employed, which is quite remarkable in its own right but not sufficient for the production of the stereochemically pure targets. Therefore, the reaction of the enantiopure **5a** (2 equiv) with the cinnamyl substrate **7** (1 equiv) was explored next (THF at −40 °C for 16 h). In the presence of the catalyst generated from $[(COD)IrCl]_2$ (2 mol %) and ligand **11** (3 mol %), (*S*)-**5a** afforded **15a** (Scheme 5) at −40 °C as the major product,[41] accompanied by its diastereoisomer **16a** (97:3 dr) and the rearranged product **13** (6%).[40,42] The opposite enantiomer (*R*)-**5a** also reacted

dx.doi.org/10.1021/jo201110z |*J. Org. Chem.* 2011, 76, 7781–7803

readily with **7** under the same conditions and in the presence of the same ligand (**11**) afforded the diastereoisomeric **17a** (97:3 dr)[41] together with the rearranged product **13** (10%).[40,42−44] Hence, ligand (R_a,R_c,R_c)-**11** promotes the construction of the (*R*)-stereocenter in the "eastern" part of the molecule with the same efficiency for both enantiomers of the nucleophilic "western" moiety. Therefore, it can be assumed that the enantiomeric ligand *ent*-**11** would give access to the remaining members of the series, i.e., **16** and **18**.

Iridium- and Rhodium-Catalyzed Reaction of Isocinnamyl-Type Carbonates 9 with Protected Diols 5. The reaction of (±)-**5b** or (*R*)-**5b** (1 equiv) with (±)-**9a** (0.55 equiv), catalyzed by $[(COD)IrCl]_2$ (4 mol %), proceeded readily (unlike with **7**) and produced **12ba** (52% and 54%, respectively) as a 1:1 mixture of diastereoisomers in each case (Scheme 4), showing that no kinetic resolution took place. The 4-fluorophenyl analogue (±)-**9e** proved to be slightly more reactive, furnishing **12be** (77%). The analogous reaction catalyzed by $[(COD)RhCl]_2$ gave **12ba** (12%) along with olefin **14a** (23%).[45] The corresponding reaction of (±)-**9e** catalyzed by $[(COD)RhCl]_2$ gave a mixture of **12be** (31%) and olefin **14b** (43%).

An improvement in the reactivity (but not in stereoselectivity) was observed when the phosphoramidite ligand **10** (2 mol %) and $[(COD)IrCl]_2$ (2 mol %) was used as the reaction of (±)-**5b** with (±)-**9a** afforded **12ba** (66%), again as an almost 1:1 diastereoisomeric mixture (6% de). A similar result (62%) was obtained when $(t\text{-BuO})_2PN(i\text{-Pr})_2$ was employed as the added ligand. Interestingly, only traces of **12ba** (5%) were obtained when the reaction of (*R*)-**5b** with (±)-**9a** was carried out in the presence of $[(COD)IrCl]_2$ (2.5 mol %) and (*S*)-BINAP (2.5 mol %), the major product being olefin **14a** (33%).[45] The latter product dominated (≤46%) in the reaction of (±)-**5b** with (±)-**9a** catalyzed by $(Ph_3P)_3RhCl$ or $[(COD)RhCl]_2$, regardless of whether an additional ligand [e.g., BINAP, $(MeO)_3P$, or $(t\text{-BuO})_2PN(i\text{-Pr})_2$] was added or not, with no **12ba** obtained; instead, the starting carbonate (±)-**9a** was recovered (≤51%), demonstrating the inferiority of the Rh-based catalysts in this particular system.

Improved yields were obtained with the silyl derivative **5a**. Thus, the reaction of (±)-**5a** or (*R*)-**5a** (1 equiv) with (±)-**9a** (0.55 equiv), catalyzed by $[(COD)IrCl]_2$ (2 mol %), afforded the bisallyl ether **12aa** as a 1:1 mixture of diastereoisomers in 84%. The combination of (*R*)-**5a** (1 equiv) and (*S*)-**9a** (0.55 equiv), catalyzed by $[(COD)IrCl]_2$ (2 mol %), afforded the bisallyl ether **12aa** as a single diastereoisomer in 79% yield. With higher amounts of carbonate (±)-**9a** (0.8 equiv), a slight decrease in the yield (74%) was observed. The 4-fluorinated carbonate (±)-**9e** (0.9 and 1.0 equiv) and the 4-brominated carbonate (±)-**9c** (0.55 equiv) behaved in a similar way, affording the corresponding products in good yields (74%, 65%, and 75%, respectively). Similarly, in the presence of the phosphoramidite ligand **10** (2 mol %), **12aa** was obtained as a ~1:1 mixture in a rather lower yield (41%), showing that neither kinetic resolution nor stereochemical isomerization of the intermediate η^3-Ir-complex took place.[46] With the catalyst generated from $[(COD)IrCl]_2$, (2 mol %) and $(t\text{-BuO})_2PN(i\text{-Pr})_2$ (2 mol %), the same conversion to **12aa** was attained (84%) but with no effect on diastereoselectivity. By contrast, only the starting carbonates were detected in the attempted reaction of (±)-**5a** (1 equiv) with (±)-**9a** or **7** (0.55 equiv), catalyzed by $[(COD)RhCl]_2$ (2 mol %), clearly demonstrating the superiority of the Ir catalyst.

Table 1. Stereocontrolled Synthesis of Bisallyl Ethers 15−18 from the Monoprotected Diol 5a and Branched Allylic Carbonates 9ad (Scheme 5)[a]

entry	alcohol[b]	carbonate[b]	product[c]	yield (%)[d,e,f]
1	(*S*)-**5a**	(*R*)-**9a**	**15a**	82
2	(*S*)-**5a**	(*R*)-**9b**	**15b**	74
3	(*S*)-**5a**	(*S*)-**9a**	**16a**	79
4	(*S*)-**5a**	(*S*)-**9b**	**16b**	78
5	(*R*)-**5a**	(*R*)-**9a**	**17a**	83
6	(*R*)-**5a**	(*R*)-**9b**	**17b**	72
7	(*R*)-**5a**	(*S*)-**9a**	**18a**	77
8	(*R*)-**5a**	(*S*)-**9b**	**18b**	73
9	(*R*)-**5a**	(*S*)-**9c**	**18c**	85
10	(*R*)-**5a**	(*S*)-**9d**	**18d**	70

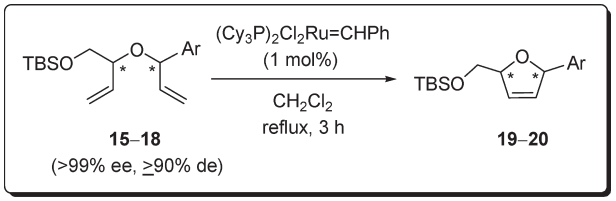
[a] The reaction was carried out at 6−17 mmol scale in THF at 20 °C for 20 h, using 1 equiv of **5a**, 0.9 equiv of **9**, and 2 mol % of the catalyst (mol % based on the metal) unless stated otherwise. [b] Purity >99% ee. [c] The relative configuration was determined after cyclization (vide infra). [d] Isolated yield. [e] The enantiopurity determined by chiral HPLC was >99% ee in all cases. [f] According to the NMR spectra of the crude products, the diastereoisomeric ratio was at least 95:5 in all cases; this ratio might actually be even higher (see the main text below for discussion of accuracy).

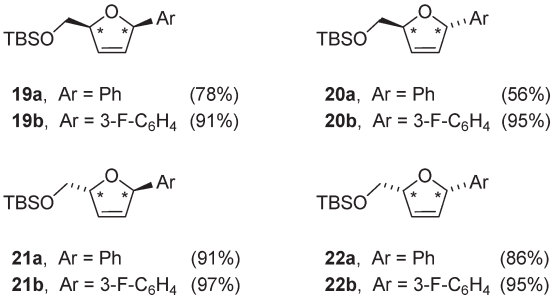
Attempted Iridium-Catalyzed Reaction of Isocinnamyl Alcohol 8a with the Allylic Carbonate 6b. The reversed disconnection, according to pathway c in Scheme 1, proved unsuccessful. Thus, the attempted reaction of carbonate (±)-**6b** with the Cu(I) alkoxide generated from the isocinnamyl alcohol (±)-**8a**, carried out in the presence of either $[(COD)IrCl]_2$, $[(COD)RhCl]_2$, or $(Ph_3P)_3RhCl$ (4−5 mol %) with or without added $(MeO)_3P$, only led to a slow decomposition, with no **12** being detected. This behavior clearly shows that the isocinnamyl-type carbonates **9** are the electrophilic partners of choice in terms of reactivity, which favors pathway b over c (and consequently d) in the disconnection diagram (Scheme 1).

Stereocontrolled Synthesis of Bisallyl Ethers 15−18. All the above experiments allow the following conclusions to be made: (1) The linear carbonate **7** (in pathway a; Scheme 1) gives diastereoisomerically almost pure products (97% de) in the presence of the chiral ligand **11**, which are however contaminated with various amounts of byproducts that are rather difficult to remove.[43] (2) The branched carbonate **9a** (pathway b) is more reactive than its linear isomer **7**. (3) The stereocontrol with the chiral ligand **11** is excellent for pathway a, whereas pathway c (and presumably d) is not suitable because of the low reactivity; the reaction has to be carried out at −40 °C to minimize the formation of byproducts. (4) For the formation of the bisallyl ether **12** from **5** and **9** (pathway b), the use of ($[Ir(COD)Cl]_2$) (2 mol %) without any additional ligand gives the best conversion at 20 °C in ≥16 h in a clean reaction. (5) Rh catalysts proved inferior. (6) Silyl protecting groups, as in **5a**,**b**, proved superior to trityl and pivaloyl (**5c**,**d**). Furthermore, **5a** proved to be superior to **5b** for pathway b. (7) Path b appears to be the most promising; here, the optimal ratio of the alcohol to carbonate **5**:**9** was found to be 1:0.8 to 1:0.9.

In view of these findings, we focused on the Ir(I)-catalyzed reaction of the enantiopure alcohol **5a** (>99% ee) with the enantiopure branched carbonates **9a**−**d** (>99% ee), aiming at a high-yielding stereospecific process (Scheme 5 and Table 1);

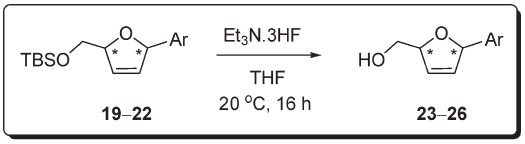
Scheme 6. Ring-Closing Metathesis[a]

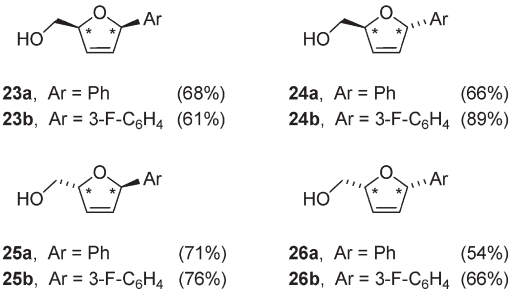




[a] TBS = (*t*-BU)Me_2Si.

Scheme 7. O-Deprotection[a]





[a] TBS = (*t*-Bu)Me_2Si.

the substitution was expected to proceed predominantly with retention of configuration (vide supra). The reactions were carried out under our standard conditions, i.e., with **5a** (1.0 equiv) and **9a**−**d** (0.9 equiv) and with $[(COD)IrCl]_2$ as catalyst (2.0 mol %, based on the metal) in THF at 20 °C for 20 h (Table 1). All stereochemical combinations of the (*R*)- and (*S*)-substrates turned out to be successful, affording the respective enantiopure products **15**−**18** (>99% ee) in good isolated yields (73−85%). The substitution itself was highly stereospecific, giving the products of retention of configuration in ≥95:5 ratio in all cases, as evidenced by the NMR spectra of the crude products. Hence, this protocol appears to be the method of choice for the construction of the bisallylic ethers required as precursors for the ring-closing metathesis. However, in contrast to the successful reactions of meta- and para-substituted phenyl derivatives **9**, their ortho-substituted congeners (e.g., 2-methyl- 2-fluoro-, 2,4-dimethyl-, and 2,4-difluorophenyl) reacted sluggishly, whereas the 3-pyridyl analogue failed to react; in both cases the corresponding carbonates gradually decomposed.

Synthesis of Protected 2′,3′-Didehydro-2′,3′-Dideoxy-*C*-Nucleosides by Ring-Closing Metathesis. The bisallyl ethers **15a,b**−**18a,b** were subjected to the standard ring-closing metathesis (RCM) reaction (Scheme 6).[48] A brief screening of the reaction conditions was carried out, employing Grubbs first- and second-generation catalysts. Because no significant difference was observed in the performance of these two catalysts, Grubbs first-generation complex was chosen. Catalyst loadings as low as 1% was found to be sufficient, and the optimized reaction conditions comprised a heating to reflux in CH_2Cl_2 for 3 h.[49] The desired 1,5-dihydrofuran derivatives **19a,b**−**22a,b** were obtained as pure stereoisomers in 78−97% isolated (with one exception, where the yield dropped to 56% due to the inefficient isolation procedure).

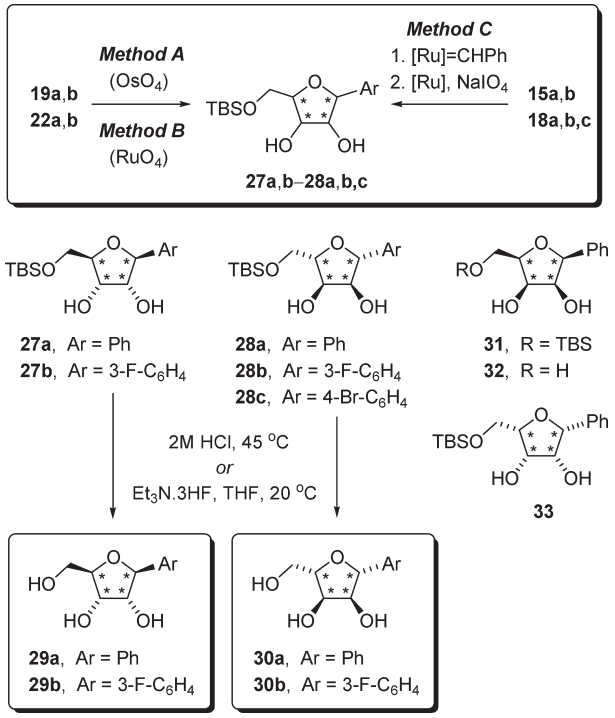
The sensitive[50] dihydrofuryl derivatives **19**−**22** were deprotected by treatment with $Et_3N{\cdot}HF$ (3 equiv) as the optimized reagent (20 °C, 16 h) to afford alcohols **23a,b**−**26a,b** in good isolated yields (Scheme 7).[51] The analogous TBDPS derivatives could be deprotected under similar conditions, but the yields, as a rule, were by ca. 20% lower due to the formation of considerable amounts of byproducts.[51a] It is pertinent to note that the latter deprotected nucleoside analogues **23**−**26** thus obtained represent, in fact, products of potential biological interest in their own right.[52]

The absolute configuration at C-4 of the deprotected products (Scheme 7) reflects the absolute configuration of the starting monoprotected diol **5a**, as no reaction occurred at this center. The configuration at C-1 (the anomeric center) is dictated by the configuration of the starting isocinnamyl carbonate **9**, as the Ir-catalyzed allylic substitution is known[28−31] to proceed with retention of configuration. Thus, for instance, the configuration of **23a**, originating from (*S*)-**5a** and (*R*)-**9a**, should be cis as shown, which is consistent with the NOE enhancement (1−2%) of 1-H and 4-H in the ^1H NMR spectrum. By contrast, anomers **24**, which should be trans-configured, exhibited no NOE effect. The relative configuration was eventually confirmed by X-ray crystallography for the products of dihydroxylation (vide infra).

The deprotection step not only represents a divergent route, broadening the synthetic utility of our new approach to *C*-nucleosides, but also offers an opportunity to accurately establish the stereochemical purity of our products, as the protected derivatives were not suitable for HPLC or GC analysis, owing either to their instability or to poor resolution. The expected appropriate NOE effect was only observed after the deprotection. All four stereoisomers of 1′-phenyl-substituted D4 nucleoside analogue **23a**−**26a** were then subjected to GC analysis. The results were compared with the chromatograms recorded for the corresponding racemic diastereoisomers (obtained from racemic starting materials). All samples of **23a**−**26a** showed high diastereo- and enantiopurity (>99% de and >99% ee). On the basis of these values, we can assume that the diastereoselectivity of the allylic substitution (Table 1) might have been higher than the ^1H NMR spectroscopy allowed to estimate (>90% de). However, we have to bear in mind that three chromatographic purification steps were used in the sequence from the allylic substitution to the deprotected derivatives **23**−**26**, which may have slightly enhanced the diastereoisomeric purity.

Construction of Ribofuranosides and Completion of the Synthesis. Dihydroxylation of the double bond in the dihydrofuran derivatives resulting from the RCM should readily afford the desired vicinal diols. However, since only the cis-derivatives

Scheme 8. Dihydroxylation of Dihydrofurans[a]



[a] TBS = (*t*-Bu)Me_2Si.

19 and **22** can be expected to react stereoselectively, the trans-derivatives **20** and **21** were excluded from the study. Two possible tactics can be considered (Scheme 8): (1) vicinal dihydroxylation of the isolated dihydrofuran derivatives **19** and **22**,[48,53] catalyzed either by osmium tetroxide (method A), or by the less toxic and far more reactive ruthenium tetroxide (method B);[53,54] or (2) a direct, one-pot procedure involving the ring-closing metathesis of **15** and **18**, followed by oxidation of the ruthenium in the reaction mixture to RuO_4, which would then catalyze the dihydroxylation of the intermediate dihydrofuran derivative (method C).[55]

These tactics were explored in various combinations of the reaction conditions. Oxidation of the enantiomers **19a** and **22a** with osmium tetroxide as catalyst (1 mol %) and *N*-methylmorpholine *N*-oxide as a stoichiometric oxidant (1.3 equiv) was carried out in a mixture of acetone and water (10:1) at room temperature. The reaction proceeded readily and was complete within 12 h, furnishing the enantiomeric D- and L-ribo-diols **27a** (80%) and **28a** (78%), respectively. Alongside these desired ribonucleosides, their lyxo-diastereoisomers **31** (14%) and **33** (13%) were obtained, respectively, which were readily separated by column chromatography.

For the dihydroxylation catalyzed by ruthenium tetroxide, the following protocols were reported previously: (1) Plietker's procedure, utilizing a catalytic amount of a ruthenium source together with certain amounts of a Lewis acid (e.g., $CeCl_3$) and a stoichiometric inorganic oxidant, most frequently $NaIO_4$.[56] (2) A modification of this method, recently reported by Blechert, combines the RCM procedure with subsequent utilization of the remaining ruthenium complex in the Plietker-type oxidation as a one-pot protocol.[55] (3) Hudlický's procedure, which does not utilize any Lewis acidic additive but requires a higher catalyst loading (10 mol %).[53] In our hands, neither of the first two modifications was overwhelmingly successful, and we feel that the main problem was the inefficient phase transfer in this heterogeneous system. Following the third protocol, the dihydrofuran derivative **19b** in a mixture of AcOEt and MeCN (1:1) was oxidized with aqueous $NaIO_4$ in the presence of $RuCl_3 \cdot H_2O$ (12 mol %) at 0 °C for 45 s to afford **27b** (61%) as the major diastereoisomer. On the other hand, extending the reaction time to 80 s resulted in a dramatic decrease of the yield to 16%, owing to the oxidation of the product with excess of $NaIO_4$. Again, the results here were very dependent on the level of homogeneity.

Finally, the one-pot experiment, combining the RCM according to Blechert, followed by Hudlický's procedure, was carried out as follows: the bisallyl ether **18b** was subjected to RCM [Grubbs first-generation catalyst (1.5 mol %), CH_2Cl_2, reflux for 3 h]. When the RCM was complete, the solvent was changed (CH_2Cl_2 was evaporated, and the residue was dissolved in a 1:1 mixture of AcOEt and MeCN), and the oxidation was carried out via Hudlický's procedure (i.e., without a Lewis acid), and with $RuCl_3 \cdot H_2O$ (up to 10% Ru in total) as an additional ruthenium source. With $NaIO_4$ as the stoichiometric oxidant at 0 °C for 15 s, the latter protocol afforded **28b** in 34% yield over the two steps. Analogous results were obtained for the one-pot reaction of bisallyl ethers **15a** and **18c**, furnishing diols **27a** (24%) and **28c** (31%) respectively.

Clearly, the protocol employing the ruthenium catalyst and $NaIO_4$ suffers from the propensity of the resulting diol to an oxidative cleavage by excess of $NaIO_4$ (which can be assumed to be faster for five-membered ring systems than for the corresponing six-memberd rings due to the inherent dihedral angle). Therefore, the reaction must be carried out like a titration, where an aqueous solution of $NaIO_4$ is added dropwise to a solution containing the reactant and Ru catalyst; the change of color from dark-brown into yellow indicates the completion of the reaction, and the mixture needs to be quenched immediately with a 50% aqueous solution of $Na_2S_2O_3$ to prevent further oxidation. Hence, in view of the difficulties associated with controlling the Ru/IO_4^- protocols, the OsO_4-catalyzed procedure can be regarded as much more reliable, robust, and reproducible. The formation of a small amount of the lyxo-derivative does not constitute a significant problem, as the two disatereoisomers can be readily separated by chromatography.

The TBS derivatives **27a** and **28a** were deprotected by treatment with 2 M aqueous hydrochloric acid at 45 °C (by coevaporation in vacuo), followed by a reverse phase column chromatography to produce the free ribonucleoside **29a** (86%) and **30a** (79%), respectively. Slightly lower yields were attained when $Et_3N \cdot 3HF$ in THF was employed (75% and 72%, respectively). The *m*-fluoro derivatives **27b** and **28b** were deprotected by using the latter method; chromatographic purification afforded triols **29b** (65%) and **30b** (62%). The TBS-protected lyxo-nucleoside **31** was transformed into the free nucleoside **32** upon treatment with 2 M HCl in the same way. Direct deprotection of the crude reaction mixtures after dihydroxylation of **19a** was also explored, but the resulting mixture of the free *ribo*- and *lyxo*-nucleosides was not separable. Therefore, the optimum deprotection sequence involves the separation of the diastereoisomeric silylated nucleosides, followed by deprotection of pure isomers. Of the two methods employed, namely 2 M HCl and $Et_3N \cdot 3HF$, the former gave slightly higher yields.[57]

The enantiomeric β-1-phenyl ribofuranoses **29a** and **30a** were isolated as crystalline compounds suitable for X-ray diffraction

dx.doi.org/10.1021/jo201110z |*J. Org. Chem.* 2011, 76, 7781–7803

analysis, which confirmed the relative configuration. Since the absolute configuration of the starting monoprotected diol **5a** was known, the absolute configuration of **29a** and **30a** can thus be regarded as fully established. The latter conclusion can be extrapolated to the fluoro derivatives **29b** and **30b** and other intermediates of the whole sequence.

CONCLUSIONS

A conceptually new synthetic route to *C*-nucleosides has been developed, comprising a divergent reaction sequence with three strategic steps followed by deprotection. The anomeric center was constructed via a stereocontrolled formation of the "endocyclic" C−O bond as the key step (route b in Scheme 1). Thus, iridium(I)-catalyzed reaction of the isocinnamyl carbonate (*R*)-**9a** with the copper(I) alkoxide, generated from the monoprotected diol (*S*)-**5a**, produced the bisallylic ether (*S*,*R*)-**15a** as a result of the stereo- and regiospecific allylic substitution that occurred with retention of configuration (>90% de) owing to a double inversion mechanism. The alternative strategy, employing the Ir-catalyzed reaction of the nonchiral cinnamyl carbonate **7** (instead of **9**) and the chiral ligand **11** (path a in Scheme 1) was also found to be highly stereoselective but less efficient, owing to the formation of byproducts that were rather difficult to separate. Subsequent ring-closing metathesis, catalyzed by the Grubbs first-generation catalyst, afforded the dihydrofuran derivative **19a** (>99% de; >99% ee), whose dihydroxylation, catalyzed by OsO_4, resulted in the formation of diol **27a** as the major diastereoisomer. The final deprotection produced the enantiopure β-D-ribofuranoside **29a**. Variation of the absolute configuration of the starting segments **5a** and **9a**,**b** allowed a stereocontrolled synthesis of all four α/β-D/L-combinations **29**/**30**. Each reaction step was investigated in detail and optimized. Our approach is suitable for the synthesis of aryl *C*-nucleosides lacking ortho-substituents and/or a coordinating nitrogen atom. Application of our protocol can be expected in the area of lipophilic isosters of ribonucleosides for RNA studies,[58] α- and β-aryl C-nucleosides for fluorescent oligonucleotide arrays,[59] and unnatural L-*C*-ribonucleosides[60] for studies of biological activity. This strategy for the de novo construction of carbohydrate molecules is likely to be general[61] and should also be suitable for the synthesis *C*-deoxyribonucleosides, which would extend its application from the RNA to DNA realm.

EXPERIMENTAL SECTION

General Methods. Melting points were determined on a Kofler block and are uncorrected. Optical rotations were recorded in $CHCl_3$ at 25 °C unless otherwise indicated with an error of <±0.1. The $[\alpha]_D$ values are given in 10^{-1} deg cm^2 g^{-1}. The NMR spectra were measured in chloroform-*d*. Residual solvent peaks (δ 7.26, ^{1}H; δ 77.00, ^{13}C) and CCl_3F (δ 0.00, ^{19}F) were used as internal standards unless otherwise indicated. Chemical shifts are given in ppm (δ-scale), coupling constants (J) in hertz. Complete assignment of all NMR signals was performed using a combination of H,H-COSY, H,C-HSQC, and H,C-HMBC experiments. IR spectra were recorded for a thin film between NaCl plates or for $CHCl_3$ solutions. Mass spectra (EI or CI-isobutane, unless otherwise specified) were measured on a dual sector mass spectrometer using direct inlet and the lowest temperature enabling evaporation. All reactions were performed under an atmosphere of dry, oxygen-free argon in oven-dried glassware three times evacuated and backfilled with the argon three times. Reaction temperature −83 °C refers to the cooling bath filled with an ethyl acetate−liquid nitrogen mixture. Solvents and solutions were transferred by syringe−septum and cannula techniques. All solvents for the reactions were of reagent grade and were dried and distilled immediately before use as follows: tetrahydrofuran (THF) from sodium/benzophenone; dichloromethane from calcium hydride. Solvents for the palladium- and ruthenium-catalyzed reactions were degassed in vacuo and stored over molecular sieves (4 Å) under argon atmosphere. Yields are given for isolated products showing one spot on a TLC plate and no impurities detectable in the NMR spectrum. The identity of the products prepared by different methods was checked by comparison of their ^{1}H NMR spectra, and ultimate elemental composition (microanalysis).

General Procedure A: Regioselective Protection of Butene-1,2-diols. A solution of the chosen protecting agent (TBSCl, TBDPSCl, or Ph_3CCl, 30.87 mmol) in THF (20 mL) was added slowly to a solution of butene-1,2-diol **4** (2.721 g, 30.87 mmol) and DMAP (400 mg, 3.27 mmol) in a mixture of Et_3N (15 mL) and THF (60 mL) at 0 °C, and the mixture was stirred overnight at 20 °C. The reaction was then quenched with water, diluted with Et_2O (200 mL), three times washed with brine, dried (Na_2SO_4), and evaporated. Chromatography on a column of silica gel with a mixture of hexanes and ethyl acetate gave the respective protected butenol **5** as a colorless oil.

(±)-1-(*tert*-Butyldimethylsilyloxy)but-3-en-2-ol (±)-(5a). Butene-1,2-diol (±)-**4** (2.721 g, 30.87 mmol) was protected with *tert*-butyl(chloro)dimethylsilane following general procedure A. Chromatography on column of silica gel (5 × 10 cm) with a mixture of hexanes and ethyl acetate (98:2) gave the butenol (±)-**5a** as a yellowish liquid (5.081 g, 81%): ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.07 (s, 6H, CH_3), 0.90 (s, 9H, *t*-Bu), 2.60 (d, $^3J_{OH,2\text{-}CH}$ = 3.4 Hz, 1H, OH), 3.44 (dd, $^2J_{1\text{-}Ha,1\text{-}Hb}$ = 10.0 Hz, $^3J_{1\text{-}Ha,2\text{-}H}$ = 7.6 Hz, 1H, 1-Ha), 3.64 (dd, $^2J_{1\text{-}Hb,1\text{-}Ha}$ = 10.0 Hz, $^3J_{1\text{-}Hb,2\text{-}H}$ = 3.8 Hz, 1H, 1-Hb), 4.15 (m, 1H, 2-H), 5.17 (ddd, $^3J_{4\text{-}Ha,3\text{-}H}$ = 10.6 Hz, $^2J_{4\text{-}Ha,4\text{-}Hb}$ = 1.5 Hz, $^4J_{4\text{-}Ha,2\text{-}H}$ = 1.4 Hz, 1H, 4-Ha), 5.33 (ddd, $^3J_{4\text{-}Hb,3\text{-}H}$ = 17.3 Hz, $^4J_{4\text{-}Hb,2\text{-}H}$ = 1.6 Hz, $^2J_{4\text{-}Hb,4\text{-}Ha}$ = 1.5 Hz, 1H, 4-Hb), 5.80 (ddd, $^3J_{3\text{-}H,4\text{-}Hb}$ = 17.3 Hz, $^3J_{3\text{-}H,4\text{-}Ha}$ = 10.6 Hz, $^3J_{3\text{-}H,2\text{-}H}$ = 5.7 Hz, 1H, 3-H); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ −5.42 (CH_3), −5.39 (CH_3), 18.3 ($C(CH_3)_3$), 25.8 ($C(CH_3)_3$), 66.9 (CH_2-1), 73.0 (CH-2), 116.4 (CH_2-4), 136.7 (CH-3). Anal. Calcd for $C_{10}H_{22}O_2Si$: C, 59.35; H, 10.96. Found: C, 59.36; H, 11.07.

(*R*)-1-(*tert*-Butyldimethylsilyloxy)but-3-en-2-ol (*R*)-(5a). Butene-1,2-diol (*R*)-**4** (2.53 g, 28.6 mmol) was protected with *tert*-butyl(chloro)dimethylsilane following general procedure A. Chromatography on column of silica gel (5 × 10 cm) with a mixture of hexanes and ethyl acetate (98:2) gave the butenol (*R*)-**5a** as a colorless oil (3.83 g, 66%) with chemical purity >99% (GC) and >99% ee (chiral GC): ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.05 (s, 6H, CH_3), 0.88 (s, 9H, *t*-Bu), 2.65 (d, $^3J_{2\text{-}OH,2\text{-}H}$ = 3.6 Hz, 1H, 2-OH), 3.43 (dd, $^2J_{1\text{-}Ha,1\text{-}Hb}$ = 9.9 Hz, $^3J_{1\text{-}Ha,2\text{-}H}$ = 7.6 Hz, 1H, 1-Ha), 3.62 (dd, $^2J_{1\text{-}Hb,1\text{-}Ha}$ = 9.9 Hz, $^3J_{1\text{-}Hb,2\text{-}H}$ = 3.8 Hz, 1H, 1-Hb), 4.10−4.15 (m, 1H, 2-H), 5.15 (dd, $^3J_{4\text{-}Ha,3\text{-}H}$ = 10.6 Hz, $^2J_{4\text{-}Ha,4\text{-}Hb}$ = 1.2 Hz, 1H, 4-Ha), 5.31 (dd, $^3J_{4\text{-}Hb,3\text{-}H}$ = 17.3 Hz, $^2J_{4\text{-}Hb,4\text{-}Ha}$ = 1.2 Hz, 1H, 4-Hb), 5.78 (ddd, $^3J_{3\text{-}H,4\text{-}Hb}$ = 17.3 Hz, $^3J_{3\text{-}H,4\text{-}Ha}$ = 10.6 Hz, $^3J_{3\text{-}H,2\text{-}H}$ = 5.7 Hz, 1H, 3-H) in agreement with an authentic sample of the racemate. Anal. Calcd for $C_{10}H_{22}O_2Si$: C, 59.35; H, 10.96. Found: C, 59.21; H, 11.13. Chiral GC showed >99% ee (Supelco β-DEX 120 column, oven 70 °C for 5 min then gradient 1 °C.min^{-1} to 105 °C) t_R = 31.48 min ((*S*)-**5a**), t_R = 32.68 min ((*R*)-**5a**). Fraction distillation of the crude product obtained by the above procedure (131 mmol scale) gave (*R*)-**5a** as a colorless liquid (21.35 g, 80%): bp 43−45 °C at 270 Pa.

(*S*)-1-(*tert*-Butyldimethylsilyloxy)but-3-en-2-ol (*S*)-(5a). Butene-1,2-diol (*S*)-**4** (5.28 g, 59.9 mmol) was protected with *tert*-butyl(chloro)dimethylsilane following general procedure A. Chromatography on a column of silica gel (8 × 10 cm) with a mixture of hexanes and ethyl acetate (98:2) gave butenol (*S*)-**5a** as a colorless oil (9.29 g, 76%) with chemical purity >99% (GC) and >99% ee (chiral

GC): ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.05 (s, 6H, CH_3), 0.88 (s, 9H, *t*-Bu), 2.65 (d, $^3J_{2\text{-OH},2\text{-H}}$ = 3.6 Hz, 1H, 2-OH), 3.43 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 9.9 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 7.6 Hz, 1H, 1-Ha), 3.62 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 9.9 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 3.8 Hz, 1H, 1-Hb), 4.10−4.15 (m, 1H, 2-H), 5.15 (dd, $^3J_{4\text{-Ha},3\text{-H}}$ = 10.6 Hz, $^2J_{4\text{-Ha},4\text{-Hb}}$ = 1.2 Hz, 1H, 4-Ha), 5.31 (dd, $^3J_{4\text{-Hb},3\text{-H}}$ = 17.3 Hz, $^2J_{4\text{-Hb},4\text{-Ha}}$ = 1.2 Hz, 1H, 4-Hb), 5.78 (ddd, $^3J_{3\text{-H},4\text{-Hb}}$ = 17.3 Hz, $^3J_{3\text{-H},4\text{-Ha}}$ = 10.6 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 5.7 Hz, 1H, 3-H) in agreement with an authentic sample of the racemate. Anal. Calcd for $C_{10}H_{22}O_2Si$: C, 59.35; H, 10.96. Found: C, 59.13; H, 11.13. Chiral GC (Supelco β-DEX 120 column, oven 70 °C for 5 min then gradient 1 °C.min^{-1} to 105 °C) showed >99% ee (t_R = 31.48 min, t_R = 32.68 min). Fraction distillation of the crude product obtained by the above procedure (156 mmol scale) gave (*S*)-**5a** as a colorless liquid (25.16 g, 80%): bp 46−48 °C at 300 Pa.

(±)-1-(*tert*-Butyldiphenylsilyloxy)but-3-en-2-ol (±)-(5b).[62] Butene-1,2-diol (±)-**4** (5.0 g, 56.8 mmol) was protected with *tert*-butyl(chloro)diphenylsilane following general procedure A. Chromatography on column of silica gel (8 × 10 cm) with a mixture of hexanes and ethyl acetate (95:5) gave the butenol (±)-**5b** as a colorless oil (17.68 g, 95%): ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 1.14 (s, 9H, *t*-Bu), 2.73 (d, $^3J_{2\text{-OH},2\text{-H}}$ = 3.9 Hz, 1H, 2-OH), 3.62 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.2 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 7.4 Hz, 1H, 1-Ha), 3.76 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.2 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 3.9 Hz, 1H, 1-Hb), 4.27−4.32 (m, 1H, 2-H), 5.21 (ddd, $^3J_{4\text{-Ha},3\text{-H}}$ = 10.6 Hz, $^2J_{4\text{-Ha},4\text{-Hb}}$ = 1.5 Hz, $^4J_{4\text{-Ha},2\text{-H}}$ = 1.5 Hz, 1H, 4-Ha), 5.37 (ddd, $^3J_{4\text{-Hb},3\text{-H}}$ = 17.3 Hz, $^2J_{4\text{-Hb},4\text{-Ha}}$ = 1.5 Hz, $^4J_{4\text{-Hb},2\text{-H}}$ = 1.5 Hz,1H, 4-Hb), 5.89 (ddd, $^3J_{3\text{-H},4\text{-Hb}}$ = 17.3 Hz, $^3J_{3\text{-H},4\text{-Ha}}$ = 10.6 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 5.6 Hz, 1H, 3-H), 7.40−7.48 (m, 6H, H-arom), 7.72−7.74 (m, 4H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ 19.2 ($C(CH_3)_3$), 26.8 ($C(CH_3)_3$), 67.6 (CH_2-1), 73.0 (CH-2), 116.4 (CH_2-4), 127.7 (CH-arom), 129.8 (CH-arom), 133.0 (CH-arom), 135.48 (C-arom), 136.59 (CH-3); consistent with the literature data.[62]

(*R*)-1-(*tert*-Butyldiphenylsilyloxy)but-3-en-2-ol (*R*)-(5b). Butene-1,2-diol (*R*)-**4** (2.18 g, 24.7 mmol) was protected with *tert*-butyl(chloro)diphenylsilane following general procedure A. Chromatography on column of silica gel (8 × 10 cm) with a mixture of hexanes and ethyl acetate (95:5) gave the butenol (*R*)-**5b** as a colorless oil (7.06 g, 88%). $[\alpha]_D$ +5.2 (*c* 0.9, $CHCl_3$). Anal. Calcd for $C_{20}H_{26}O_2Si$: C, 73.57; H, 8.03. Found: C, 73.49; H, 8.13. For further characterization of the corresponding racemate, see the previous paragraph and the literature.[62]

(*S*)-1-(*tert*-Butyldiphenylsilyloxy)but-3-en-2-ol (*S*)-(5b).[62] Butene-1,2-diol (*S*)-**4** (2.20 g, 25.0 mmol) was protected with *tert*-butyl(chloro)diphenylsilane following general procedure A. Chromatography on column of silica gel (5 × 10 cm) with a mixture of hexanes and ethyl acetate (95:5) gave the butenol (*S*)-**5b** as a colorless oil (7.02 g, 86%). $[\alpha]_D$ −4.9 (*c* 1.2, $CHCl_3$). Anal. Calcd for $C_{20}H_{26}O_2Si$: C, 73.57; H, 8.03. Found: C, 73.31; H, 8.39. For further characterization of the corresponding racemate, see the previous paragraph and the literature.[62]

(±)-1-(Trityloxy)but-3-en-2-ol (5c).[63] Butene-1,2-diol (±)-**4** (1.76 g, 20.0 mmol) was protected with chloro(triphenyl)methane following general procedure A. Reaction time was prolonged to 24 h. Chromatography on column of silica gel (5 × 10 cm) with a mixture of hexanes and ethyl acetate (95:5) gave the butenol (±)-**5c** as a colorless oil (5.82 g, 88%): ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 2.44 (d, $^3J_{2\text{-OH},2\text{-H}}$ = 3.9 Hz, 1H, 2-OH), 3.14 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 9.4 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 7.5 Hz, 1H, 1-Ha), 3.24 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 9.4 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 3.7 Hz, 1H, 1-Hb), 4.27−4.33 (m, 1H, 2-H), 5.18 (ddd, $^3J_{4\text{-Ha},3\text{-H}}$ = 10.6 Hz, $^2J_{4\text{-Ha},4\text{-Hb}}$ = 1.4 Hz, $^4J_{4\text{-Ha},2\text{-H}}$ = 1.4 Hz, 1H, 4-Ha), 5.32 (ddd, $^3J_{4\text{-Hb},3\text{-H}}$ = 17.2 Hz, $^2J_{4\text{-Hb},4\text{-Ha}}$ = 1.4 Hz, $^4J_{4\text{-Hb},2\text{-H}}$ = 1.4 Hz, 1H, 4-Hb), 5.83 (ddd, $^3J_{3\text{-H},4\text{-Hb}}$ = 17.2 Hz, $^3J_{3\text{-H},4\text{-Ha}}$ = 10.6 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 5.7 Hz, 1H, 3-H), 7.25−7.29 (m, 3H, H-arom), 7.31−7.35 (m, 6H, H-arom), 7.44−7.48 (m, 6H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$): δ 67.4 (CH_2-1), 72.0 (CH-2), 86.7 (CPh_3), 116.3 (CH_2-4), 127.1 (CH-arom), 127.9 (CH-arom), 128.6 (CH-arom), 136.9 (CH-3), 143.7 (C-arom); MS (EI) *m*/*z* (%) 330 (1, M^+) 243 (100, Trt), 228 (15), 215 (15), 183 (22), 165 (90), 105 (40), 77 (25), consistent with the literature data.[63] Anal. Calcd for $C_{23}H_{22}O_2$: C,83.60; H, 6.71. Found: C, 83.43; H, 6.58.

(±)-2-Hydroxybut-3-enyl Pivalate (5d).[62] Pivaloyl chloride (2.40 g, 19.9 mmol) was slowly added to a cold (0 °C) solution of diol (±)-**4** (1.78 g, 20.2 mmol), Et_3N (10 mL), and DMAP (100 mg, 0.82 mmol) in dichloromethane (20 mL), and the reaction mixture was stirred at room temperature for 24 h and then quenched with saturated aqueous NaCl (50 mL), extracted with ethyl acetate (3 × 100 mL), dried (Na_2SO_4), and evaporated. Gradient chromatography on a column of silica gel (5 × 10 cm) with a mixture of hexanes and ethyl acetate (95:5 to 80:20) gave (±)-**5d** as a colorless oil (1.81 g, 53%): ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 1.13 (s, 9H, *t*-Bu), 2.94 (s, 1H, 2-OH), 3.99 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 11.4 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 6.6 Hz, 1H, 1-Ha), 4.04 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 11.4 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 4.3 Hz, 1H, 1-Hb), 4.26−4.31 (m, 1H, 2-H), 5.14 (ddd, $^3J_{4\text{-Ha},3\text{-H}}$ = 10.6 Hz, $^2J_{4\text{-Ha},4\text{-Hb}}$ = 1.4 Hz, $^4J_{4\text{-Ha},2\text{-H}}$ = 1.4 Hz, 1H, 4-Ha), 5.29 (ddd, $^3J_{4\text{-Hb},3\text{-H}}$ = 17.2 Hz, $^2J_{4\text{-Hb},4\text{-Ha}}$ = 1.4 Hz, $^4J_{4\text{-Hb},2\text{-H}}$ = 1.4 Hz,1H, 4-Hb), 5.78 (ddd, $^3J_{3\text{-H},4\text{-Hb}}$ = 17.2 Hz, $^3J_{3\text{-H},4\text{-Ha}}$ = 10.6 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 5.6 Hz, 1H, 3-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 27.0 ($C(CH_3)_3$), 38.6 ($C(CH_3)_3$), 67.3 (CH_2-1), 70.7 (CH-2), 116.6 (CH_2-4), 136.4 (CH-3), 178.6 (CO carbonyl); MS (CI) *m*/*z* (%) 173 (98, M + H^+), 155 (100, M^+ − OH), 103 (22, M^+ − *t*Bu − H_2O); HRMS (CI) 173.1180 [$C_9H_{17}O_3$ (M + H^+) requires 173.1178]; consistent with the literature data.[62]

(±)-*tert*-Butyl 1-(*tert*-Butyldiphenylsilyloxy)but-3-en-2-yl Carbonate (±)-(6b). A solution of *n*-butyllithium (5.0 mL, 2.0 M in pentane) was added slowly to a solution of silylated diol (±)-**5b** (3.260 g, 9.98 mmol) in THF (10 mL) at 0 °C. The resulting solution was stirred at 0 °C for 20 min and than transferred, at room temperature (via canula), to a solution of Boc anhydride (2.45 g, 11.2 mmol) in THF (30 mL) and stirred at room temperature overnight. The reaction was quenched with brine (20 mL), diluted with ethyl acetate (100 mL), washed with brine (3 × 50 mL), dried (Na_2SO_4), and evaporated. Chromatography on a column of silica gel (5 × 15 cm) with a mixture of hexanes and ethyl acetate (95:5) gave (±)-**6b** as a yellowish oil (4.03 g, 94%): ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 1.06 (s, 9H, *t*-Bu), 1.51 (s, 9H, *t*-Bu), 3.70 (dd, $^2J_{1\text{-H},1\text{-H}}$ = 10.9 Hz, $^3J_{1\text{-H},2\text{-H}}$ = 4.5 Hz, 1H, 1-H), 3.77 (dd, $^2J_{1\text{-H},1\text{-H}}$ = 10.9 Hz, $^3J_{1\text{-H},2\text{-H}}$ = 7.3 Hz, 1H, 1-H), 5.23 (dt, $^3J_{\text{cis-4-H},3\text{-H}}$ = 10.7 Hz, $^2J_{4\text{-H},4\text{-H}}$ = 1.2 Hz, 1H, 4-H), 5.26 (m, 1H, 2-H), 5.34 (dt, $^3J_{\textit{trans}\text{-4-H},3\text{-H}}$ = 17.3 Hz, $^2J_{4\text{-H},4\text{-H}}$ = 1.2 Hz, 1H, 4-H), 5.81 (ddd, $^3J_{3\text{-H},\textit{trans}\text{-4-H}}$ = 17.1 Hz, $^3J_{3\text{-H},\textit{cis}\text{-4-H}}$ = 10.6 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 6.4 Hz, 1H, 3-H), 7.37−7.46 (m, 6H, H-arom), 7.68−7.72 (m, 4H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 19.2 ($C(CH_3)_3$), 26.7 ($C(CH_3)_3$), 27.8 ($C(CH_3)_3$), 65.4 (CH_2-1), 77.9 (CH-2), 81.9 ($C(CH_3)_3$), 118.2 (CH_2-4), 127.6 (CH-arom), 129.7 (CH-arom), 133.2 (CH-3), 133.3 (C-arom), 135.6 (CH-arom), 153.0 (CO carbonate); IR (neat) ν 2932 (m), 2858 (m), 1743 (s, CO carbonate), 1428 (m), 1368 (m), 1276 (s), 1254 (s), 1165 (s), 1113 (s), 702 (s) cm^{-1}; MS (CI-NH_3) *m*/*z* (%) 444 (M + NH_4^+, 100), 388 ([M + NH_4^+] − C_4H_8, 15), 371 (5), 326 (5), 309 (MH^+ − C_4H_8−CO_2 − H_2O, 20), 216 (8). Anal. Calcd for $C_{25}H_{34}O_4Si$: C, 70.38; H, 8.03. Found: C, 70.31; H, 8.12.

(*R*)-*tert*-Butyl 1-(*tert*-Butyldiphenylsilyloxy)but-3-en-2-yl Carbonate (*R*)-(+)-(6b). A solution of *n*-butyllithium (2.5 mL, 2.0 M in pentane) was added slowly to a solution of silylated diol (*R*)-**5b** (1.630 g, 4.99 mmol) in THF (10 mL) at 0 °C. The resulting solution was stirred at 0 °C for 20 min and than transferred, at room temperature (via canula), to a solution of Boc anhydride (1.230 g, 5.63 mmol) in THF (20 mL), and the mixture was stirred at room temperature overnight. The reaction was quenched with brine, diluted with ethyl acetate (100 mL), washed with brine (3 × 50 mL), dried (Na_2SO_4), and evaporated. Chromatography on a column of silica gel (5 × 15 cm) with a mixture of hexanes and ethyl acetate (95:5) gave (*R*)-**6b** as a yellowish oil (2.02 g, 95%): $[\alpha]_D$ +17.0 (*c* 1.7, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 1.06 (s, 9H, *t*-Bu), 1.51 (s, 9H, *t*-Bu), 3.70 (dd, $^2J_{1\text{-H},1\text{-H}}$ = 10.9 Hz, $^3J_{1\text{-H},2\text{-H}}$ = 4.5 Hz, 1H, 1-H), 3.77 (dd, $^2J_{1\text{-H},1\text{-H}}$ = 10.9 Hz,

$^3J_{1\text{-H},2\text{-H}}$ = 7.3 Hz, 1H, 1-H), 5.23 (dt, $^3J_{cis\text{-}4\text{-H},3\text{-H}}$ = 10.7 Hz, $^2J_{4\text{-H},4\text{-H}}$ = 1.2 Hz, 1H, 4-H), 5.26 (m, 1H, 2-H), 5.34 (dt, $^3J_{trans\text{-}4\text{-H},3\text{-H}}$ = 17.3 Hz, $^2J_{4\text{-H},4\text{-H}}$ = 1.2 Hz, 1H, 4-H), 5.81 (ddd, $^3J_{3\text{-H},trans\text{-}4\text{-H}}$ = 17.1 Hz, $^3J_{3\text{-H},cis\text{-}4\text{-H}}$ = 10.6 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 6.4 Hz, 1H, 3-H), 7.37−7.46 (m, 6H, H-arom), 7.68−7.72 (m, 4H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 19.2 ($C(CH_3)_3$), 26.7 ($C(CH_3)_3$), 27.8 ($C(CH_3)_3$), 65.4 (CH_2-1), 77.9 (CH-2), 81.9 ($C(CH_3)_3$), 118.2 (CH_2-4), 127.6 (CH-arom), 129.7 (CH-arom), 133.2 (CH-3), 133.3 (C-arom), 135.6 (CH-arom), 152.95 (CO carbonate). Anal. Calcd for $C_{25}H_{34}O_4Si$: C, 70.38; H, 8.03. Found: C, 70.15; H, 8.10.

***tert*-Butyl(dimethyl)(2-(1′-(phenyl)allyloxy)but-3-enyloxy)-silane (12aa).** *n*-Butyllithium (0.5 mL, 1.0 mmol, 2.0 M solution in pentane) was added slowly to a solution of protected butenediol (±)-**5a** (206 mg, 1.00 mmol) in THF (1 mL), and the mixture was stirred at 0 °C for 15 min. The lithium alkoxide thus generated was transferred (via cannula) to a suspension of copper(I) iodide (200 mg, 1.05 mmol) in THF (2 mL) at room temperature. The mixture turned light yellow and was then stirred for 30 min.[64] The resulting mixture was cooled to 0 °C, a cold (0 °C) solution of $[Ir(COD)Cl]_2$ (7.8 mg, 0.011 mmol) and $(t\text{-BuO})_2PN(i\text{Pr})_2$ (6.0 mg, 0.021 mmol) in THF (1 mL) and allyl carbonate (±)-**9a** (124 mg, 0.53 mmol, neat) were added consecutively. The cooling bath was then removed, and the reaction mixture was stirred at room temperature for 16 h. The catalyst was precipitated by adding hexane (5 mL), the mixture was filtered through a pad of silica (3 × 3 cm), and the product was eluted with a mixture of hexanes and ethyl acetate (90:10). Chromatography on a column of silica gel (3 × 10 cm) with a mixture of hexanes and ethyl acetate (98.5:1.5) gave silane **12aa** as a colorless oil (142 mg, 84%, an equimolar mixture of diastereoisomers **A** and **B**): ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.03 (s, 6H, CH_3), 0.08 (s, 3H, CH_3), 0.09 (s, 3H, CH_3), 0.89 (s, 9H, *t*-Bu), 0.92 (s, 9H, *t*-Bu), 3.57 (dd, $^2J_{1A\text{-Ha},1A\text{-Hb}}$ = 10.5 Hz, $^3J_{1A\text{-Ha},2A\text{-H}}$ = 5.3 Hz, 1H, 1A-Ha), 3.63 (dd, $^2J_{1B\text{-Ha},1B\text{-Hb}}$ = 10.5 Hz, $^3J_{1B\text{-Ha},2B\text{-H}}$ = 5.3 Hz, 1H, 1B-Ha), 3.70 (dd, $^2J_{1A\text{-Hb},1A\text{-Ha}}$ = 10.5 Hz, $^3J_{1A\text{-Hb},2A\text{-H}}$ = 6.6 Hz, 1H, 1A-Hb), 3.76 (dd, $^2J_{1B\text{-Hb},1B\text{-Ha}}$ = 10.5 Hz, $^3J_{1B\text{-Hb},2B\text{-H}}$ = 6.6 Hz, 1H, 1B-Hb), 3.83 (ddddd, $^3J_{2\text{-H},3\text{-H}}$ = 6.9 Hz, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.6 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 5.3 Hz, $^4J_{2\text{-H},4\text{-Ha}}$ = 1.0 Hz, $^4J_{2\text{-H},4\text{-Hb}}$ = 1.0 Hz, 1H, 2A-H or 2B-H), 4.06 (ddddd, $^3J_{2\text{-H},3\text{-H}}$ = 6.9 Hz, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.6 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 5.3 Hz, $^4J_{2\text{-H},4\text{-Ha}}$ = 1.0 Hz, $^4J_{2\text{-H},4\text{-Hb}}$ = 1.0 Hz, 1H, 2B-H or 2A-H), 4.95 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 7.2 Hz, 1H, 1′A-H or 1′B-H), 4.95 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.1 Hz, 1H, 1′B-H or 1′A-H), 5.10−5.34 (m, 8H, 4A-H, 3′A-H, 4B-H, and 3′B-H), 5.74 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 17.3 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 10.4 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 6.9 Hz, 1H, 3A-H or 3B-H), 5.77 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 16.2 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 11.5 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 6.9 Hz, 1H, 3B-H or 3A-H), 5.90 (ddd, $^3J_{2'\text{-H},3'\text{-Ha}}$ = 17.3 Hz, $^3J_{2'\text{-H},3'\text{-Hb}}$ = 10.2 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 7.2 Hz, 1H, 2′A-H or 2′B-H), 5.98 (ddd, $^3J_{2'\text{-H},3'\text{-Ha}}$ = 17.2 Hz, $^3J_{2'\text{-H},3'\text{-Hb}}$ = 10.3 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 6.1 Hz, 1H, 2′B-H or 2′A-H), 7.23−7.38 (m, 10H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.37 (CH_3), −5.31 (CH_3), −5.28 (CH_3), −5.18 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.2, and 66.3 (CH_2-1), 78.5, and 78.8 (CH-2), 79.9, and 80.3 (CH-1′), 115.3, 116.7, 117.9, and 118.1 (CH_2-4, and CH_2-3′), 126.7, 127.2, 127.34, 127.5, 128.25, and 128.35 (CH-arom), 136.1, and 136.3 (CH-3), 138.8, and 139.5 (CH-2′), 141.0, and 141.5 (C-arom); IR (NaCl, neat) ν 2956 (s), 2929 (s), 2857 (s), 1472 (m), 1257 (s), 1087 (s), 838 (s) cm^{-1}; MS (CI-NH_3, 160 °C) *m*/*z* (%) 336 ([M + NH_4^+], 30), 117 (100); HRMS (CI-NH_3, 100 °C) 336.2357 [$C_{19}H_{34}NO_2Si$ (M + NH_4^+) requires 336.2359]. Anal. Calcd for $C_{19}H_{30}O_2Si$: C, 71.64; H, 9.49. Found: C, 71.26; H, 9.57.

***tert*-Butyl(2-(1′-(phenyl)allyloxy)but-3-enyloxy)diphenylsilane (12ba).** *n*-Butyllithium (0.4 mL, 1.0 mmol, 2.5 M solution in hexanes) was added slowly to a solution of protected butenediol (±)-**5b** (326 mg, 1.00 mmol) in THF (1 mL), and the mixture was stirred at 0 °C for 15 min. The lithium alkoxide thus generated was transferred (via cannula) to a suspension of copper(I) iodide (200 mg, 1.05 mmol) in THF (2 mL) at room temperature. The mixture turned light yellow and was then stirred for 30 min.[64] The resulting mixture was cooled to 0 °C, and a cold (0 °C) solution of catalyst ($[Ir(COD)Cl]_2$ (14.0 mg, 0.020 mmol) and ligand (R_a,R_c,R_c)-**11** (14.0 mg, 0.044 mmol) in THF (1 mL) and allyl carbonate **7** (120 mg, 0.51 mmol, neat) were added, respectively. The cooling bath was then removed, and the reaction mixture was stirred at room temperature for 16 h. The catalyst was precipitated by adding hexane (5 mL), the mixture was filtered through a pad of silica (3 × 3 cm), and the product was eluted with a mixture of hexanes and ethyl acetate (90:10). Chromatography on a column of silica gel (3 × 10 cm) with a mixture of hexanes and Et_2O (95:5) gave **12ba** as a colorless oil (198 mg, 93%): ^{1}H NMR (400.1 MHz, $CDCl_3$, a mixture of diastereoisomers in a 1:1.8 ratio, the minor diastereoisomer is marked with * where possible) δ 1.07* 1.10 (s, 9H, *t*-Bu), 3.28*−3.50* 3.62−3.86 (m, 2H, CH_2), 3.92*−3.97* 4.14−4.18 (m, 1H, CH_2CH), 4.98 (d, J_{HH} = 7.2 Hz, 0.6H, PhC*H*), 5.06* (d, J_{HH} = 7.5 Hz, 0.4H, PhC*H*), 5.11−5.36 (m, 4H, CH_2=CH), 5.72−5.80 and 5.77*−5.84* and 5.86−5.96 and 5.95*−6.04* (m, 2H, CH_2=C*H*), 7.22−7.47 and 7.66−7.76 (m, 15H, Ph); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 26.8 and 27.0 (*t*Bu), 66.8 (CH_2CH), 78.4 and 78.5 (CH_2CH), 79.7 and 80.2 (PhCH), 115.1 and 116.6 and 117.9 and 118.1 (CH_2=CH), 126.7, 127.2, 127.6, 129.5, 129.6, 133.5, 133.6, 135.6, 135.7, 135.9, 136.0, 136.1, 141.0, 141.5. MS (CI-NH_3, 150 °C) *m*/*z* (%) 460 ([M + NH_4^+], 95), 444 (5), 364 (10), 252 (30), 193 (15), 52 (100); HRMS (CI-NH_3, 100 °C) 460.2670 [$C_{29}H_{38}NO_2Si$ (M + NH_4^+) requires 460.2672].

***tert*-Butyl(2-(1′-(4″-bromophenyl)allyloxy)but-3-enyloxy)-diphenylsilane (12bc).** *n*-BuLi (1.2 mL, 3.0 mmol, 2.5 M solution in hexanes) was slowly added to a solution of the protected butenediol (±)-**5b** (920 mg, 2.82 mmol) in THF (3 mL) at 0 °C, and the mixture was stirred for 15 min at 0 °C and then transferred (via cannula) to a suspension of copper(I) iodide (600 mg, 1.15 mmol) in THF (6 mL) at room temperature. The mixture turned to light yellow and was stirred for 30 min. The resulting mixture was cooled to 0 °C, and a cold (0 °C) solution of $[Ir(COD)Cl]_2$ (19.7 mg, 0.029 mmol)) in THF (2 mL) was added, followed by allyl carbonate (±)-**9c** (674 mg, 2.15 mmol, neat). The cooling bath was removed, and the reaction mixture was stirred at room temperature for 16 h. The catalyst was precipitated by adding hexane (5 mL), and the mixture was filtered through a pad of silica (3 × 3 cm), using a mixture of hexanes and AcOEt (9:1) as eleuent. Chromatography of the crude product on a column of silica gel (3 × 10 cm) with a mixture of hexanes and AcOEt (98.5:1.5) afforded pure silane **12bc** as a colorless oil (711 mg, 62%, mixture of diastereoisomers **A**, **B**): ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 1.05 (s, 9H, *t*-Bu), 1.08 (s, 9H, *t*-Bu), 3.62 (dd, $^2J_{1A\text{-Ha},1A\text{-Hb}}$ = 10.5 Hz, $^3J_{1A\text{-Ha},2A\text{-H}}$ = 4.7 Hz, 1H, 1A-Ha), 3.69 (dd, $^2J_{1B\text{-Ha},1B\text{-Hb}}$ = 10.5 Hz, $^3J_{1B\text{-Ha},2B\text{-H}}$ = 4.8 Hz, 1H, 1B-Ha), 3.75 (dd, $^2J_{1A\text{-Hb},1A\text{-Ha}}$ = 10.5 Hz, $^3J_{1A\text{-Hb},2A\text{-H}}$ = 6.9 Hz, 1H, 1A-Hb), 3.81 (dd, $^2J_{1B\text{-Hb},1B\text{-Ha}}$ = 10.5 Hz, $^3J_{1B\text{-Hb},2B\text{-H}}$ = 6.7 Hz, 1H, 1B-Hb), 3.87 (dddt, $^3J_{2A\text{-H},1A\text{-Hb}}$ = 6.9 Hz, $^3J_{2A\text{-H},3A\text{-H}}$ = 5.7 Hz, $^3J_{2A\text{-H},1A\text{-Ha}}$ = 4.7 Hz, $^4J_{2A\text{-H},4A\text{-H}}$ = 1.0 Hz, 1H, 2A-H), 4.11 (tdt, $^3J_{2B\text{-H},1B\text{-Hb}}$ = 6.7 Hz, $^3J_{2B\text{-H},3B\text{-H}}$ = 6.7 Hz, $^3J_{2B\text{-H},1B\text{-Ha}}$ = 4.8 Hz, $^4J_{2B\text{-H},4B\text{-H}}$ = 1.0 Hz, 1H, 2B-H), 4.90−4.92 (m, 2H, 1′A-H, and 1′B-H), 5.12−5.33 (m, 8H, 3′A-H, 3′B-H, 4A-H, and 4B-H), 5.68−5.97 (m, 4H, 2′A-H, 2′B-H, 3A-H, and 3B-H), 7.22−7.51 (m, 20H, H-arom), 7.65−7.74 (m, 8H, H-arom). Anal. Calcd for $C_{29}H_{33}BrO_2Si$: C, 66.78; H, 6.38. Found: C, 66.64; H, 6.72.

***tert*-Butyl(2-(1′-(4″-fluorophenyl)allyloxy)but-3-enyloxy)-diphenylsilane (12be).** *n*-Butyllithium (1.2 mL, 3.0 mmol, 2.5 M solution in hexanes) was added slowly to a solution of protected butenediol (±)-**5b** (986 mg, 3.02 mmol) in THF (3 mL), and the mixture was stirred at 0 °C for 15 min. The lithium alkoxide thus generated was transferred (via cannula) to a suspension of copper(I) iodide (600 mg, 3.15 mmol) in THF (6 mL) at room temperature. The mixture turned light yellow and was then stirred for 30 min.[63] The resulting mixture was cooled to 0 °C, and a cold (0 °C) solution of $[Ir(COD)Cl]_2$ (20.7 mg, 0.031 mmol) in THF (3 mL) and allyl carbonate (±)-**9e** (508 mg, 2.01 mmol, neat) were added consecutively. The cooling bath was then removed, and the reaction mixture was stirred at room temperature for 16 h. The catalyst was precipitated by adding

hexane (5 mL), the mixture was filtered through a pad of silica (3 × 3 cm), and the product was eluted with a mixture of hexanes and ethyl acetate (90:10). Chromatography on a column of silica gel (3 × 10 cm) with a mixture of hexanes and ethyl acetate (98.5:1.5) gave silane **12be** as a colorless oil (733 mg, 79%, mixture of diastereoisomers **A**, **B**: ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 1.06 (s, 9H, *t*-Bu), 1.09 (s, 9H, *t*-Bu), 3.63 (dd, $^2J_{1A\text{-}Ha,1A\text{-}Hb}$ = 10.5 Hz, $^3J_{1A\text{-}Ha,2A\text{-}H}$ = 4.7 Hz, 1H, 1A-Ha), 3.70 (dd, $^2J_{1B\text{-}Ha,1B\text{-}Hb}$ = 10.5 Hz, $^3J_{1B\text{-}Ha,2B\text{-}H}$ = 4.9 Hz, 1H, 1B-Ha), 3.76 (dd, $^2J_{1A\text{-}Hb,1A\text{-}Ha}$ = 10.5 Hz, $^3J_{1A\text{-}Hb,2A\text{-}H}$ = 6.8 Hz, 1H, 1A-Hb), 3.83 (dd, $^2J_{1B\text{-}Hb,1B\text{-}Ha}$ = 10.5 Hz, $^3J_{1B\text{-}Hb,2B\text{-}H}$ = 6.6 Hz, 1H, 1B-Hb), 3.89 (dddt, $^3J_{2A\text{-}H,1A\text{-}Hb}$ = 6.8 Hz, $^3J_{2A\text{-}H,3A\text{-}H}$ = 5.7 Hz, $^3J_{2A\text{-}H,1A\text{-}Ha}$ = 4.7 Hz, $^4J_{2A\text{-}H,4A\text{-}H}$ = 1.0 Hz, 1H, 2A-H), 4.13 (dddt, $^3J_{2B\text{-}H,1B\text{-}Hb}$ = 6.6 Hz, $^3J_{2B\text{-}H,3B\text{-}H}$ = 5.9 Hz, $^3J_{2B\text{-}H,1B\text{-}Ha}$ = 4.9 Hz, $^4J_{2B\text{-}H,4B\text{-}H}$ = 1.1 Hz, 1H, 2B-H), 4.93−4.96 (m, 2H, 1′A-H, and 1′B-H), 5.12−5.34 (m, 8H, 3′A-H, 3′B-H, 4A-H, and 4B-H), 5.70−6.00 (m, 4H, 2′A-H, 2′B-H, 3A-H, and 3B-H), 6.98−7.05 (m, 4H, H-arom), 7.31−7.47 (m, 16H, H-arom), 7.65−7.76 (m, 8H, H-arom); HRMS (CI-NH_3, 100 °C) 478.2576 [$C_{29}H_{37}FNO_2Si$ (M + NH_4^+) requires 478.2578].

(*E*)-1,3-Diphenylpropene (14a). *n*-Butyllithium (0.5 mL, 1.0 mmol, 2.0 M solution in pentane) was added slowly to a solution of protected butenediol **5b** (326 mg, 1.00 mmol) in THF (1 mL), and the mixture was stirred at 0 °C for 15 min. The lithium alkoxide thus generated was transferred (via cannula) to a suspension of copper(I) iodide (200 mg, 1.05 mmol) in THF (2 mL) at room temperature. The mixture turned light yellow and was then stirred for 30 min.[64] The resulting mixture was cooled to 0 °C, and a cold (0 °C) solution of $Rh(PPh)_3Cl$ (61.1 mg, 0.066 mmol) and $P(OMe)_3$ (25.0 mg, 0.201 mmol) in THF (1.0 mL) and allyl carbonate **9a** (136 mg, 0.58 mmol, neat) were added, respectively. The cooling bath was then removed, and the reaction mixture was stirred at room temperature for 16 h. The catalyst was precipitated by adding hexane (5 mL), the mixture was filtered through a pad of silica (3 × 3 cm), and the product was eluted with a mixture of hexanes and ethyl acetate (90:10). Chromatography on a column of silica gel (3 × 10 cm) with hexanes gave **14a** as a colorless oil (26 mg, 46% of theory, 77% based on recovered carbonate). Subsequent elution with a mixture of hexanes and ethyl acetate (98.5:1.5) gave carbonate **9a** as a colorless oil (55 mg, 40% recovered). **14a**: ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 3.47 (d, $^3J_{3\text{-}H,2\text{-}H}$ = 6.6 Hz, 2H, 3-H), 6.28 (dt, $^3J_{2\text{-}H,1\text{-}H}$ = 15.8 Hz, $^3J_{2\text{-}H,3\text{-}H}$ = 6.6 Hz, 1H, 2-H), 6.38 (d, $^3J_{1\text{-}H,2\text{-}H}$ = 15.8 Hz, 1H, 1-H), 7.10−7.29 (m, 10H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 39.3 (CH_2-3), 126.1, 126.2, 127.1, 128.47, 128.48, and 128.65 (CH-arom), 129.2 (CH-2), 131.1 (CH-1), 137.5 (C-1′), 140.1 (C-1″); MS (EI) *m*/*z* (%) 194 (M^+, 40), 179 (15), 115 (20), 83 (100); HRMS (EI) 194.1094 [$C_{15}H_{14}$ (M^+) requires 194.1096], consistent with the literature data.[65]

(*E*)-1,3-Bis(4′-fluorophenyl)propene (14b). *n*-Butyllithium (0.4 mL, 1.0 mmol, 2.5 M solution in hexanes) was added slowly to a solution of protected butenediol **5b** (326 mg, 1.00 mmol) in THF (1 mL), and the mixture was stirred at 0 °C for 15 min. The lithium alkoxide thus generated was transferred (via cannula) to a suspension of copper(I) iodide (200 mg, 1.05 mmol) in THF (2 mL) at room temperature. The mixture turned light yellow and was then stirred for 30 min.[64] The resulting mixture was cooled to 0 °C, and a cold (0 °C) solution of $[Rh(COD)Cl]_2$ (10.1 mg, 0.020 mmol) in THF (1.0 mL) and allyl carbonate **9e** (136 mg, 0.54 mmol, neat) were added, respectively. The cooling bath was then removed, and the reaction mixture was stirred at room temperature for 16 h. The catalyst was precipitated by adding hexane (5 mL), the mixture was filtered through a pad of silica (3 × 3 cm), and the product was eluted with a mixture of hexanes and ethyl acetate (90:10). Chromatography on a column of silica gel (3 × 10 cm) with hexanes gave **14b** as a colorless oil (27 mg, 43%). Subsequent elution with a mixture of hexanes and ethyl acetate (98.5:1.5) gave diallyl ether **12be** as a colorless oil (78 mg, 31%). **14b**: ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 3.45 (d, $^3J_{3\text{-}H,2\text{-}H}$ = 6.8 Hz, 2H, 3-H), 6.19 (dt, $^3J_{2\text{-}H,1\text{-}H}$ = 15.7 Hz, $^3J_{2\text{-}H,3\text{-}H}$ = 6.8 Hz, 1H, 2-H), 6.33 (d, $^3J_{1\text{-}H,2\text{-}H}$ = 15.7 Hz, 1H, 1-H), 6.87−6.92 (m, 2H, H-arom), 7.12−7.25 (m, 6H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 38.2 (CH_2-3), 114.8 (d, $^2J_{CF}$ = 21.7 Hz, CH-3″), 115.3 (d, $^2J_{CF}$ = 22.9 Hz, CH-3′), 126.3 (CH-2), 130.1 (d, $^3J_{CF}$ = 8.1 Hz, CH-2′), 130.3 (d, $^3J_{CF}$ = 8.2 Hz, CH-2″), 130.9 (CH-1), 133.7 (d, $^4J_{CF}$ = 1.1 Hz, C-1′), 136.8 (d, $^4J_{CF}$ = 3.1 Hz, C-1″), 160.3 (d, $^1J_{CF}$ = 249.2 Hz, CF-4′), 162.1 (d, $^1J_{CF}$ = 246.1 Hz, CF-4″); HRMS (EI) 230.0910 [$C_{15}H_{12}F_2$ (M^+) requires 230.0907].

General Procedure B: Iridium-Catalyzed Allylic Substitution with Chiral Precursors. *n*-Buthyllithium (3.0 mL, 6.0 mmol, 2.0 M solution in pentane) was added slowly to a solution of the protected enantiopure butenediol **5** (1.236 g, 6.11 mmol) in THF (6 mL), and the mixture was stirred at 0 °C for 15 min. The lithium alkoxide thus generated was transferred (via cannula) to a suspension of copper(I) iodide (1.200 g, 6.30 mmol) in THF (12 mL) at room temperature. The mixture turned light yellow and was then stirred for 30 min.[64] The resulting mixture was cooled to 0 °C, and a cold (0 °C) solution of $[Ir(COD)Cl]_2$ (40.0 mg, 0.060 mmol) in THF (3.5 mL) and enantiopure allyl carbonate **9** (1.133 g, 4.84 mmol, neat) were added consecutively. The cooling bath was then removed, and the reaction mixture was stirred at room temperature for 16 h. The catalyst was precipitated by adding hexane (5 mL), the mixture was filtered through a pad of silica (3 × 3 cm), and the product was eluted with a mixture of hexanes and ethyl acetate (90:10). Chromatography on a column of silica gel (3 × 10 cm) with a mixture of hexanes and ethyl acetate (98.5:1.5) gave respective silane (**15**−**18**) as a colorless oil.

(2*S*,1′*R*)-*tert*-Butyl(dimethyl)(2-(1′-(phenyl)allyloxy)but-3-enyloxy)silane (2*S*,1′*R*)-(15a). Method 1. Following general procedure B, the protected butenediol (*S*)-**5a** (1.236 g, 6.11 mmol) was coupled with allyl carbonate (*R*)-**9a** (1.133 g, 4.84 mmol, neat) to obtain ether (2*S*,1′*R*)-**15a** as a colorless oil (1.263 g, 82%, as a single diastereoisomer): $[\alpha]_D$ +25.3 (*c* 1.11, MeOH); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.04 (s, 6H, CH_3), 0.89 (s, 9H, *t*-Bu), 3.58 (dd, $^2J_{1\text{-}Ha,1\text{-}Hb}$ = 10.5 Hz, $^3J_{1\text{-}Ha,2\text{-}H}$ = 5.3 Hz, 1H, 1-Ha), 3.71 (dd, $^2J_{1\text{-}Hb,1\text{-}Ha}$ = 10.5 Hz, $^3J_{1\text{-}Hb,2\text{-}H}$ = 6.6 Hz, 1H, 1-Hb), 3.84 (ddddd, $^3J_{2\text{-}H,3\text{-}H}$ = 7.0 Hz, $^3J_{2\text{-}H,1\text{-}Hb}$ = 6.6 Hz, $^3J_{2\text{-}H,1\text{-}Ha}$ = 5.3 Hz, $^4J_{2\text{-}H,4\text{-}Ha}$ = 0.8 Hz, $^4J_{2\text{-}H,4\text{-}Hb}$ = 0.8 Hz, 1H, 2-H), 4.96 (d, $^3J_{1'\text{-}H,2'\text{-}H}$ = 6.1 Hz, 1H, 1′-H), 5.12−5.28 (m, 4H, 4-H, and 3′-H), 5.78 (ddd, $^3J_{3\text{-}H,4\text{-}Ha}$ = 16.2 Hz, $^3J_{3\text{-}H,4\text{-}Hb}$ = 11.4 Hz, $^3J_{3\text{-}H,2\text{-}H}$ = 7.0 Hz, 1H, 3-H), 5.98 (ddd, $^3J_{2'\text{-}H,3'\text{-}Ha}$ = 17.1 Hz, $^3J_{2'\text{-}H,3'\text{-}Hb}$ = 10.4 Hz, $^3J_{2'\text{-}H,1'\text{-}H}$ = 6.1 Hz, 1H, 2′-H), 7.25−7.38 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.37 (CH_3), −5.28 (CH_3), 18.3 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.2 (CH_2-1), 78.5 (CH-2), 79.9 (CH-1′), 115.3, and 118.1 (CH_2-4, and CH_2-3′), 127.2, 127.5, and 128.3 (CH-arom), 136.1 (CH-3), 139.5 (CH-2′), 141.0 (C-arom); IR (NaCl, neat) ν 2955 (s), 2928 (s), 2857 (s), 1471 (m), 1255 (s), 1121 (s), 1083 (s), 838 (s) cm^{-1}; MS (CI-NH_3, 150 °C) *m*/*z* (%) 336 ([M + NH_4^+], 100), 134 (90), 117 (60). Anal. Calcd for $C_{19}H_{30}O_2Si$: C, 71.64; H, 9.49. Found: C, 71.80; H, 9.52.

Method 2. *n*-Butyllithium (1.25 mL, 2.0 mmol, 1.6 M solution in hexanes) was added dropwise to a solution of the protected butenediol (*S*)-**5a** (419 mg, 2.07 mmol) in THF (2 mL), and the mixture was stirred at −40 °C for 30 min. The lithium alkoxide thus generated was rapidly transferred to a suspension of copper(I) iodide (400 mg, 2.10 mmol) in THF (4 mL) at −40 °C. The mixture was stirred for 30 min at −40 °C, placed in an ice bath, and stirred for another 30 min. Finally, a cold (0 °C) solution of $[Ir(COD)Cl]_2$ (13.8 mg, 0.040 mmol) and the chiral ligand (R_a,R_c,R_c)-**11** (37.0 mg, 0.060 mmol) in THF (2 mL) and cinnamyl carbonate **7** (235 mg, 1.00 mmol, neat) were added consecutively. The cooling bath was then removed, and the reaction mixture was stirred at room temperature for 16 h. The catalyst was precipitated by adding hexane (5 mL), the mixture was filtered through a pad of silica (3 × 3 cm), and the product was eluted with a mixture of hexanes and ethyl acetate (90:10). Chromatography on a column of silica gel (15 g) with a mixture of hexanes, ether, and acetone (250:1:1) afforded silane

(2*S*,1′*R*)-**15a** as a colorless oil together with its diastereoisomer (2*S*,1′*S*)-**16a** and the rearranged silane **13** (195 mg, 61% combined yield; in a 91:3:6 ratio as shown by GC): ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.04 (s, 6H, CH_3), 0.89 (s, 9H, *t*-Bu), 3.58 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.5 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 5.3 Hz, 1H, 1-H_a), 3.71 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.5 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.6 Hz, 1H, 1-H_b), 3.84 (ddddd, $^3J_{2\text{-H},3\text{-H}}$ = 7.0 Hz, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.6 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 5.3 Hz, $^4J_{2\text{-H},4\text{-Ha}}$ = 0.8 Hz, $^4J_{2\text{-H},4\text{-Hb}}$ = 0.8 Hz, 1H, 2-H), 4.96 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.1 Hz, 1H, 1′-H), 5.12−5.28 (m, 4H, 4-H, and 3′-H), 5.78 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 16.2 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 11.4 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 7.0 Hz, 1H, 3-H), 5.98 (ddd, $^3J_{2'\text{-H},3'\text{-Ha}}$ = 17.1 Hz, $^3J_{2'\text{-H},3'\text{-Hb}}$ = 10.4 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 6.1 Hz, 1H, 2′-H), 7.25−7.38 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.37 (CH_3), −5.28 (CH_3), 18.3 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.2 (CH_2-1), 78.5 (CH-2), 79.9 (CH-1′), 115.3, and 118.1 (CH_2-4, and CH_2-3′), 127.2, 127.5, and 128.3 (CH-arom), 136.1 (CH-3), 139.5 (CH-2′), 141.0 (C-arom); MS (CI-NH_3, 150 °C) *m*/*z* (%) 336 ([M + NH_4^+], 100), 134 (90), 117 (60); chiral GC (Supelco γ-DEX 120 column, oven for 1 min at 160 °C, then 0.5 deg·min^{-1}) showed 97:3 dr (t_{SR} = 16.4 min, t_{SS} = 18.3 min) and 6% of the rearranged product (t_{xSR} = 18.5 min).

(2*S*,1′*R*)-*tert*-Butyl(2-(1′-(3″-fluorophenyl)allyloxy)but-3-enyloxy)dimethylsilane (2*S*,1′*R*)-(15b). Following general procedure B, the protected butenediol (*S*)-**5a** (3.440 g, 17.00 mmol) was coupled with allyl carbonate (*R*)-**9b** (3.605 g, 14.29 mmol, neat) to obtain ether (2*S*,1′*R*)-**15b** as a colorless oil (3.557 g, 74%): $[\alpha]_D$ +18.3 (*c* 3.06, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.06 (s, 6H, CH_3), 0.90 (s, 9H, *t*-Bu), 3.60 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.6 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 4.9 Hz, 1H, 1-Ha), 3.71 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.6 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.8 Hz, 1H, 1-Hb), 3.85 (ddddd, $^3J_{2\text{-H},3\text{-H}}$ = 7.0 Hz, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.8 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 4.9 Hz, J_{HH} = 1.0 Hz, J_{HH} = 1.0 Hz, 1H, 2-H), 4.96 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.1 Hz, 1H, 1′-H), 5.15 (ddd, J_{HH} = 10.4 Hz, J_{HH} = 1.4 Hz, J_{HH} = 1.4 Hz, 1H, 3′′′′-Ha or 3′-Hb), 5.21−5.29 (m, 3H, 3′-Hb or 3′-Ha, 4-Ha, and 4-Hb), 5.76 (ddd, J_{HH} = 17.4 Hz, J_{HH} = 10.8 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 7.0 Hz, 1H, 3-H), 5.94 (ddd, J_{HH} = 17.1 Hz, J_{HH} = 10.3 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 6.1 Hz, 1H, 2′-H), 6.94−6.99 (m, 1H, 4″-H), 7.10−7.14 (m, 2H, 2″-H, and 6″-H), 7.27−7.32 (m, 1H, 5″-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.39 (CH_3), −5.30 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.3 (CH_2-1), 78.4 (d, $^4J_{CF}$ = 1.7 Hz, CH-1′), 79.0 (CH-2), 114.0 (d, $^2J_{CF}$ = 21.7 Hz, CH-2″), 114.4 (d, $^2J_{CF}$ = 21.3 Hz, CH-4″), 115.7 (CH_2-3′), 118.2 (CH_2-4), 122.7 (d, $^4J_{CF}$ = 2.8 Hz, CH-6″), 129.8 (d, $^3J_{CF}$ = 8.1 Hz, CH-5″), 136.9 (CH-3), 139.0 (CH-2′), 143.9 (d, $^3J_{CF}$ = 6.6 Hz, C-1″), 163.0 (d, $^1J_{CF}$ = 245.9 Hz, CF-3″); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.6; IR (NaCl, neat) ν 2955 (s), 2929 (s), 2858 (s), 1614 (m), 1592 (m), 1296 (s), 1126 (s), 1086 (s) cm^{-1}; MS (CI) *m*/*z* (%) 337 ([M + H^+], 5), 135 (100); HRMS (CI) 337.1997 [$C_{19}H_{30}FO_2Si$ (M + H^+) requires 337.1999]. Anal. Calcd for $C_{19}H_{29}FO_2Si$: C, 67.81; H, 8.69. Found: C, 67.55; H, 8.70.

(2*S*,1′*S*)-*tert*-Butyl(dimethyl)(2-(1′-(phenyl)allyloxy)but-3-enyloxy)silane (2*S*,1′*S*)-(16a). Method 1. Following general procedure B, the protected butenediol (*S*)-**5a** (556 mg, 2.74 mmol) was coupled with allyl carbonate (*S*)-**9a** (436 mg, 1.86 mmol, neat) to obtain ether (2*S*,1′*S*)-**16a** as a colorless oil (468 mg, 79%, as a single diastereoisomer): $[\alpha]_D$ +11.5 (*c* 0.78, MeOH); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.08 (s, 3H, CH_3), 0.09 (s, 3H, CH_3), 0.92 (s, 9H, *t*-Bu), 3.63 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.5 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 5.3 Hz, 1H, 1-Ha), 3.76 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.5 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.6 Hz, 1H, 1-Hb), 4.06 (ddddd, $^3J_{2\text{-H},3\text{-H}}$ = 6.9 Hz, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.6 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 5.3 Hz, $^4J_{2\text{-H},4\text{-Ha}}$ = 0.9 Hz, $^4J_{2\text{-H},4\text{-Hb}}$ = 0.9 Hz, 1H, 2-H), 4.95 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 7.3 Hz, 1H, 1′-H), 5.20−5.35 (m, 4H, 4-Ha, 4-Hb, 3′-Ha, and 3′-Hb), 5.74 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 17.3 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 10.4 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 6.9 Hz, 1H, 3-H), 5.90 (ddd, $^3J_{2'\text{-H},3'\text{-Ha}}$ = 17.3 Hz, $^3J_{2'\text{-H},3'\text{-Hb}}$ = 10.2 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 7.3 Hz, 1H, 2′-H), 7.23−7.38 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.3 (CH_3), −5.2 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.3 (CH_2-1), 78.8 (CH-2), 80.3 (CH-1′), 116.7, 117.8 (CH_2-4, and CH_2-3′), 126.7, 127.3, and 128.3 (CH-arom), 136.3 (CH-3), 138.8 (CH-2′), 141.5 (C-arom); IR (NaCl, neat) ν 2955 (s), 2928 (s), 2857 (s), 1471 (m), 1255 (s), 1128 (s), 1086 (s) cm^{-1}; MS (CI-NH_3, 150 °C) *m*/*z* (%) 336 ([M + NH_4^+], 95), 117 (100). Anal. Calcd for $C_{19}H_{30}O_2Si$: C, 71.64; H, 9.49. Found: C, 71.75; H, 9.57.

Method 2. *n*-Butyllithium (0.625 mL, 1.0 mmol, 1.6 M solution in pentane) was added slowly to a solution of protected butenediol (*S*)-**5a** (205 mg, 1.01 mmol) in THF (1 mL), and the mixture was stirred at 0 °C for 15 min. The lithium alkoxide thus generated was transferred (via cannula) to a suspension of copper(I) iodide (205 mg, 1.05 mmol) in THF (2 mL) at room temperature. The mixture turned light yellow and was then stirred for 30 min. The resulting mixture was cooled to 0 °C, and a cold (0 °C) solution of $[Ir(COD)Cl]_2$ (7.5 mg, 0.011 mmol) and ligand (S_a,S_c,S_c)-**10** (12.5 mg, 0.023 mmol) in THF (2 mL) and cinnamyl carbonate **7** (190 mg, 0.81 mmol, neat) were added consecutively. The cooling bath was then removed, and the reaction mixture was stirred at room temperature for 48 h. The catalyst was precipitated by adding hexane (5 mL), the mixture was filtered through a pad of silica (1.5 × 1.5 cm), and the product was eluted with a mixture of hexanes and ethyl acetate (90:10). Chromatography on a column of silica gel (1 × 15 cm) with a mixture of hexanes and ethyl acetate (98.5:1.5) afforded silane (2*S*,1′*S*)-**16a** as a colorless oil together with its diastereoisomer (2*S*,1′*R*)-**15a** and the rearranged silane **13** (102 mg, 40% combined yield; in 73:3:24 ratio as shown by ^{1}H NMR): ^{1}H NMR (400.1 MHz, $CDCl_3$, the regioisomer **13** is marked with * where possible) δ 0.08 0.09 0.10* (s, 6H, CH_3), 0.92 (s, 9H, *t*-Bu), 3.31* (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 9.6 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 5.6 Hz, 1H, 1-H_a), 3.41* (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 9.6 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.9 Hz, 1H, 1-H_b), 3.63 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.5 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 5.3 Hz, 1H, 1-H_a), 3.76 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.5 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.6 Hz, 1H, 1-H_b), 4.06 (ddddd, $^3J_{2\text{-H},3\text{-H}}$ = 6.9 Hz, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.6 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 5.3 Hz, $^4J_{2\text{-H},4\text{-Ha}}$ = 0.9 Hz, $^4J_{2\text{-H},4\text{-Hb}}$ = 0.9 Hz, 1H, 2-H), 4.34−4.38* (m, 1H, 2-H), 4.78* (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.7 Hz, 1H, 1′-H), 4.95 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 7.3 Hz, 1H, 1′-H), 5.10−5.35 (m, 4H, 4-H_a, 4-H_b, 3′-H_a, and 3′-H_b), 5.74 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 17.3 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 10.4 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 6.9 Hz, 1H, 3-H), 5.82−5.97 (m, 1H, 2′-H, 2′-H*, 3-H*), 7.23−7.38 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ -5.3 (CH_3), −5.2 (CH_3), −4.7* (CH_3), 18.32* 18.35 ($C(CH_3)_3$), 25.85* 25.91 ($C(CH_3)_3$), 66.3 (CH_2-1), 72.8* (CH_2-2), 73.2* (CH_2-1), 78.8 (CH-2), 80.3 (CH-1′), 83.4* (CH-1′), 114.9*, 116.0* (CH_2-4, and CH_2-3′), 116.7 (CH_2-3′), 117.8 (CH_2-4), 126.7, 126.8*, 127.3, 127.5*, 128.25 and 128.34 (CH-arom), 136.3 (CH-3), 138.6* (CH-double bond) 138.8 (CH-2′), 138.98* (CH-double bond), 141.06*, 141.53 (C-arom).

(2*S*,1′*S*)-*tert*-Butyl(dimethyl)(2-(1′-(3″-fluorophenyl)allyloxy)-but-3-enyloxy)silane (2*S*,1′*S*)-(16b). Following general procedure B, the protected butenediol (*S*)-**5a** (1.641 g, 8.11 mmol) was coupled with allyl carbonate (*S*)-**9b** (1.700 g, 6.73 mmol, neat) to obtain ether (2*S*,1′*S*)-**16b** as a colorless oil (1.765 g, 78%): $[\alpha]_D$ +15.2 (*c* 3.10, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.10 (s, 3H, CH_3), 0.11 (s, 3H, CH_3), 0.94 (s, 9H, *t*-Bu), 3.66 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.5 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 5.1 Hz, 1H, 1-Ha), 3.78 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.5 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.6 Hz, 1H, 1-Hb), 4.07 (ddddd, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.6 Hz, $^3J_{2\text{-H},3\text{-H}}$ = 6.2 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 5.1 Hz, $^4J_{2\text{-H},4\text{-Ha}}$ = 1.2 Hz, $^4J_{2\text{-H},4\text{-Hb}}$ = 1.0 Hz, 1H, 2-H), 4.96 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 7.3 Hz, 1H, 1′-H), 5.25 (ddd, $^3J_{4\text{-Hb},3\text{-H}}$ = 10.4 Hz, $^2J_{4\text{-Hb},4\text{-Ha}}$ = 1.9 Hz, $^4J_{4\text{-Hb},2\text{-H}}$ = 1.0 Hz, 1H, 4-Hb), 5.28 (ddd, $^3J_{3'\text{-Hb},2'\text{-H}}$ = 10.2 Hz, $^3J_{3'\text{-Hb},3'\text{-Ha}}$ = 1.7 Hz, J_{HH} = 0.8 Hz, 1H, 3′-Hb), 5.29 (ddd, $^3J_{4\text{-Ha},3\text{-H}}$ = 17.4 Hz, $^3J_{4\text{-Ha},4\text{-Hb}}$ = 1.9 Hz, $^4J_{4\text{-Ha},2\text{-H}}$ = 1.2 Hz, 1H, 4-Ha), 5.35 (ddd, $^3J_{3'\text{-Ha},2'\text{-H}}$ = 17.4 Hz, $^3J_{3'\text{-Ha},3'\text{-Hb}}$ = 1.7 Hz, J_{HH} = 1.1 Hz, 1H, 3′-Ha), 5.75 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 17.4 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 10.4 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 6.2 Hz, 1H, 3-H), 5.88 (ddd, $^3J_{2'\text{-H},3'\text{-Ha}}$ = 17.4 Hz, $^3J_{2'\text{-H},3'\text{-Hb}}$ = 10.2 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 7.3 Hz, 1H, 2′-H), 6.93−6.98 (m, 1H, 4″-H), 7.11−7.14 (m, 1H, 2″-H), 7.14−1.16 (m, 1H, 6″-H), 7.30 (ddd, J_{HH} = 8.1 Hz, J_{HH} = 8.1 Hz, $^4J_{5''\text{-H},F}$ = 5.9 Hz, 1H, 5″-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.3 (CH_3), −5.2 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.3 (CH_2-1), 79.0 (CH-2), 79.6 (d, $^4J_{CF}$ = 1.8 Hz, CH-1′), 113.6 (d, $^2J_{CF}$ = 22.1 Hz, CH-2″), 114.1 (d, $^2J_{CF}$ = 21.2 Hz, CH-4″), 117.2 (CH_2-3′), 118.0 (CH_2-4), 122.3 (d, $^4J_{CF}$ = 2.9 Hz, CH-6″), 129.6 (d, $^3J_{CF}$ = 8.2 Hz, CH-5″), 136.1 (CH-3), 138.3 (CH-2′), 144.3 (d, $^3J_{CF}$ = 6.9 Hz, C-1″), 162.9 (d, $^1J_{CF}$ = 245.5 Hz, CF-3″); ^{19}F NMR

(376.5 MHz, $CDCl_3$) δ −113.8; IR (NaCl, neat) ν 2958 (s), 2931 (s), 2858 (s), 2360 (s), 1593 (m), 1253 (s), 1128 (s) cm^{-1}; MS (CI) m/z (%) 337 ([M + H^+], 10), 135 (100); HRMS (CI) 337.1998 [$C_{19}H_{30}FO_2Si$ (M + H^+) requires 337.1999]. Anal. Calcd for $C_{19}H_{29}FO_2Si$: C, 67.81; H, 8.69. Found: C, 67.74; H, 8.79.

(2*R*,1′*R*)-*tert*-Butyl(dimethyl)(2-(1′-(phenyl)allyloxy)but-3-enyloxy)silane (2*R*,1′*R*)-(17a). Method 1. Following general procedure B, the protected butenediol (*R*)-**5a** (1.236 g, 6.11 mmol) was coupled with allyl carbonate (*R*)-**9a** (1.226 g, 5.23 mmol, neat) to obtain ether (2*R*,1′*R*)-**17a** as a colorless oil (1.388 g, 83%, as a single diastereoisomer): $[\alpha]_D$ −10.2 (*c* 3.73, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.08 (s, 3H, CH_3), 0.09 (s, 3H, CH_3), 0.92 (s, 9H, *t*-Bu), 3.63 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.5 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 5.3 Hz, 1H, 1-Ha), 3.76 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.5 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.6 Hz, 1H, 1-Hb), 4.06 (ddddd, $^3J_{2\text{-H},3\text{-H}}$ = 6.9 Hz, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.6 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 5.3 Hz, $^4J_{2\text{-H},4\text{-Ha}}$ = 0.9 Hz, $^4J_{2\text{-H},4\text{-Hb}}$ = 0.9 Hz, 1H, 2-H), 4.95 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 7.3 Hz, 1H, 1′-H), 5.20−5.35 (m, 4H, 4-Ha, 4-Hb, 3′-Ha, and 3′-Hb), 5.74 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 17.3 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 10.4 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 6.9 Hz, 1H, 3-H), 5.90 (ddd, $^3J_{2'\text{-H},3'\text{-Ha}}$ = 17.3 Hz, $^3J_{2'\text{-H},3'\text{-Hb}}$ = 10.2 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 7.3 Hz, 1H, 2′-H), 7.23−7.38 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.3 (CH_3), −5.2 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.3 (CH_2-1), 78.8 (CH-2), 80.3 (CH-1′), 116.7, 117.8 (CH_2-4, and CH_2-3′), 126.7, 127.3, and 128.3 (CH-arom), 136.3 (CH-3), 138.8 (CH-2′), 141.5 (C-arom); IR (NaCl, neat) ν 2955 (s), 2928 (s), 2857 (s), 1471 (m), 1255 (s), 1128 (s), 1086 (s) cm^{-1}; MS (CI-iso, 150 °C) m/z (%) 319 ([M + H^+], 5), 117 (100); HRMS (CI) 319.2091 [$C_{19}H_{31}O_2Si$ (M + H^+) requires 319.2093]. Anal. Calcd for $C_{19}H_{30}O_2Si$: C, 71.64; H, 9.49. Found: C, 71.45; H, 9.54.

Method 2. *n*-Butyllithium (1.25 mL, 2.0 mmol, 1.6 M solution in hexanes) was added dropwise to a solution of the protected butenediol (*R*)-**5a** (419 mg, 2.07 mmol) in THF (2 mL), and the mixture was stirred at −40 °C for 30 min. The lithium alkoxide thus generated was rapidly transferred to a suspension of copper(I) iodide (400 mg, 2.10 mmol) in THF (4 mL) at −40 °C. The mixture was stirred for 30 min at −40 °C, placed in an ice bath, and stirred for another 30 min. Finally, a cold (0 °C) solution of $[Ir(COD)Cl]_2$ (13.8 mg, 0.040 mmol) and the chiral ligand (R_a,R_c,R_c)-**11** (37.0 mg, 0.060 mmol) in THF (2 mL) and cinnamyl carbonate **7** (235 mg, 1.00 mmol, neat) were added consecutively. The cooling bath was then removed, and the reaction mixture was stirred at room temperature for 16 h. The catalyst was precipitated by adding hexane (5 mL), the mixture was filtered through a pad of silica (3 × 3 cm), and the product was eluted with a mixture of hexanes and ethyl acetate (90:10). Chromatography on a column of silica gel (15 g) with a mixture of hexanes, ether, and acetone (250:1:1) gave silane (2*R*,1′*R*)-**17a** as a colorless oil, together with its diastereoisomer (2*R*,1′*S*)-**18a** and the rearranged silane **13** (187 mg, 59% combined yield; in an 88:2.5:9.5 ratio as shown by GC): ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.08 (s, 3H, CH_3), 0.09 (s, 3H, CH_3), 0.92 (s, 9H, *t*-Bu), 3.63 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.5 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 5.3 Hz, 1H, 1-H_a), 3.76 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.5 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.6 Hz, 1H, 1-H_b), 4.06 (ddddd, $^3J_{2\text{-H},3\text{-H}}$ = 6.9 Hz, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.6 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 5.3 Hz, $^4J_{2\text{-H},4\text{-Ha}}$ = 0.9 Hz, $^4J_{2\text{-H},4\text{-Hb}}$ = 0.9 Hz, 1H, 2-H), 4.95 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 7.3 Hz, 1H, 1′-H), 5.20−5.35 (m, 4H, 4-H_a, 4-H_b, 3′-H_a, and 3′-H_b), 5.74 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 17.3 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 10.4 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 6.9 Hz, 1H, 3-H), 5.90 (ddd, $^3J_{2'\text{-H},3'\text{-Ha}}$ = 17.3 Hz, $^3J_{2'\text{-H},3'\text{-Hb}}$ = 10.2 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 7.3 Hz, 1H, 2′-H), 7.23−7.38 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.3 (CH_3), −5.2 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.3 (CH_2-1), 78.8 (CH-2), 80.3 (CH-1′), 116.7, 117.8 (CH_2-4, and CH_2-3′), 126.7, 127.3, and 128.3 (CH-arom), 136.3 (CH-3), 138.8 (CH-2′), 141.5 (C-arom); MS (CI-NH_3, 150 °C) m/z (%) 336 ([M + NH_4^+], 95), 117(100); chiral GC (Supelco γ-DEX 120 column, oven for 1 min at 160 °C, then 0.5 deg·min^{-1}) showed 3:97 dr (t_{RS} = 16.4 min, t_{RR} = 18.3 min) and 10% of the rearranged product (t_{xRR} = 19.1 min).

(2*R*,1′*R*)-*tert*-Butyl(dimethyl)(2-(1′-(3″-fluorophenyl)allyloxy)-but-3-enyloxy)silane (2*R*,1′*R*)-(17b). Following general procedure B, the protected butenediol (*R*)-**5a** (1.209 g, 5.97 mmol) was coupled with allyl carbonate (*R*)-**9b** (1.208 g, 4.79 mmol, neat) to obtain ether (2*R*,1′*R*)-**17b** as a colorless oil (1.161 g, 72%): $[\alpha]_D$ −14.7 (*c* 1.84, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.10 (s, 3H, CH_3), 0.11 (s, 3H, CH_3), 0.94 (s, 9H, *t*-Bu), 3.66 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.5 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 5.1 Hz, 1H, 1-Ha), 3.78 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.5 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.6 Hz, 1H, 1-Hb), 4.07 (ddddd, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.6 Hz, $^3J_{2\text{-H},3\text{-H}}$ = 6.2 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 5.1 Hz, $^4J_{2\text{-H},4\text{-Ha}}$ = 1.2 Hz, $^4J_{2\text{-H},4\text{-Hb}}$ = 1.0 Hz, 1H, 2-H), 4.96 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 7.3 Hz, 1H, 1′-H), 5.25 (ddd, $^3J_{4\text{-Hb},3\text{-H}}$ = 10.4 Hz, $^2J_{4\text{-Hb},4\text{-Ha}}$ = 1.9 Hz, $^4J_{4\text{-Hb},2\text{-H}}$ = 1.0 Hz, 1H, 4-Hb), 5.28 (ddd, $^3J_{3'\text{-Hb},2'\text{-H}}$ = 10.2 Hz, $^3J_{3'\text{-Hb},3'\text{-Ha}}$ = 1.7 Hz, J_{HH} = 0.8 Hz, 1H, 3′-Hb), 5.29 (ddd, $^3J_{4\text{-Ha},3\text{-H}}$ = 17.4 Hz, $^3J_{4\text{-Ha},4\text{-Hb}}$ = 1.9 Hz, $^4J_{4\text{-Ha},2\text{-H}}$ = 1.2 Hz, 1H, 4-Ha), 5.35 (ddd, $^3J_{3'\text{-Ha},2'\text{-H}}$ = 17.4 Hz, $^3J_{3'\text{-Ha},3'\text{-Hb}}$ = 1.7 Hz, J_{HH} = 1.1 Hz, 1H, 3′-Ha), 5.75 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 17.4 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 10.4 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 6.2 Hz, 1H, 3-H), 5.88 (ddd, $^3J_{2'\text{-H},3'\text{-Ha}}$ = 17.4 Hz, $^3J_{2'\text{-H},3'\text{-Hb}}$ = 10.2 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 7.3 Hz, 1H, 2′-H), 6.93−6.98 (m, 1H, 4″-H), 7.11−7.14 (m, 1H, 2″-H), 7.14−1.16 (m, 1H, 6″-H), 7.30 (ddd, J_{HH} = 8.1 Hz, J_{HH} = 8.1 Hz, $^4J_{5''\text{-H,F}}$ = 5.9 Hz, 1H, 5″-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.3 (CH_3), −5.2 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.3 (CH_2-1), 79.0 (CH-2), 79.6 (d, $^4J_{CF}$ = 1.8 Hz, CH-1′), 113.6 (d, $^2J_{CF}$ = 22.1 Hz, CH-2″), 114.1 (d, $^2J_{CF}$ = 21.2 Hz, CH-4″), 117.2 (CH_2-3′), 118.0 (CH_2-4), 122.3 (d, $^4J_{CF}$ = 2.9 Hz, CH-6″), 129.6 (d, $^3J_{CF}$ = 8.2 Hz, CH-5″), 136.1 (CH-3), 138.3 (CH-2′), 144.3 (d, $^3J_{CF}$ = 6.9 Hz, C-1″), 162.9 (d, $^1J_{CF}$ = 245.5 Hz, CF-3″); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.8; IR (NaCl, neat) ν 2958 (s), 2931 (s), 2858 (s), 2360 (s), 1593 (m), 1253 (s), 1128 (s) cm^{-1}; MS (CI) m/z (%) 337 ([M + H^+], 10), 135 (100); HRMS (CI) 337.1998 [$C_{19}H_{30}FO_2Si$ (M + H^+) requires 337.1999]. Anal. Calcd for $C_{19}H_{29}FO_2Si$: C, 67.81; H, 8.69. Found: C, 67.71; H, 8.55.

(2*R*,1′*S*)-*tert*-Butyl(dimethyl)(2-(1′-(phenyl)allyloxy)but-3-enyloxy)silane (2*R*,1′*S*)-(18a). Method 1. Following general procedure B, the protected butenediol (*R*)-**5a** (1.252 g, 6.19 mmol) was coupled with allyl carbonate (*S*)-**9a** (1.180 g, 5.04 mmol, neat) to obtain ether (2*R*,1′*S*)-**18a** as a colorless oil (1.232 g, 77%, as a single diastereoisomer): $[\alpha]_D$ −23.3 (*c* 2.62, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.04 (s, 6H, CH_3), 0.89 (s, 9H, *t*-Bu), 3.58 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.5 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 5.3 Hz, 1H, 1-Ha), 3.71 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.5 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.6 Hz, 1H, 1-Hb), 3.84 (ddddd, $^3J_{2\text{-H},3\text{-H}}$ = 7.0 Hz, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.6 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 5.3 Hz, $^4J_{2\text{-H},4\text{-Ha}}$ = 0.8 Hz, $^4J_{2\text{-H},4\text{-Hb}}$ = 0.8 Hz, 1H, 2-H), 4.96 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.1 Hz, 1H, 1′-H), 5.12−5.28 (m, 4H, 4-H, and 3′-H), 5.78 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 16.2 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 11.4 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 7.0 Hz, 1H, 3-H), 5.98 (ddd, $^3J_{2'\text{-H},3'\text{-Ha}}$ = 17.1 Hz, $^3J_{2'\text{-H},3'\text{-Hb}}$ = 10.4 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 6.1 Hz, 1H, 2′-H), 7.25−7.38 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.37 (CH_3), −5.28 (CH_3), 18.3 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.2 (CH_2-1), 78.5 (CH-2), 79.9 (CH-1′), 115.3, and 118.1 (CH_2-4, and CH_2-3′), 127.2, 127.5, and 128.3 (CH-arom), 136.1 (CH-3), 139.5 (CH-2′), 141.0 (C-arom); IR (NaCl, neat) ν 2955 (s), 2928 (s), 2857 (s), 1471 (m), 1255 (s), 1121 (s), 1083 (s), 838 (s) cm^{-1}; MS (CI-Iso, 150 °C) m/z (%) 319 ([M + H^+], 3), 185 (10), 117 (100); HRMS (CI) 319.2092 [$C_{19}H_{31}O_2Si$ (M + H^+) requires 319.2093]. Anal. Calcd for $C_{19}H_{30}O_2Si$: C, 71.64; H, 9.49. Found: C, 71.45; H, 9.57.

Method 2. *n*-Butyllithium (0.625 mL, 1.0 mmol, 1.6 M solution in pentane) was added slowly to a solution of protected butenediol (*R*)-**5a** (205 mg, 1.01 mmol) in THF (1 mL), and the mixture was stirred at 0 °C for 15 min. The lithium alkoxide thus generated was transferred (via cannula) to a suspension of copper(I) iodide (205 mg, 1.05 mmol) in THF (2 mL) at room temperature. The mixture turned light yellow and was then stirred for 30 min. The resulting mixture was cooled to 0 °C, and a cold (0 °C) solution of $[Ir(COD)Cl]_2$ (7.5 mg, 0.011 mmol) and ligand (S_a,S_c,S_c)-**10** (12.5 mg, 0.023 mmol) in THF (1 mL) and cinnamyl carbonate **7** (120 mg, 0.51 mmol, neat) were added consecutively. The cooling bath was then removed, and the reaction mixture was stirred at room temperature for 48 h. The catalyst was precipitated by adding hexane (5 mL), the mixture was filtered through a pad of silica

dx.doi.org/10.1021/jo201110z |*J. Org. Chem.* 2011, 76, 7781–7803

(1.5 × 1.5 cm), and the product was eluted with a mixture of hexanes and ethyl acetate (90:10). Chromatography on a column of silica gel (1 × 15 cm) with a mixture of hexanes and ethyl acetate (98.5:1.5) afforded silane (2*R*,1′*S*)-**18a** as a colorless oil together with its diastereoisomer (2*R*,1′*R*)-**17a** and the rearranged silane **13** (61 mg, 38% combined yield; in 71:4:24 ratio as shown by ^{1}H NMR): ^{1}H NMR (400.1 MHz, $CDCl_3$, the regioisomer **13** is marked with * where possible) δ 0.04, 0.07* (s, 6H, CH_3), 0.89, 0.91* (s, 9H, *t*-Bu), 3.34−3.41* (m, 2H, CH_2-1), 3.58 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.5 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 5.3 Hz, 1H, 1-H$_a$), 3.71 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.5 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.6 Hz, 1H, 1-H$_b$), 3.84 (ddddd, $^3J_{2\text{-H},3\text{-H}}$ = 7.0 Hz, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.6 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 5.3 Hz, $^4J_{2\text{-H},4\text{-Ha}}$ = 0.8 Hz, $^4J_{2\text{-H},4\text{-Hb}}$ = 0.8 Hz, 1H, 2-H), 4.34−4.39* (m, 1H, 2H), 4.79* (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.3 Hz, 1H, 1′-H), 4.96 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.1 Hz, 1H, 1′-H), 5.11−5.33 (m, 4H, 4-H, and 3′-H), 5.78 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 16.2 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 11.4 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 7.0 Hz, 1H, 3-H), 5.84−6.03 (m, 1H, 2′-H, 2′-H*, 3-H*), 7.25−7.38 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.36, −5.27, −4.8* (CH_3), 18.4 ($C(CH_3)_3$), 25.8*, 25.9 ($C(CH_3)_3$), 66.3 (CH_2-1), 72.7* (CH-2), 73.1* (CH_2-1), 78.5 (CH-2), 79.9 (CH-1′), 83.4* (CH-1′), 114.9*, 115.3, 115.9, and 118.1 (CH_2-4, and CH_2-3′), 126.8, 127.2, 127.5, 128.3, and 128.4 (CH-arom), 136.2 (CH-3), 138.6*, 139.1* (CH-2′ and CH-3), 139.5 (CH-2′), 141.0 (C-arom).

(2*R*,1′*S*)-*tert*-Butyl(dimethyl)(2-(1′-(3″-fluorophenyl)allyloxy)-but-3-enyloxy)silane (2*R*,1′*S*)-(18b). Following general procedure B, the protected butenediol (*R*)-**5a** (2.024 g, 10.02 mmol) was coupled with allyl carbonate (*S*)-**9b** (2.005 g, 7.94 mmol, neat) to obtain ether (2*R*,1′*S*)-**18b** as a colorless oil (1.951 g, 73%): $[\alpha]_D$ −18.4 (*c* 1.96, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.06 (s, 6H, CH_3), 0.90 (s, 9H, *t*-Bu), 3.60 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.6 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 4.9 Hz, 1H, 1-Ha), 3.71 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.6 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.8 Hz, 1H, 1-Hb), 3.85 (ddddd, $^3J_{2\text{-H},3\text{-H}}$ = 7.0 Hz, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.8 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 4.9 Hz, J_{HH} = 1.0 Hz, J_{HH} = 1.0 Hz, 1H, 2-H), 4.96 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.1 Hz, 1H, 1′-H), 5.15 (ddd, J_{HH} = 10.4 Hz, J_{HH} = 1.4 Hz, J_{HH} = 1.4 Hz, 1H, 3′-Ha or 3′-Hb), 5.21−5.29 (m, 3H, 3′-Hb or 3′-Ha, 4-Ha, and 4-Hb), 5.76 (ddd, J_{HH} = 17.4 Hz, J_{HH} = 10.8 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 7.0 Hz, 1H, 3-H), 5.94 (ddd, J_{HH} = 17.1 Hz, J_{HH} = 10.3 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 6.1 Hz, 1H, 2′-H), 6.94−6.99 (m, 1H, 4″-H), 7.10−7.14 (m, 2H, 2″-H, and 6″-H), 7.27−7.32 (m, 1H, 5″-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.39 (CH_3), −5.30 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.3 (CH_2-1), 79.0 (CH-2), 78.4 (d, $^4J_{CF}$ = 1.7 Hz, CH-1′), 114.0 (d, $^2J_{CF}$ = 21.7 Hz, CH-2″), 114.4 (d, $^2J_{CF}$ = 21.3 Hz, CH-4″), 115.7 (CH_2-3′), 118.2 (CH_2-4), 122.7 (d, $^4J_{CF}$ = 2.8 Hz, CH-6″), 129.8 (d, $^3J_{CF}$ = 8.1 Hz, CH-5″), 136.9 (CH-3), 139.0 (CH-2′), 143.9 (d, $^3J_{CF}$ = 6.6 Hz, C-1″), 163.0 (d, $^1J_{CF}$ = 245.9 Hz, CF-3″); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.6; IR (NaCl, neat) ν 2955 (s), 2929 (s), 2858 (s), 1614 (m), 1592 (m), 1296 (s), 1126 (s), 1086 (s) cm^{-1}; MS (CI) *m*/*z* (%) 337 ([M + H$^+$], 5), 135 (100); HRMS (CI) 337.1997 [$C_{19}H_{30}FO_2Si$ (M + H$^+$) requires 337.1999]. Anal. Calcd for $C_{19}H_{29}FO_2Si$: C, 67.81; H, 8.69. Found: C, 67.64; H, 8.80.

(2*R*,1′*S*)-(2-(1′-(4″-Bromophenyl)allyloxy)but-3-enyloxy)-(*tert*-butyl)dimethylsilane (2*R*,1′*S*)-(18c). Following general procedure B, the protected butenediol (*R*)-**5a** (2.022 g, 9.99 mmol) was coupled with allyl carbonate (*S*)-**9c** (2.527 g, 8.07 mmol, neat) to obtain ether (2*R*,1′*S*)-**18c** as yellowish oil (2.724 g, 85%): $[\alpha]_D$ −18.8 (*c* 2.02, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.11 (s, 6H, CH_3), 0.95 (s, 9H, *t*-Bu), 3.63 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.5 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 4.9 Hz, 1H, 1-Ha), 3.73 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.5 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.9 Hz, 1H, 1-Hb), 3.85 (ddddd, $^3J_{2\text{-H},3\text{-H}}$ = 7.0 Hz, $^3J_{2\text{-H},1\text{-Hb}}$ = 6.9 Hz, $^3J_{2\text{-H},1\text{-Ha}}$ = 4.9 Hz, $^4J_{2\text{-H},4\text{-Ha}}$ = 1.0 Hz, $^4J_{2\text{-H},4\text{-Hb}}$ = 1.0 Hz, 1H, 2-H), 4.97 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.1 Hz, $^4J_{1'\text{-H},3'\text{-Ha}}$ = 1.2 Hz, $^4J_{1'\text{-H},3'\text{-Hb}}$ = 1.2 Hz, 1H, 1′-H), 5.19 (ddd, $^3J_{3'\text{-Hb},2'\text{-H}}$ = 10.3 Hz, J_{HH} = 1.7 Hz, $^4J_{3'\text{-Hb},1'\text{-H}}$ = 1.2 Hz, 1H, 3′-Hb), 5.24−5.34 (m, 3H, 3′-Ha, 4-Ha, and 4-Hb), 5.79 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 16.9 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 10.8 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 7.0 Hz, 1H, 3-H), 5.97 (ddd, $^3J_{2'\text{-H},3'\text{-Ha}}$ = 17.2 Hz, $^3J_{2'\text{-H},3'\text{-Hb}}$ = 10.3 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 6.1 Hz, 1H, 2′-H), 7.30 (d, $^3J_{2''\text{-H},3''\text{-H}}$ = 8.2 Hz, 2H, 2″-H, and 6″-H), 7.52 (d, $^3J_{3''\text{-H},2''\text{-H}}$ = 8.2 Hz, 2H, 3″-H, and 5″-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.38 (CH_3), −5.27 (CH_3), 18.3 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.2 (CH_2-1), 78.8 (CH-2), 79.2 (CH-1′), 115.7 (CH_2-3′), 118.3 (CH_2-4), 121.3 (C-4″), 128.9 (CH-2″, and CH-6″), 131.4 (CH-3″, and CH-5″), 135.8 (CH-3), 139.0 (CH-2′), 140.1 (C-1″); IR (NaCl, neat) ν 2954 (s), 2928 (s), 2857 (s), 1487 (m), 1472 (m), 1255 (s), 1121 (s), 1073 (s) cm^{-1}; MS (CI) *m*/*z* (%) 397/399 ([M + H$^+$], 10), 369 (30), 195/197 (100); HRMS (CI) 397.1156/399.1200 [$C_{19}H_{30}BrO_2Si$ (M + H$^+$) requires 397.1198/399.1180].

(2*R*,1′*S*)-*tert*-Butyl(dimethyl)(2-(1′-(3″,4″-dimethoxyphenyl)allyloxy)but-3-enyloxy)silane (2*R*,1′*S*)-(18d). Following general procedure B, the protected butenediol (*R*)-**5a** (2.022 g, 9.99 mmol) was coupled with allyl carbonate (*S*)-**9d** (2.511 g, 8.53 mmol, neat) to obtain silane (2*R*,1′*S*)-**18d** as a colorless oil (2.267 g, 70%): $[\alpha]_D$ −20.4 (*c* 2.30, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ −0.04 (s, 3H, CH_3), −0.01 (s, 3H, CH_3), 0.84 (s, 9H, *t*-Bu), 3.54 (dd, $^2J_{1\text{-Ha},1\text{-Hb}}$ = 10.4 Hz, $^3J_{1\text{-Ha},2\text{-H}}$ = 5.6 Hz, 1H, 1-Ha), 3.66 (dd, $^2J_{1\text{-Hb},1\text{-Ha}}$ = 10.4 Hz, $^3J_{1\text{-Hb},2\text{-H}}$ = 6.3 Hz, 1H, 1-Hb), 3.77−3.82 (m, 1H, 2-H), 3.84 (s, 3H, CH_3O), 3.85 (s, 3H, CH_3O), 4.87 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 5.9 Hz, J_{HH} = 1.3 Hz, J_{HH} = 1.3 Hz, 1H, 1′-H), 5.08 (ddd, $^3J_{3'\text{-Hb},2'\text{-H}}$ = 10.4 Hz, J_{HH} = 1.7 Hz, J_{HH} = 1.3 Hz, 1H, 3′-Hb), 5.16−5.24 (m, 3H, 3′-Ha, 4-Ha, and 4-Hb), 5.75 (ddd, $^3J_{3\text{-H},4\text{-Ha}}$ = 16.3 Hz, $^3J_{3\text{-H},4\text{-Hb}}$ = 11.4 Hz, $^3J_{3\text{-H},2\text{-H}}$ = 7.0 Hz, 1H, 3-H), 5.95 (ddd, $^3J_{2'\text{-H},3'\text{-Ha}}$ = 17.2 Hz, $^3J_{2'\text{-H},3'\text{-Hb}}$ = 10.4 Hz, $^3J_{2'\text{-H},1'\text{-H}}$ = 5.9 Hz, 1H, 2′-H), 6.80 (d, $^3J_{5''\text{-H},6''\text{-H}}$ = 8.0 Hz, 1H, 5″-H), 6.84 (d, $^4J_{2''\text{-H},6''\text{-H}}$ = 1.8 Hz, 1H, 2″-H), 6.86 (ddd, $^3J_{6''\text{-H},5''\text{-H}}$ = 8.0 Hz, $^4J_{6''\text{-H},2''\text{-H}}$ = 1.8 Hz, J_{HH} = 0.4 Hz, 1H, 6″-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.47 (CH_3), −5.40 (CH_3), 18.2 ($C(CH_3)_3$), 25.8 ($C(CH_3)_3$), 55.65, and 55.68 (2 × CH_3O), 66.2 (CH_2-1), 78.1 (CH-2), 79.5 (CH-1′), 110.0 (CH-2″), 110.7 (CH-5″), 114.9 (CH_2-3′), 117.9 (CH_2-4), 119.6 (CH-6″), 133.4 (C-1″), 136.2 (CH-3), 139.4 (CH-2′), 148.4, and 148.9 (C-3″, and C-4″); IR (NaCl, neat) ν 2955 (s), 2928 (s), 2858 (s), 1614 (m), 1256 (s) cm^{-1}; MS (EI) *m*/*z* (%) 378 ([M$^+$], 80), 321 (100), 265 (90), 246 (60); HRMS (CI) 378.2225 [$C_{21}H_{34}O_4Si$ (M$^+$) requires 378.2226].

General Procedure C: Ring Closure by Metathesis. Grubbs first-generation catalyst **C1** (6.9 mg, 0.008 mmol) was added to a solution of silane **15**−**18** (0.83 mmol) in dichloromethane (10 mL) under a stream of argon atmosphere, and the mixture was stirred at 40 °C for 5 h. The resulting solution was evaporated, and the residue was chromatographed on a column of silica gel (3 × 10 cm) with a mixture of hexanes and ethyl acetate (98.5:1.5) to give, respectively, silane **19**−**22** as a colorless oil.

(−)-5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-didehydro-2′,3′-dideoxy-1′-phenyl-β-D-ribofuranose (19a). Employing general procedure C, the silane (2*S*,1′*R*)-**15a** (483 mg, 1.52 mmol) was converted to dihydrofuran **19a** (441 mg, 78%): $[\alpha]_D$ −35.5 (*c* 1.24, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.09 (s, 6H, CH_3), 0.93 (s, 9H, *t*-Bu), 3.73 (dd, $^2J_{5\text{-Ha},5\text{-Hb}}$ = 10.3 Hz, $^3J_{5-\text{Ha},4\text{-H}}$ = 5.9 Hz, 1H, 5-Ha), 3.85 (dd, $^2J_{5\text{-Hb},5\text{-Ha}}$ = 10.3 Hz, $^3J_{5\text{-Hb},4\text{-H}}$ = 4.8 Hz, 1H, 5-Hb), 4.96 (ddddd, $^3J_{4\text{-H},5\text{-Ha}}$ = 5.9 Hz, $^3J_{4\text{-H},5\text{-Hb}}$ = 4.8 Hz, $^4J_{4\text{-H},1\text{-H}}$ = 4.0 Hz, $^3J_{4\text{-H},3\text{-H}}$ = 2.1 Hz, $^4J_{4\text{-H},2\text{-H}}$ = 1.4 Hz, 1H, 4-H), 5.80 (ddd, $^4J_{1\text{-H},4\text{-H}}$ = 4.0 Hz, $^3J_{1\text{-H},2\text{-H}}$ = 2.4 Hz, $^4J_{1\text{-H},3\text{-H}}$ = 1.6 Hz, 1H, 1-H), 5.92 (ddd, $^3J_{3\text{-H},2\text{-H}}$ = 6.1 Hz, $^3J_{3\text{-H},4\text{-H}}$ = 2.1 Hz, $^4J_{3\text{-H},1\text{-H}}$ = 1.6 Hz, 1H, 3-H), 6.02 (ddd, $^3J_{2\text{-H},3\text{-H}}$ = 6.1 Hz, $^3J_{2\text{-H},1\text{-H}}$ = 2.4 Hz, $^4J_{2\text{-H},4\text{-H}}$ = 1.4 Hz, 1H, 2-H), 7.27−7.40 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.4 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.4 (CH_2-5), 87.2 (CH-4), 88.0 (CH-1), 126.8, 127.8, and 128.27 (CH-arom), 128.33 (CH-2), 131.0 (CH-3), 141.7 (C-arom); IR (NaCl, $CHCl_3$) ν 2954 (s), 2930 (s), 2858 (s), 1726 (m), 1257 (s), 1113 (s), 836 (s) cm^{-1};[66] MS (CI) *m*/*z* (%) 305 (100), 291 ([M$^+$], 50); HRMS (CI) 291.1778 [$C_{17}H_{27}O_2Si$ (M$^+$) requires 291.1780].

(+)-5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-didehydro-1′,2′,3′-trideoxy-1′-(3-fluorophenyl)-β-D-ribofuranose (19b). Employing general procedure C, the silane (2*S*,1′*R*)-**15b** (1.346 g, 4.00 mmol) was converted to dihydrofuran **19b** (1.185 g, 96%): $[\alpha]_D$ +8.0 (*c* 2.63, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.09 (s, 6H, CH_3), 0.93 (s, 9H, *t*-Bu), 3.71 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 10.5 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 5.5 Hz, 1H,

5′-Ha), 3.77 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 10.5 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 4.9 Hz, 1H, 5′-Hb), 4.89−4.95 (m, 1H, 4′-H), 5.73−5.75 (m, 1H, 1′-H), 5.94 (ddd, $^3J_{3'\text{-H},2'\text{-H}}$ = 6.1 Hz, J_{HH} = 1.8 Hz, J_{HH} = 1.2 Hz, 1H, 3′-H), 5.97 (ddd, $^3J_{2'\text{-H},3'\text{-H}}$ = 6.1 Hz, J_{HH} = 2.2 Hz, J_{HH} = 1.1 Hz, 1H, 2′-H), 6.98−7.11 (m, 3H, 2-H, 4-H, and 6-H), 7.30−7.32 (m, 1H, 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.4 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 63.0 (CH_2-5′), 87.2 (d, $^4J_{CF}$ = 1.8 Hz, CH-1′), 87.3 (CH-4′), 113.8 (d, $^2J_{CF}$ = 21.7 Hz, CH-2), 114.8 (d, $^2J_{CF}$ = 21.2 Hz, CH-4), 122.4 (d, $^4J_{CF}$ = 2.9 Hz, CH-6), 129.5 (CH-2′), 130.0 (d, $^3J_{CF}$ = 8.1 Hz, CH-5), 130.2 (CH-3′), 144.4 (d, $^3J_{CF}$ = 6.6 Hz, C-1), 163.0 (d, $^1J_{CF}$ = 246.3 Hz, CF-3); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.3; IR (NaCl, neat) ν 2954 (s), 2931 (s), 2858 (s), 1742 (m), 1592 (m), 1258 (s) cm^{-1};[66] MS (CI) m/z (%) 309 ([M + H$^+$], 100); HRMS (CI) 309.1687 [$C_{17}H_{26}FO_2Si$ (M + H$^+$) requires 309.1686].

(−)-5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-didehydro-2′,3′-dideoxy-1′-phenyl-α-D-ribofuranose (20a). Employing general procedure C, the silane (2*S*,1′*S*)-**16a** (266 mg, 0.83 mmol) was converted to dihydrofuran **20a** (136 mg, 56%): $[\alpha]_D$ −69.6 (*c* 1.02, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.06 (s, 3H, CH_3), 0.07 (s, 3H, CH_3), 0.90 (s, 9H, *t*-Bu), 3.66 (dd, $^2J_{5\text{-Ha},5\text{-Hb}}$ = 10.3 Hz, $^3J_{5\text{-Ha},4\text{-H}}$ = 5.7 Hz, 1H, 5-Ha), 3.77 (dd, $^2J_{5\text{-Hb},5\text{-Ha}}$ = 10.3 Hz, $^3J_{5\text{-Hb},4\text{-H}}$ = 4.6 Hz, 1H, 5-Hb), 5.02−5.07 (m, 1H, 4-H), 5.78−5.80 (m, 1H, 1-H), 5.92 (ddd, $^3J_{3\text{-H},2\text{-H}}$ = 6.1 Hz, J_{HH} = 2.1 Hz, J_{HH} = 1.4 Hz, 1H, 3-H), 5.97 (ddd, $^3J_{2\text{-H},3\text{-H}}$ = 6.1 Hz, J_{HH} = 2.2 Hz, J_{HH} = 1.5 Hz, 1H, 2-H), 7.22−7.36 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.33 (CH_3), −5.28 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.0 (CH_2-5), 87.2 (CH-4), 88.0 (CH-1), 126.4, and 127.8 (CH-arom), 128.1 (CH-2), 128.4 (CH-arom), 131.3 (CH-3), 141.9 (C-arom); IR (NaCl, neat) ν 2954 (s), 2930 (s), 2858 (s), 1725 (m), 1257 (s), 1113 (m), 836 (s) cm^{-1};[66] MS (CI) m/z (%) 291 ([M + H$^+$], 70), 149 (100); HRMS (CI) 291.1776 [$C_{17}H_{27}O_2Si$ (M + H$^+$) requires 291.1780].

(−)-5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-didehydro-1′,2′,3′-trideoxy-1′-(3-fluorophenyl)-α-D-ribofuranose (20b). Employing general procedure C, the silane (2*S*,1′*S*)-**16b** (329 mg, 0.97 mmol) was converted to dihydrofuran **20b** (285 mg, 95%): $[\alpha]_D$ −154.4 (*c* 1.80, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.09 (s, 3H, CH_3), 0.10 (s, 3H, CH_3), 0.93 (s, 9H, *t*-Bu), 3.70 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 10.4 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 5.5 Hz, 1H, 5′-Ha), 3.80 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 10.4 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 4.6 Hz, 1H, 5′-Hb), 5.05−5.11 (m, 1H, 4′-H), 5.81−5.82 (m, 1H, 1′-H), 5.93 (ddd, $^3J_{3'\text{-H},2'\text{-H}}$ = 6.1 Hz, J_{HH} = 2.0 Hz, J_{HH} = 1.6 Hz, 1H, 3′-H), 6.01 (ddd, $^3J_{2'\text{-H},3'\text{-H}}$ = 6.1 Hz, J_{HH} = 2.3 Hz, J_{HH} = 1.5 Hz, 1H, 2′-H), 6.96 (dddd, $^3J_{4\text{-H,F}}$ = 9.5 Hz, $^3J_{4\text{-H},5\text{-H}}$ = 8.5 Hz, $^4J_{4\text{-H},2\text{-H}}$ = 2.6 Hz, $^4J_{4\text{-H},6\text{-H}}$ = 1.0 Hz, 1H, 4-H), 7.03 (ddd, $^3J_{2\text{-H,F}}$ = 9.7 Hz, $^4J_{2\text{-H},4\text{-H}}$ = 2.6 Hz, $^4J_{2\text{-H},6\text{-H}}$ = 1.6 Hz, 1H, 2-H), 7.07−7.10 (m, 1H, 6-H), 7.30 (ddd, $^3J_{5\text{-H},4\text{-H}}$ = 8.5 Hz, $^3J_{5\text{-H},6\text{-H}}$ = 7.7 Hz, $^4J_{5\text{-H,F}}$ = 5.8 Hz, 1H, 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.34 (CH_3), −5.30 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 65.9 (CH_2-5′), 87.4 (d, $^4J_{CF}$ = 1.8 Hz, CH-1′), 87.5 (CH-4′), 113.2 (d, $^2J_{CF}$ = 21.8 Hz, CH-2), 114.6 (d, $^2J_{CF}$ = 21.3 Hz, CH-4), 121.8 (d, $^4J_{CF}$ = 2.9 Hz, CH-6), 128.5 (CH-2′), 129.9 (d, $^3J_{CF}$ = 8.1 Hz, CH-5), 130.9 (CH-3′), 144.7 (d, $^3J_{CF}$ = 6.5 Hz, C-1), 163.0 (d, $^1J_{CF}$ = 246.1 Hz, CF-3); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.6; IR (NaCl, neat) ν 2955 (s), 2930 (s), 2858 (s), 1730 (m), 1593 (s), 1258 (s) cm^{-1};[66] MS (CI) m/z (%) 309 ([M + H$^+$], 100); HRMS (CI) 309.1682 [$C_{17}H_{26}FO_2Si$ (M + H$^+$) requires 309.1686].

(+)-5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-didehydro-2′,3′-dideoxy-1′-phenyl-α-L-ribofuranose (21a). Employing general procedure C, the silane (2*R*,1′*R*)-**17a** (1.226 g, 3.85 mmol) was converted to dihydrofuran **21a** (1.019 g, 91%): $[\alpha]_D$ +202.6 (*c* 1.90, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.06 (s, 3H, CH_3), 0.07 (s, 3H, CH_3), 0.90 (s, 9H, *t*-Bu), 3.66 (dd, $^2J_{5\text{-Ha},5\text{-Hb}}$ = 10.3 Hz, $^3J_{5\text{-Ha},4\text{-H}}$ = 5.7 Hz, 1H, 5-Ha), 3.77 (dd, $^2J_{5\text{-Hb},5\text{-Ha}}$ = 10.3 Hz, $^3J_{5\text{-Hb},4\text{-H}}$ = 4.6 Hz, 1H, 5-Hb), 5.02−5.07 (m, 1H, 4-H), 5.78−5.80 (m, 1H, 1-H), 5.92 (ddd, $^3J_{3\text{-H},2\text{-H}}$ = 6.1 Hz, J_{HH} = 2.1 Hz, J_{HH} = 1.4 Hz, 1H, 3-H), 5.97 (ddd, $^3J_{2\text{-H},3\text{-H}}$ = 6.1 Hz, J_{HH} = 2.2 Hz, J_{HH} = 1.5 Hz, 1H, 2-H), 7.22−7.36 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.33 (CH_3), −5.28 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.0 (CH_2-5), 87.2 (CH-4), 88.0 (CH-1), 126.4, and 127.8 (CH-arom), 128.1 (CH-2), 128.4 (CH-arom), 131.3 (CH-3), 141.9 (C-arom); IR (NaCl, neat) ν 2931 (s), 2858 (s), 1730 (m), 1467 (m), 1257 (s), 1113 (s), 837 (s) cm^{-1};[66] MS (CI) m/z (%) 291 ([M + H$^+$], 100); HRMS (CI) 291.1779 [$C_{17}H_{27}O_2Si$ (M + H$^+$) requires 291.1780].

(+)-5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-didehydro-1′,2′,3′-trideoxy-1′-(3-fluorophenyl)-α-L-ribofuranose (21b). Employing general procedure C, the silane (2*R*,1′*R*)-**17b** (650 mg, 1.93 mmol) was converted to dihydrofuran **21b** (580 mg, 97%), obtained as a colorless oil: $[\alpha]_D$ +147.1 (*c* 2.40, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.09 (s, 3H, CH_3), 0.10 (s, 3H, CH_3), 0.93 (s, 9H, *t*-Bu), 3.70 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 10.4 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 5.5 Hz, 1H, 5′-Ha), 3.80 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 10.4 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 4.6 Hz, 1H, 5′-Hb), 5.05−5.11 (m, 1H, 4′-H), 5.81−5.82 (m, 1H, 1′-H), 5.93 (ddd, $^3J_{3'\text{-H},2'\text{-H}}$ = 6.1 Hz, J_{HH} = 2.0 Hz, J_{HH} = 1.6 Hz, 1H, 3′-H), 6.01 (ddd, $^3J_{2'\text{-H},3'\text{-H}}$ = 6.1 Hz, J_{HH} = 2.3 Hz, J_{HH} = 1.5 Hz, 1H, 2′-H), 6.96 (dddd, $^3J_{4\text{-H,F}}$ = 9.5 Hz, $^3J_{4\text{-H},5\text{-H}}$ = 8.5 Hz, $^4J_{4\text{-H},2\text{-H}}$ = 2.6 Hz, $^4J_{4\text{-H},6\text{-H}}$ = 1.0 Hz, 1H, 4-H), 7.03 (ddd, $^3J_{2\text{-H,F}}$ = 9.7 Hz, $^4J_{2\text{-H},4\text{-H}}$ = 2.6 Hz, $^4J_{2\text{-H},6\text{-H}}$ = 1.6 Hz, 1H, 2-H), 7.07−7.10 (m, 1H, 6-H), 7.30 (ddd, $^3J_{5\text{-H},4\text{-H}}$ = 8.5 Hz, $^3J_{5\text{-H},6\text{-H}}$ = 7.7 Hz, $^4J_{5\text{-H,F}}$ = 5.8 Hz, 1H, 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.34 (CH_3), −5.30 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 65.9 (CH_2-5′), 87.4 (d, $^4J_{CF}$ = 1.8 Hz, CH-1′), 87.5 (CH-4′), 113.2 (d, $^2J_{CF}$ = 21.8 Hz, CH-2), 114.6 (d, $^2J_{CF}$ = 21.3 Hz, CH-4), 121.8 (d, $^4J_{CF}$ = 2.9 Hz, CH-6), 128.5 (CH-2′), 129.9 (d, $^3J_{CF}$ = 8.1 Hz, CH-5), 130.9 (CH-3′), 144.7 (d, $^3J_{CF}$ = 6.5 Hz, C-1), 163.0 (d, $^1J_{CF}$ = 246.1 Hz, CF-3); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.6; IR (NaCl, neat) ν 2955 (s), 2930 (s), 2858 (s), 1730 (m), 1593 (s), 1258 (s) cm^{-1};[66] MS (CI) m/z (%) 309 ([M + H$^+$], 100); HRMS (CI) 309.1682 [$C_{17}H_{26}FO_2Si$ (M + H$^+$) requires 309.1686].

(−)-5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-didehydro-2′,3′-dideoxy-1′-phenyl-β-L-ribofuranose (22a). Employing general procedure C, the silane (2*R*,1′*S*)-**18a** (1.129 g, 3.54 mmol) was converted to dihydrofuran **22a** (880 mg, 86%): $[\alpha]_D$ −24.6 (*c* 1.83, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.09 (s, 6H, CH_3), 0.93 (s, 9H, *t*-Bu), 3.73 (dd, $^2J_{5\text{-Ha},5\text{-Hb}}$ = 10.3 Hz, $^3J_{5\text{-Ha},4\text{-H}}$ = 5.9 Hz, 1H, 5-Ha), 3.85 (dd, $^2J_{5\text{-Hb},5\text{-Ha}}$ = 10.3 Hz, $^3J_{5\text{-Hb},4\text{-H}}$ = 4.8 Hz, 1H, 5-Hb), 4.96 (ddddd, $^3J_{4\text{-H},5\text{-Ha}}$ = 5.9 Hz, $^3J_{4\text{-H},5\text{-Hb}}$ = 4.8 Hz, $^4J_{4\text{-H},1\text{-H}}$ = 4.0 Hz, $^3J_{4\text{-H},3\text{-H}}$ = 2.1 Hz, $^4J_{4\text{-H},2\text{-H}}$ = 1.4 Hz, 1H, 4-H), 5.80 (ddd, $^4J_{1\text{-H},4\text{-H}}$ = 4.0 Hz, $^3J_{1\text{-H},2\text{-H}}$ = 2.4 Hz, $^4J_{1\text{-H},3\text{-H}}$ = 1.6 Hz, 1H, 1-H), 5.92 (ddd, $^3J_{3\text{-H},2\text{-H}}$ = 6.1 Hz, $^3J_{3\text{-H},4\text{-H}}$ = 2.1 Hz, $^4J_{3\text{-H},1\text{-H}}$ = 1.6 Hz, 1H, 3-H), 6.02 (ddd, $^3J_{2\text{-H},3\text{-H}}$ = 6.1 Hz, $^3J_{2\text{-H},1\text{-H}}$ = 2.4 Hz, $^4J_{2\text{-H},4\text{-H}}$ = 1.4 Hz, 1H, 2-H), 7.27−7.40 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.4 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 66.4 (CH_2-5), 87.2 (CH-4), 88.0 (CH-1), 126.8, 127.8, and 128.27 (CH-arom), 128.33 (CH-2), 131.0 (CH-3), 141.7 (C-arom); IR (NaCl, neat) ν 2954 (s), 2931 (s), 2858 (s), 1468 (m), 1255 (s), 1103 (s), 839 (s) cm^{-1}; MS (CI) m/z (%) 291 ([M + H$^+$], 100); HRMS (CI) 291.1760 [$C_{17}H_{27}O_2Si$ (M + H$^+$) requires 291.1780].

(−)-5′-*O*-(*tert*-Butyldimethylsilyl)-2′,3′-didehydro-1′,2′,3′-trideoxy-1′-(3-fluorophenyl)-β-L-ribofuranose (22b). Employing general procedure C, the silane (2*R*,1′*S*)-**18b** (1.088 g, 3.23 mmol) was converted to dihydrofuran **22b** (946 mg, 95%): $[\alpha]_D$ −7.7 (*c* 1.14, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.09 (s, 6H, CH_3), 0.93 (s, 9H, *t*-Bu), 3.71 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 10.5 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 5.5 Hz, 1H, 5′-Ha), 3.77 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 10.5 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 4.9 Hz, 1H, 5′-Hb), 4.89−4.95 (m, 1H, 4′-H), 5.73−5.75 (m, 1H, 1′-H), 5.94 (ddd, $^3J_{3'\text{-H},2'\text{-H}}$ = 6.1 Hz, J_{HH} = 1.8 Hz, J_{HH} = 1.2 Hz, 1H, 3′-H), 5.97 (ddd, $^3J_{2'\text{-H},3'\text{-H}}$ = 6.1 Hz, J_{HH} = 2.2 Hz, J_{HH} = 1.1 Hz, 1H, 2′-H), 6.98−7.11 (m, 3H, 2-H, 4-H, and 6-H), 7.30−7.32 (m, 1H, 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.4 (CH_3), 18.4 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 63.0 (CH_2-5′), 87.2 (d, $^4J_{CF}$ = 1.8 Hz, CH-1′), 87.3 (CH-4′), 113.8 (d, $^2J_{CF}$ = 21.7 Hz, CH-2), 114.8 (d, $^2J_{CF}$ = 21.2 Hz, CH-4), 122.4 (d, $^4J_{CF}$ = 2.9 Hz,

CH-6), 129.5 (CH-2′), 130.0 (d, $^3J_{CF}$ = 8.1 Hz, CH-5), 130.2 (CH-3′), 144.4 (d, $^3J_{CF}$ = 6.6 Hz, C-1), 163.0 (d, $^1J_{CF}$ = 246.3 Hz, CF-3); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.3; IR (NaCl, neat) ν 2954 (s), 2931 (s), 2858 (s), 1742 (m), 1592 (m), 1258 (s) cm^{-1};[66] MS (CI) m/z (%) 309 ([M + H$^+$], 100); HRMS (CI) 309.1687 [$C_{17}H_{26}FO_2Si$ (M + H$^+$) requires 309.1686].

General Procedure D: Removal of the TBS Group. Complex $Et_3N \cdot 3HF$ (1.0 mL, 6.1 mmol) was added to a solution of silane **19**−**22** (1.52 mmol) in THF (10 mL), and the reaction mixture was stirred at 20 °C overnight and then evaporated. Gradient chromatography on a column of silica gel (3 × 10 cm) with a mixture of hexanes and ethyl acetate (95:5 to 67:33) gave alcohol **23**−**26** as a colorless oil.

(+)-2′,3′-Didehydro-1′,2′,3′-trideoxy-1′-phenyl-β-D-ribofuranose (23a). Silane **19a** (203 mg, 0.70 mmol) was deprotected using general procedure D to obtain alcohol **23a** (84 mg, 68%): $[\alpha]_D$ +77.5 (*c* 1.28, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 1.96 (t, $^3J_{5\text{-}OH,5\text{-}H}$ = 6.0 Hz, 1H, 5-OH), 3.67 (ddd, $^2J_{5\text{-}Ha,5\text{-}Hb}$ = 11.6 Hz, $^3J_{5\text{-}Ha,5\text{-}OH}$ = 6.1 Hz, $^3J_{5\text{-}Ha,4\text{-}H}$ = 5.2 Hz, 1H, 5-Ha), 3.78 (ddd, $^2J_{5\text{-}Hb,5\text{-}Ha}$ = 11.6 Hz, $^3J_{5\text{-}Hb,5\text{-}OH}$ = 5.9 Hz, $^3J_{5\text{-}Hb,4\text{-}H}$ = 3.3 Hz, 1H, 5-Hb), 5.00−5.03 (m, 1H, 4-H), 5.80−5.82 (m, 1H, 1-H), 5.94 (ddd, $^3J_{3\text{-}H,2\text{-}H}$ = 6.1 Hz, J_{HH} = 2.4 Hz, J_{HH} = 1.4 Hz, 1H, 3-H), 6.00 (ddd, $^3J_{2\text{-}H,3\text{-}H}$ = 6.1 Hz, J_{HH} = 2.2 Hz, J_{HH} = 1.5 Hz, 1H, 2-H), 7.29−7.38 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 65.0 (CH_2-5), 87.2 (CH-4), 87.9 (CH-1), 127.0 (CH-arom), 127.7 (CH-3), 128.1 (CH-arom), 128.6 (CH-arom), 131.5 (CH-2), 141.1 (C-arom); IR (NaCl, neat) ν 3365 (m, OH), 2929 (m), 2858 (m), 2360 (s), 1454 (m) cm^{-1}; MS (CI) m/z (%) 177 ([M + H$^+$], 80), 159 ([M + H$^+$] − H_2O, 100); HRMS (CI) 177.0918 [$C_{11}H_{13}O_2$ (M + H$^+$) requires 177.0916].

(+)-2′,3′-Didehydro-1′,2′,3′-trideoxy-1′-(3-fluorophenyl)-β-D-ribofuranose (23b). Silane **19b** (459 mg, 1.49 mmol) was deprotected using general procedure D to obtain alcohol **23b** (176 mg, 61%): $[\alpha]_D$ +64.2 (*c* 1.90, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 2.19 (bs, 1H, OH), 3.66 (dd, $^2J_{5'\text{-}Ha,5'\text{-}Hb}$ = 11.8 Hz, $^3J_{5'\text{-}Ha,4'\text{-}H}$ = 5.2 Hz, 1H, 5′-Ha), 3.78 (dd, $^2J_{5'\text{-}Hb,5'\text{-}Ha}$ = 11.8 Hz, $^3J_{5'\text{-}Hb,4'\text{-}H}$ = 3.4 Hz, 1H, 5′-Hb), 4.98−5.02 (m, 1H, 4′-H), 5.78 (d, $^3J_{1'\text{-}H,F}$ = 5.9 Hz, 1H, 1′-H), 5.93 (ddd, $^3J_{2'\text{-}H,3'\text{-}H}$ = 6.1 Hz, J_{HH} = 2.1 Hz, J_{HH} = 1.1 Hz, 1H, 2′-H), 5.96 (ddd, $^3J_{3'\text{-}H,2'\text{-}H}$ = 6.1 Hz, J_{HH} = 2.1 Hz, J_{HH} = 1.2 Hz, 1H, 3′-H), 6.99 (dddd, $^3J_{4\text{-}H,F}$ = 8.4 Hz, $^3J_{4\text{-}H,5\text{-}H}$ = 8.0 Hz, $^4J_{4\text{-}H,2\text{-}H}$ = 2.6 Hz, $^4J_{4\text{-}H,6\text{-}H}$ = 1.0 Hz, 1H, 4-H), 7.07 (ddd, $^3J_{2\text{-}H,F}$ = 9.7 Hz, $^4J_{2\text{-}H,4\text{-}H}$ = 2.6 Hz, $^4J_{2\text{-}H,6\text{-}H}$ = 1.6 Hz, 1H, 2-H), 7.12 (dddd, $^3J_{6\text{-}H,5\text{-}H}$ = 7.7 Hz, $^4J_{6\text{-}H,2\text{-}H}$ = 1.6 Hz, $^4J_{6\text{-}H,4\text{-}H}$ = 1.0 Hz, $^5J_{6\text{-}H,F}$ = 0.5 Hz, 1H, 6-H), 7.32 (ddd, $^3J_{5\text{-}H,4\text{-}H}$ = 8.0 Hz, $^3J_{5\text{-}H,6\text{-}H}$ = 7.7 Hz, $^4J_{5\text{-}H,F}$ = 5.8 Hz, 1H, 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 65.0 (CH_2-5′), 87.2 (d, $^4J_{CF}$ = 1.8 Hz, CH-1′), 87.4 (CH-4′), 113.8 (d, $^2J_{CF}$ = 21.8 Hz, CH-2), 115.0 (d, $^2J_{CF}$ = 21.2 Hz, CH-4), 122.4 (d, $^4J_{CF}$ = 2.9 Hz, CH-6), 127.9 (CH-2′), 130.1 (d, $^3J_{CF}$ = 8.1 Hz, CH-5), 131.2 (CH-3′), 143.8 (d, $^3J_{CF}$ = 6.5 Hz, C-1), 163.0 (d, $^1J_{CF}$ = 246.5 Hz, CF-3); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.1; IR (NaCl, neat) ν 3406 (s, OH), 2929 (m), 2870 (m), 1615 (s), 1592 (s), 1488 (s), 1449 (s), 1263 (s) cm^{-1}; MS (CI) m/z (%) 195 ([M + H$^+$], 30), 177 ([M + H$^+$] − H_2O, 100); HRMS (CI) 195.0819 [$C_{11}H_{12}FO_2$ (M + H$^+$) requires 195.0821]. Anal. Calcd for $C_{11}H_{11}FO_2$: C, 68.03; H, 5.71. Found: C, 68.23; H, 5.72.

(−)-2′,3′-Didehydro-1′,2′,3′-trideoxy-1′-phenyl-α-D-ribofuranose (24a). Silane **20a** (441 mg, 1.52 mmol) was deprotected using general procedure D to obtain alcohol **24a** (176 mg, 66%): $[\alpha]_D$ −332.4 (*c* 1.71, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 2.42 (s, 1H, OH), 3.59 (dd, $^2J_{5'\text{-}Ha,5'\text{-}Hb}$ = 11.7 Hz, $^3J_{5'\text{-}Ha,4'\text{-}H}$ = 5.2 Hz, 1H, 5′-Ha), 3.74 (dd, $^2J_{5'\text{-}Hb,5'\text{-}Ha}$ = 11.7 Hz, $^3J_{5'\text{-}Hb,4'\text{-}H}$ = 3.2 Hz, 1H, 5′-Hb), 5.10 (m, 1H, 4′-H), 5.81 (ddd, $^4J_{1'\text{-}H,4'\text{-}H}$ = 5.7 Hz, J_{HH} = 2.3 Hz, J_{HH} = 1.6 Hz, 1H, 1′-H), 5.85 (ddd, $^3J_{3'\text{-}H,2'\text{-}H}$ = 6.1 Hz, J_{HH} = 2.3 Hz, J_{HH} = 1.6 Hz, 1H, 3′-H), 5.95 (ddd, $^3J_{2'\text{-}H,3'\text{-}H}$ = 6.1 Hz, J_{HH} = 2.3 Hz, J_{HH} = 1.6 Hz, 1H, 2′-H), 7.24−7.33 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 65.0 (CH_2-5′), 87.4 (CH-4′), 88.0 (CH-1′), 126.3 (CH-arom), 126.5 (CH-3′), 128.0, and 128.5 (CH-arom), 132.2 (CH-2′), 141.3 (C-arom); IR (NaCl, neat) ν 3406 (s, OH), 2868 (s), 1493 (m), 1454 (m), 1065 (s) cm^{-1}; MS (CI) m/z (%) 177 ([M + H$^+$], 95), 159 ([M + H$^+$] − H_2O, 100); HRMS (CI) 177.0917 [$C_{11}H_{13}O_2$ (M + H$^+$) requires 177.0916]. Anal. Calcd for $C_{11}H_{12}O_2$: C, 74.98; H, 6.86. Found: C, 74.82; H, 6.96.

(−)-2′,3′-Didehydro-1′,2′,3′-trideoxy-1′-(3-fluorophenyl)-α-D-ribofuranose (24b). Silane **20b** (178 mg, 0.57 mmol) was deprotected using general procedure D to obtain alcohol **24b** (97 mg, 88%): $[\alpha]_D$ −236.8 (*c* 1.90, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 2.05 (bs, 1H, OH), 3.65 (dd, $^2J_{5'\text{-}Ha,5'\text{-}Hb}$ = 11.7 Hz, $^3J_{5'\text{-}Ha,4'\text{-}H}$ = 5.2 Hz, 1H, 5′-Ha), 3.81 (dd, $^2J_{5'\text{-}Hb,5'\text{-}Ha}$ = 11.7 Hz, $^3J_{5'\text{-}Hb,4'\text{-}H}$ = 3.2 Hz, 1H, 5′-Hb), 5.14−5.18 (m, 1H, 4′-H), 5.85 (ddd, $^3J_{1'\text{-}H,F}$ = 5.8 Hz, J_{HH} = 2.1 Hz, J_{HH} = 2.1 Hz, 1H, 1′-H), 5.92 (ddd, $^3J_{2'\text{-}H,3'\text{-}H}$ = 6.1 Hz, J_{HH} = 2.3 Hz, J_{HH} = 1.5 Hz, 1H, 2′-H), 6.00 (ddd, $^3J_{3'\text{-}H,2'\text{-}H}$ = 6.1 Hz, J_{HH} = 2.2 Hz, J_{HH} = 1.6 Hz, 1H, 3′-H), 6.95−7.13 (m, 3H, 2-H, 4-H, and 6-H), 7.31 (ddd, $^3J_{HH}$ = 7.9 Hz, $^3J_{HH}$ = 7.7 Hz, $^4J_{5\text{-}H,F}$ = 5.8 Hz, 1H, 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 65.0 (CH_2-5′), 87.4 (d, $^4J_{CF}$ = 1.8 Hz, CH-1′), 87.5 (CH-4′), 113.1 (d, $^2J_{CF}$ = 21.9 Hz, CH-2), 114.7 (d, $^2J_{CF}$ = 21.3 Hz, CH-4), 121.8 (d, $^4J_{CF}$ = 2.9 Hz, CH-6), 126.9 (CH-2′), 130.1 (d, $^3J_{CF}$ = 8.1 Hz, CH-5), 131.8 (CH-3′), 144.1 (d, $^3J_{CF}$ = 6.4 Hz, C-1), 163.0 (d, $^1J_{CF}$ = 246.3 Hz, CF-3); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.3; IR (NaCl, neat) ν 3405 (s, OH), 2928 (m), 2874 (m), 1615 (s), 1592 (s), 1488 (s), 1449 (s), 1264 (s) cm^{-1}; MS (CI) m/z (%) 195 ([M + H$^+$], 15), 177 ([M + H$^+$] − H_2O, 100); HRMS (CI) 195.0816 [$C_{11}H_{12}FO_2$ (M + H$^+$) requires 195.0821].

(+)-2′,3′-Didehydro-1′,2′,3′-trideoxy-1′-phenyl-α-L-ribofuranose (25a). Silane **21a** (463 mg, 1.59 mmol) was deprotected using general procedure D to obtain alcohol **25a** (199 mg, 71%): $[\alpha]_D$ +334.6 (*c* 1.79, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 2.42 (s, 1H, OH), 3.59 (dd, $^2J_{5'\text{-}Ha,5'\text{-}Hb}$ = 11.7 Hz, $^3J_{5'\text{-}Ha,4'\text{-}H}$ = 5.2 Hz, 1H, 5′-Ha), 3.74 (dd, $^2J_{5'\text{-}Hb,5'\text{-}Ha}$ = 11.7 Hz, $^3J_{5'\text{-}Hb,4'\text{-}H}$ = 3.2 Hz, 1H, 5′-Hb), 5.10 (m, 1H, 4′-H), 5.81 (ddd, $^4J_{1'\text{-}H,4'\text{-}H}$ = 5.7 Hz, J_{HH} = 2.3 Hz, J_{HH} = 1.6 Hz, 1H, 1′-H), 5.85 (ddd, $^3J_{3'\text{-}H,2'\text{-}H}$ = 6.1 Hz, J_{HH} = 2.3 Hz, J_{HH} = 1.6 Hz, 1H, 3′-H), 5.95 (ddd, $^3J_{2'\text{-}H,3'\text{-}H}$ = 6.1 Hz, J_{HH} = 2.3 Hz, J_{HH} = 1.6 Hz, 1H, 2′-H), 7.24−7.33 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 65.0 (CH_2-5′), 87.4 (CH-4′), 88.0 (CH-1′), 126.3 (CH-arom), 126.5 (CH-3′), 128.0, and 128.5 (CH-arom), 132.2 (CH-2′), 141.3 (C-arom); IR (NaCl, neat) ν 3406 (s, OH), 2868 (s), 1493 (m), 1454 (m), 1065 (s) cm^{-1}; MS (CI) m/z (%) 177 ([M + H$^+$], 95), 159 ([M + H$^+$] − H_2O, 100); HRMS (CI) 177.0918 [$C_{11}H_{13}O_2$ (M + H$^+$) requires 177.0916]. Anal. Calcd for $C_{11}H_{12}O_2$: C, 74.98; H, 6.86. Found: C, 74.73; H, 6.95.

(+)-2′,3′-Didehydro-1′,2′,3′-trideoxy-1′-(3-fluorophenyl)-α-L-ribofuranose (25b). Silane **21b** (455 mg, 1.48 mmol) was deprotected using general procedure D to obtain alcohol **25b** (218 mg, 76%): $[\alpha]_D$ +288.2 (*c* 2.04, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 2.05 (bs, 1H, OH), 3.65 (dd, $^2J_{5'\text{-}Ha,5'\text{-}Hb}$ = 11.7 Hz, $^3J_{5'\text{-}Ha,4'\text{-}H}$ = 5.2 Hz, 1H, 5′-Ha), 3.81 (dd, $^2J_{5'\text{-}Hb,5'\text{-}Ha}$ = 11.7 Hz, $^3J_{5'\text{-}Hb,4'\text{-}H}$ = 3.2 Hz, 1H, 5′-Hb), 5.14−5.18 (m, 1H, 4′-H), 5.85 (ddd, $^3J_{1'\text{-}H,F}$ = 5.8 Hz, J_{HH} = 2.1 Hz, J_{HH} = 2.1 Hz, 1H, 1′-H), 5.92 (ddd, $^3J_{2'\text{-}H,3'\text{-}H}$ = 6.1 Hz, J_{HH} = 2.3 Hz, J_{HH} = 1.5 Hz, 1H, 2′-H), 6.00 (ddd, $^3J_{3'\text{-}H,2'\text{-}H}$ = 6.1 Hz, J_{HH} = 2.2 Hz, J_{HH} = 1.6 Hz, 1H, 3′-H), 6.95−7.13 (m, 3H, 2-H, 4-H, and 6-H), 7.31 (ddd, $^3J_{HH}$ = 7.9 Hz, $^3J_{HH}$ = 7.7 Hz, $^4J_{5\text{-}H,F}$ = 5.8 Hz, 1H, 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 65.0 (CH_2-5′), 87.4 (d, $^4J_{CF}$ = 1.8 Hz, CH-1′), 87.5 (CH-4′), 113.1 (d, $^2J_{CF}$ = 21.9 Hz, CH-2), 114.7 (d, $^2J_{CF}$ = 21.3 Hz, CH-4), 121.8 (d, $^4J_{CF}$ = 2.9 Hz, CH-6), 126.9 (CH-2′), 130.1 (d, $^3J_{CF}$ = 8.1 Hz, CH-5), 131.8 (CH-3′), 144.1 (d, $^3J_{CF}$ = 6.4 Hz, C-1), 163.0 (d, $^1J_{CF}$ = 246.3 Hz, CF-3); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.3; IR (NaCl, neat) ν 3405 (s, OH), 2928 (m), 2874 (m), 1615 (s), 1592 (s), 1488 (s), 1449 (s), 1264 (s) cm^{-1}; MS (CI) m/z (%) 195 ([M + H$^+$], 40), 177 ([M + H$^+$] − H_2O, 100); HRMS (CI) 195.0824 [$C_{11}H_{12}FO_2$ (M + H$^+$) requires 195.0821].

(−)-2′,3′-Didehydro-1′,2′,3′-trideoxy-1′-phenyl-β-L-ribofuranose (26a). Silane **22a** (254 mg, 0.87 mmol) was deprotected

using general procedure D to obtain alcohol **26a** (82 mg, 54%): $[\alpha]_D$ −78.8 (*c* 1.32, $CHCl_3$); ^1H NMR (400.1 MHz, $CDCl_3$) δ 1.96 (t, $^3J_{5\text{-OH},5\text{-H}}$ = 6.0 Hz, 1H, 5-OH), 3.67 (ddd, $^2J_{5\text{-Ha},5\text{-Hb}}$ = 11.6 Hz, $^3J_{5\text{-Ha},5\text{-OH}}$ = 6.1 Hz, $^3J_{5\text{-Ha},4\text{-H}}$ = 5.2 Hz, 1H, 5-Ha), 3.78 (ddd, $^2J_{5\text{-Hb},5\text{-Ha}}$ = 11.6 Hz, $^3J_{5\text{-Hb},5\text{-OH}}$ = 5.9 Hz, $^3J_{5\text{-Hb},4\text{-H}}$ = 3.3 Hz, 1H, 5-Hb), 5.00−5.03 (m, 1H, 4-H), 5.80−5.82 (m, 1H, 1-H), 5.94 (ddd, $^3J_{3\text{-H},2\text{-H}}$ = 6.1 Hz, J_{HH} = 2.4 Hz, J_{HH} = 1.4 Hz, 1H, 3-H), 6.00 (ddd, $^3J_{2\text{-H},3\text{-H}}$ = 6.1 Hz, J_{HH} = 2.2 Hz, J_{HH} = 1.5 Hz, 1H, 2-H), 7.29−7.38 (m, 5H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 65.0 (CH_2-5), 87.2 (CH-4), 87.9 (CH-1), 127.0 (CH-arom), 127.7 (CH-3), 128.1 (CH-arom), 128.6 (CH-arom), 131.5 (CH-2), 141.1 (C-arom); IR (NaCl, neat) ν 3365 (m, OH), 2929 (m), 2858 (m), 2360 (s), 1454 (m) cm^{-1}; MS (CI) *m*/*z* (%) 177 ([M + H^+], 80), 159 ([M + H^+] − H_2O, 100); HRMS (CI) 177.0918 [$C_{11}H_{13}O_2$ (M + H^+) requires 177.0916]. Anal. Calcd for $C_{11}H_{12}O_2$: C, 74.98; H, 6.86. Found: C, 74.59; H, 6.82.

(−)-2′,3′-Didehydro-1′,2′,3′-trideoxy-1′-(3-fluorophenyl)-β-L-ribofuranose (26b). Silane **22b** (100 mg, 0.32 mmol) was deprotected using general procedure D to obtain alcohol **26b** (42 mg, 67%): $[\alpha]_D$ −63.4 (*c* 1.90, $CHCl_3$); ^1H NMR (400.1 MHz, $CDCl_3$) δ 2.22 (bs, 1H, OH), 3.64 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 11.8 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 5.2 Hz, 1H, 5′-Ha), 3.75 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 11.8 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 3.4 Hz, 1H, 5′-Hb), 4.95−5.00 (m, 1H, 4′-H), 5.76 (d, $^3J_{1'\text{-H,F}}$ = 5.9 Hz, 1H, 1′-H), 5.91 (ddd, $^3J_{2'\text{-H},3'\text{-H}}$ = 6.1 Hz, J_{HH} = 2.1 Hz, J_{HH} = 1.1 Hz, 1H, 2′-H), 5.95 (ddd, $^3J_{3'\text{-H},2'\text{-H}}$ = 6.1 Hz, J_{HH} = 2.1 Hz, J_{HH} = 1.2 Hz, 1H, 3′-H), 6.96 (dddd, $^3J_{4\text{-H,F}}$ = 8.4 Hz, $^3J_{4\text{-H},5\text{-H}}$ = 8.0 Hz, $^4J_{4\text{-H},2\text{-H}}$ = 2.6 Hz, $^4J_{4\text{-H},6\text{-H}}$ = 1.0 Hz, 1H, 4-H), 7.05 (ddd, $^3J_{2\text{-H,F}}$ = 9.7 Hz, $^4J_{2\text{-H},4\text{-H}}$ = 2.6 Hz, $^4J_{2\text{-H},6\text{-H}}$ = 1.6 Hz, 1H, 2-H), 7.11 (dddd, $^3J_{6\text{-H},5\text{-H}}$ = 7.7 Hz, $^4J_{6\text{-H},2\text{-H}}$ = 1.6 Hz, $^4J_{6\text{-H},4\text{-H}}$ = 1.0 Hz, $^5J_{6\text{-H,F}}$ = 0.5 Hz, 1H, 6-H), 7.29 (ddd, $^3J_{5\text{-H},4\text{-H}}$ = 8.0 Hz, $^3J_{5\text{-H},6\text{-H}}$ = 7.7 Hz, $^4J_{5\text{-H,F}}$ = 5.8 Hz, 1H, 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 65.0 (CH_2-5′), 87.2 (d, $^4J_{CF}$ = 1.8 Hz, CH-1′), 87.4 (CH-4′), 113.8 (d, $^2J_{CF}$ = 21.8 Hz, CH-2), 115.0 (d, $^2J_{CF}$ = 21.2 Hz, CH-4), 122.4 (d, $^4J_{CF}$ = 2.9 Hz, CH-6), 127.9 (CH-2′), 130.1 (d, $^3J_{CF}$ = 8.1 Hz, CH-5), 131.2 (CH-3′), 143.8 (d, $^3J_{CF}$ = 6.5 Hz, C-1), 163.0 (d, $^1J_{CF}$ = 246.5 Hz, CF-3); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.1; IR (NaCl, neat) ν 3406 (s, OH), 2929 (m), 2870 (m), 1615 (s), 1592 (s), 1488 (s), 1449 (s), 1263 (s) cm^{-1}, MS (CI) *m*/*z* (%) 195 ([M + H^+], 30), 177 ([M + H^+] − H_2O, 100); HRMS (CI) 195.0820 [$C_{11}H_{12}FO_2$ (M + H^+) requires 195.0821]. Anal. Calcd for $C_{11}H_{11}FO_2$: C, 68.03; H, 5.71. Found: C, 68.19; H, 5.77.

General Procedure E: OsO_4-Catalyzed Dihydroxylation. A solution of OsO_4 (0.01 mmol) in water (0.127 mL) [prepared as a stock solution of OsO_4 (100 mg) in water (5 mL)] was added to a solution of the respective alkene **19a** or **22a** (1 mmol, 290.5 mg) in a mixture of acetone (2.3 mL), water (0.2 mL), and an aqueous solution of 4-methylmorpholine 4-oxide (NMO) (1.3 mmol, 0.274 mL of a 50% solution in water), and the resulting solution was stirred at room temperature overnight. The solution was then evaporated at reduced pressure, and the residue was chromatographed on a column of silica gel (3 × 20 cm) with a mixture of chloroform and methanol (50:1) to afford the corresponding silanes.

(−)-5′-*O*-(*tert*-Butyldimethylsilyl)-1′-phenyl-β-D-ribofuranose (27a). Method 1. Grubbs first-generation catalyst **C1** (42.4 mg, 0.051 mmol) was added to a solution of silane (2*S*,1′*R*)-**15a** (328 mg, 1.03 mmol) in dichloromethane (20 mL) under a stream of argon atmosphere, and the mixture was stirred at 40 °C for 3 h, and then evaporated. The resulting residue was dissolved in a mixture of ethyl acetate (5 mL) and acetonitrile (5 mL), cooled to 0 °C, and a cold (0 °C) solution of $RuCl_3 \cdot H_2O$ (30 mg, 0.12 mmol), and $NaIO_4$ (357 mg, 1.67 mmol) in water (4 mL) was added in one portion. After 15 s, the reaction was quenched with a 50% aqueous solution of $Na_2S_2O_3$ (10 mL). The aqueous layer was separated and extracted with ethyl acetate (3 × 50 mL). The combined organic phase was dried (Na_2SO_4) and evaporated, and the residue was chromatographed on a column of silica gel (3 × 10 cm) with a mixture of hexanes and ethyl acetate (80:20) to afford silane **27a** as a colorless oil (83 mg, 24%): $[\alpha]_D$ −10.2 (*c* 0.74, $CHCl_3$); ^1H NMR (400.1 MHz, $CDCl_3$) δ 0.10 (s, 3H, CH_3), 0.11 (s, 3H, CH_3), 0.92 (s, 9H, *t*-Bu), 3.28 (bs, 2H, OH), 3.85 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 10.8 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 4.3 Hz, 1H, 5′-Ha), 3.89 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 10.8 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 3.4 Hz, 1H, 5′-Hb), 4.00 (dd, $^3J_{2'\text{-H},1'\text{-H}}$ = 6.4 Hz, $^3J_{2'\text{-H},3'\text{-H}}$ = 5.5 Hz, 1H, 2′-H), 4.06 (dd, $^3J_{4'\text{-H},5'\text{-Ha}}$ = 4.3 Hz, $^3J_{4'\text{-H},5'\text{-Hb}}$ = 3.4 Hz, 1H, 4′-H), 4.21 (dd, $^3J_{3'\text{-H},2'\text{-H}}$ = 5.5 Hz, J_{HH} = 4.0 Hz, 1H, 3′-H), 4.76 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.4 Hz, 1H, 1′-H), 7.28−7.37 (m, 3H, H-arom), 7.42−7.44 (m, 2H, H-arom); NMR (100.6 MHz, $CDCl_3$) δ −5.53 (CH_3), −5.4 (CH_3), 18.3 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 63.7 (CH_2-5′), 72.8 (CH-3′), 78.0 (CH-2′), 84.2 (CH-4′), 84.3 (CH-1′), 126.1, 127.8, and 128.4 (CH-arom), 140.0 (C-arom); IR (NaCl, neat) ν 3421, 2929 (s), 2858 (s), 2360 (s), 1255 (s) cm^{-1}; MS (CI) *m*/*z* (%) 325 ([M + H^+], 100); HRMS (CI) 325.1837 [$C_{17}H_{29}O_4Si$ (M + H^+) requires 325.1835].

Method 2. Dihydroxylation of alkene **19a** (207 mg, 0.713 mmol) with OsO_4 (general Procedure E) afforded a mixture of diastereoisomeric diols, which was separated by column chromatography to furnish first diol **31** (32 mg, 14%) as a yellowish oil, followed by diol **27a** (86 mg, 80%) as a colorless oil, whose spectra data were identical to those of the product obtained by Method 1. **31**: $[\alpha]_D$ +33.2 (*c* 0.30, MeOH); ^1H NMR (600.1 MHz, $CDCl_3$): 0.15 and 0.16 (2 × s, 2 × 3H, CH_3Si); 0.91 (s, 9H, $(CH_3)_3C$); 3.04 (d, 1H, $J_{OH,3}$ = 9.4, OH-3); 3.58 (d, 1H, $J_{OH,2}$ = 11.2, OH-2); 3.89 (dd, 1H, J_{gem} = 11.1, $J_{5b,4}$ = 1.7, H-5b); 3.97 (dd, 1H, J_{gem} = 11.1, $J_{5a,4}$ = 3.1, H-5a); 4.10 (ddd, 1H, $J_{2,OH}$ = 11.2, $J_{2,3}$ = 4.8, $J_{2,1}$ = 3.3, H-2); 4.23 (ddd, 1H, $J_{4,3}$ = 8.1, $J_{4,5}$ = 3.1, 1.7, H-4); 4.66 (ddd, 1H, $J_{3,OH}$ = 9.4, $J_{3,4}$ = 8.1, $J_{3,2}$ = 4.8, H-3); 4.91 (d, 1H, $J_{1,2}$ = 3.3, H-1); 7.26 (m, 1H, H-*p*-Ph); 7.33 (m, 2H, H-*m*-Ph); 7.36 (m, 2H, H-*o*-Ph). ^{13}C NMR (150.9 MHz, $CDCl_3$): −5.7 and −5.6 (CH_3Si); 18.2 ($C(CH_3)_3$); 25.8 ($(CH_3)_3C$); 62.4 (CH_2-5); 73.3 (CH-2); 74.4 (CH-3); 78.6 (CH-4); 81.3 (CH-1); 126.5 (CH-*o*-Ph); 127.6 (CH-*p*-Ph); 128.0 (CH-*m*-Ph); 136.9 (C-*i*-Ph); HRMS (ESI) 325.1831 [$C_{17}H_{29}O_4Si$ (M + H) requires 325.1830]; IR (CCl_4) ν 3549, 3379, 3090, 3067, 3032, 2957, 1606, 1497, 1471, 1461, 1453, 1406, 1392, 1363, 1316, 1259, 1208, 1167, 1142, 1128, 1110, 1080, 1030, 939, 909, 839, 726, 697, 673 cm^{-1}; HRMS (ESI) 347.1647 [$C_{17}H_{28}O_4NaSi$: (M + Na) requires 347.1649].

(−)-5′-*O*-(*tert*-Butyldimethylsilyl)-1′-deoxy-1′-(3-fluorophenyl)-β-D-ribofuranose (27b). Silane **19b** (313 mg, 1.01 mmol) was dissolved in a mixture of ethyl acetate (5 mL) and acetonitrile (5 mL) and cooled to 0 °C, and a cold (0 °C) solution of $RuCl_3 \cdot H_2O$ (30 mg, 0.12 mmol) and $NaIO_4$ (320 mg, 1.50 mmol) in water (4 mL) was added in one portion. After 45 s, the reaction was quenched with a 50% aqueous solution of $Na_2S_2O_3$ (15 mL). The aqueous layer was separated and extracted with ethyl acetate (3 × 50 mL). The combined organic phase was dried (Na_2SO_4), evaporated, and chromatographed on a column of silica gel (3 × 10 cm) with a mixture of hexanes and ethyl acetate (80:20) to afford diol **27b** as a colorless oil (211 mg, 61%): $[\alpha]_D$ −16.7 (*c* 1.20, $CHCl_3$); ^1H NMR (400.1 MHz, $CDCl_3$) δ 0.10 (s, 3H, CH_3), 0.11 (s, 3H, CH_3), 0.91 (s, 9H, *t*-Bu), 2.56 (bs, 2H, OH), 3.86 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 10.8 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 4.0 Hz, 1H, 5′-Ha), 3.89 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 10.8 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 3.2 Hz, 1H, 5′-Hb), 3.97−4.01 (m, 1H, 2′-H), 4.08 (dd, $^3J_{4'\text{-H},5'\text{-Ha}}$ = 4.0 Hz, $^3J_{4'\text{-H},5'\text{-Hb}}$ = 3.2 Hz, 1H, 4′-H), 4.22−4.25 (m, 1H, 3′-H), 4.76 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.5 Hz, 1H, 1′-H), 6.97 (dddd, $^3J_{4\text{-H,F}}$ = 8.4 Hz, J_{HH} = 8.3 Hz, J_{HH} = 2.2 Hz, J_{HH} = 1.5 Hz, 1H, 4-H), 7.11−7.16 (m, 1H, 2-H), 7.18−7.21 (m, 1H, 6-H), 7.27−7.33 (m, 1H, 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.6 (CH_3), −5.4 (CH_3), 18.3 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 63.6 (CH_2-5′), 72.8 (CH-3′), 78.1 (CH-2′), 83.6 (d, $^4J_{CF}$ = 1.9 Hz, CH-1′), 84.4 (CH-4′), 112.8 (d, $^2J_{CF}$ = 22.3 Hz, CH-2), 114.6 (d, $^2J_{CF}$ = 21.2 Hz, CH-4), 121.6 (d, $^4J_{CF}$ = 2.9 Hz, CH-6), 129.8 (d, $^3J_{CF}$ = 8.2 Hz, CH-5), 143.9 (d, $^3J_{CF}$ = 6.6 Hz, C-1), 163.0 (d, $^1J_{CF}$ = 246.7 Hz, CF-3); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.6; IR (NaCl, neat) ν 3398 (s, OH), 2929 (s), 2858 (s), 1617 (s), 1592 (s) cm^{-1}; MS (CI) *m*/*z* (%) 343 ([M + H^+], 100); HRMS (CI) 343.1740 [$C_{17}H_{28}FO_4Si$ (M + H^+) requires 343.1741]. Anal. Calcd for $C_{17}H_{27}FO_4Si$: C, 59.62; H, 7.95. Found: C, 59.47; H, 8.06.

(+)-5′-*O*-(*tert*-Butyldimethylsilyl)-1′-deoxy-1′-phenyl-β-L-ribofuranose (28a). Method 1. Silane **22a** (337 mg, 1.16 mmol) was dissolved in a mixture of ethyl acetate (5 mL) and acetonitrile (5 mL) and cooled to 0 °C, and a cold (0 °C) solution of $RuCl_3 \cdot H_2O$ (30 mg, 0.12 mmol) and $NaIO_4$ (400 mg, 1.87 mmol) in water (5 mL) was added in one portion. After 15 s, the reaction was quenched with 50% aqueous solution of $Na_2S_2O_3$ (15 mL). The aqueous layer was separated and extracted with ethyl acetate (3 × 50 mL). The combined organic phase was dried (Na_2SO_4), evaporated, and the residue was chromatographed on a column of silica gel (3 × 10 cm) with a mixture of hexanes and ethyl acetate (80:20) to afford starting silane **22a** (232 mg, 69% of starting mass), followed by diol **28a** (colorless oil, 103 mg, 27%; 87% based on the recovered silane): $[\alpha]_D$ +10.8 (*c* 0.37, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.10 (s, 3H, CH_3), 0.11 (s, 3H, CH_3), 0.92 (s, 9H, *t*-Bu), 3.28 (bs, 2H, OH), 3.85 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 10.8 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 4.3 Hz, 1H, 5′-Ha), 3.89 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 10.8 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 3.4 Hz, 1H, 5′-Hb), 4.00 (dd, $^3J_{2'\text{-H},1'\text{-H}}$ = 6.4 Hz, $^3J_{2'\text{-H},3'\text{-H}}$ = 5.5 Hz, 1H, 2′-H), 4.06 (dd, $^3J_{4'\text{-H},5'\text{-Ha}}$ = 4.3 Hz, $^3J_{4'\text{-H},5'\text{-Hb}}$ = 3.4 Hz, 1H, 4′-H), 4.21 (dd, $^3J_{3'\text{-H},2'\text{-H}}$ = 5.5 Hz, J_{HH} = 4.0 Hz, 1H, 3′-H), 4.76 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.4 Hz, 1H, 1′-H), 7.28−7.37 (m, 3H, H-arom), 7.42−7.44 (m, 2H, H-arom); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.53 (CH_3), −5.40 (CH_3), 18.31 ($C(CH_3)_3$), 25.90 ($C(CH_3)_3$), 63.71 (CH_2-5′), 72.75 (CH-3′), 77.97 (CH-2′), 84.15 (CH-4′), 84.33 (CH-1′), 126.05, 127.82, and 128.35 (CH-arom), 140.02 (C-arom); IR (NaCl, neat) ν 3421, 2929 (s), 2858 (s), 2360 (s), 1255 (s) cm^{-1}; MS (CI) *m*/*z* (%) 325 ([M + H^+], 100); HRMS (CI) 325.1836 [$C_{17}H_{29}O_4Si$ (M + H^+) requires 325.1835].

Mehtod 2. Dihydroxylation of alkene **22a** (0.709 mmol, 206 mg) with OsO_4 (general procedure E) afforded a mixture of diastereoisomeric diols, which was separated by column chromatography to furnish first the diol **33** (30 mg, 13%) as a yellowish oil, followed by diol **28a** (179 mg, 78%) as a colorless oil, whose spectra data were identical to those of the product obtained by Method 1.

(−)-5′-*O*-(*tert*-Butyldimethylsilyl)-1′-deoxy-1′-(3-fluorophenyl)-β-L-ribofuranose (28b). Grubbs first-generation catalyst **C1** (71.0 mg, 0.090 mmol) was added to a solution of silane (2*R*,1′*S*)-**18b** (1.951 g, 5.80 mmol) in dichloromethane (50 mL) under a stream of argon atmosphere, and the mixture was stirred at 40 °C for 3 h and then evaporated. The resulting residue was dissolved in a mixture of ethyl acetate (25 mL) and acetonitrile (25 mL), cooled to 0 °C, and intensively stirred with a mechanical overhead stirrer. A cold (0 °C) solution of $RuCl_3 \cdot H_2O$ (140 mg, 0.60 mmol) and $NaIO_4$ (1.430 g, 6.69 mmol) in water (20 mL) was added in one portion. After 15 s, the reaction was quenched with a 50% aqueous solution of $Na_2S_2O_3$ (50 mL), and the aqueous layer was separated and extracted with ethyl acetate (3 × 250 mL). The combined organic phase was dried (Na_2SO_4), evaporated, and chromatographed on a column of silica gel (3 cm ×10 cm) with a mixture of hexanes and ethyl acetate (80:20) to afford diol **28b** as a colorless oil (667 mg, 34%): $[\alpha]_D$ −15.7 (*c* 1.15, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.10 (s, 3H, CH_3), 0.11 (s, 3H, CH_3), 0.91 (s, 9H, *t*-Bu), 2.56 (bs, 2H, OH), 3.86 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 10.8 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 4.0 Hz, 1H, 5′-Ha), 3.89 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 10.8 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 3.2 Hz, 1H, 5′-Hb), 3.97−4.01 (m, 1H, 2′-H), 4.08 (dd, $^3J_{4'\text{-H},5'\text{-Ha}}$ = 4.0 Hz, $^3J_{4'\text{-H},5'\text{-Hb}}$ = 3.2 Hz, 1H, 4′-H), 4.22−4.25 (m, 1H, 3′-H), 4.76 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.5 Hz, 1H, 1′-H), 6.97 (dddd, $^3J_{4\text{-H,F}}$ = 8.4 Hz, J_{HH} = 8.3 Hz, J_{HH} = 2.2 Hz, J_{HH} = 1.5 Hz, 1H, 4-H), 7.11−7.16 (m, 1H, 2-H), 7.18−7.21 (m, 1H, 6-H), 7.27−7.33 (m, 1H, 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.6 (CH_3), −5.4 (CH_3), 18.3 ($C(CH_3)_3$), 25.9 ($C(CH_3)_3$), 63.6 (CH_2-5′), 72.8 (CH-3′), 78.1 (CH-2′), 83.6 (d, $^4J_{CF}$ = 1.9 Hz, CH-1′), 84.4 (CH-4′), 112.8 (d, $^2J_{CF}$ = 22.3 Hz, CH-2), 114.6 (d, $^2J_{CF}$ = 21.2 Hz, CH-4), 121.6 (d, $^4J_{CF}$ = 2.9 Hz, CH-6), 129.8 (d, $^3J_{CF}$ = 8.2 Hz, CH-5), 143.9 (d, $^3J_{CF}$ = 6.6 Hz, C-1), 163.0 (d, $^1J_{CF}$ = 246.7 Hz, CF-3); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.6; IR (NaCl, neat) ν 3398 (s, OH), 2929 (s), 2858 (s), 1617 (s), 1592 (s) cm^{-1}; MS (CI) *m*/*z* (%) 343 ([M + H^+], 100); HRMS (CI) 343.1740 [$C_{17}H_{28}FO_4Si$ (M + H^+) requires 343.1741]. Anal. Calcd for $C_{17}H_{27}FO_4Si$: C, 59.62; H, 7.95. Found: C, 59.47; H, 8.06.

(−)-5′-*O*-(*tert*-Butyldimethylsilyl)-1′-(4-bromophenyl)-1′-deoxy-β-L-ribofuranose (28c). Grubbs first-generation catalyst **C1** (72.0 mg, 0.087 mmol) was added to a solution of silane (2*R*,1′*S*)-**18c** (2.483 g, 6.25 mmol) in dichloromethane (60 mL) under a stream of argon atmosphere, and the mixture was stirred at 40 °C for 3 h and then evaporated. The resulting residue was dissolved in a mixture of ethyl acetate (30 mL) and acetonitrile (30 mL), cooled to 0 °C, and intensively stirred with mechanical overhead stirrer. A cold (0 °C) solution of $RuCl_3 \cdot H_2O$ (166 mg, 0.67 mmol) and $NaIO_4$ (1.656 g, 7.74 mmol) in water (25 mL) was added in one portion. After 15 s, the reaction was quenched with a 50% aqueous solution of $Na_2S_2O_3$ (50 mL). The aqueous layer was separated and extracted with dichloromethane (3 × 300 mL). The combined organic phase was dried (Na_2SO_4) and evaporated. Chromatography on a column of silica gel (3 × 10 cm) with a mixture of hexanes and ethyl acetate (80:20) gave diol **28c** (colorless oil, 786 mg, 31%): $[\alpha]_D$ −35.1 (*c* 0.74, $CHCl_3$); ^{1}H NMR (400.1 MHz, $CDCl_3$) δ 0.04 (s, 3H, CH_3), 0.05 (s, 3H, CH_3), 0.90 (s, 9H, *t*-Bu), 2.57 (bs, 2H, OH), 3.55−3.76 (m, 4H), 4.54−4.56 (m, 1H), 7.34 (d, $^3J_{2\text{-H},3\text{-H}}$ = 8.4 Hz, 2H, 2-H, and 6-H), 7.50 (d, $^3J_{3\text{-H},2\text{-H}}$ = 8.4 Hz, 2H, 3-H, and 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ −5.42 (CH_3), −5.40 (CH_3), 18.3 ($C(CH_3)_3$), 25.8 ($C(CH_3)_3$), 66.0 (CH_2-5′), 73.1 (CH-3′), 74.3 (CH-2′), 79.3 (CH-1′), 79.7 (CH-4′), 120.1 (C-4), 129.2 (CH-2, and CH-6), 131.6 (CH-3, and CH-5), 137.4 (C-1); IR (NaCl, neat) ν 3420 (s, OH), 2954 (s), 2928 (s), 2857 (s), 1255 (s) cm^{-1}; MS (CI) *m*/*z* (%) 403/405 ([M + H^+], 100); HRMS (CI) 403.0916/405.0774 [$C_{17}H_{28}BrO_4Si$ (M + H^+) requires 403.0940/405.0922].

(−)-1′-Deoxy-1′-phenyl-β-D-ribofuranose (29a).[58b] **Method 1.** Following general procedure D, **27a** (76 mg, 0.23 mmol) was deprotected, and flash chromatography on a column of silica gel (3 × 10 cm) with ethyl acetate gave **29a** (36 mg, 75%) as a white crystalline solid: mp 112−113 °C (ethyl acetate), (lit.[58b] mp 121−122 °C); $[\alpha]_D$ −24.8 (*c* 0.44, MeOH); ^{1}H NMR (400.1 MHz, CD_3OD) δ 3.73 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 12.1 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 4.8 Hz, 1H, 5′-Ha), 3.79 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 12.1 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 3.9 Hz, 1H, 5′-Hb), 3.88 (dd, $^3J_{2'\text{-H},1'\text{-H}}$ = 6.4 Hz, $^3J_{2'\text{-H},3'\text{-H}}$ = 5.8 Hz, 1H, 2′-H), 3.95 (ddd, $^3J_{4'\text{-H},3'\text{-H}}$ = 4.8 Hz, $^3J_{4'\text{-H},5'\text{-Ha}}$ = 4.8 Hz, $^3J_{4'\text{-H},5'\text{-Hb}}$ = 3.9 Hz, 1H, 4′-H), 4.03 (dd, $^3J_{3'\text{-H},2'\text{-H}}$ = 5.8 Hz, $^3J_{3'\text{-H},4'\text{-H}}$ = 4.8 Hz, 1H, 3′-H), 4.69 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.4 Hz, 1H, 1′-H), 5.28 (s, 3H, OH), 7.22−7.32 (m, 3H, H-arom), 7.36−7.39 (m, 2H, H-arom); ^{13}C NMR (100.6 MHz, CD_3OD) δ 62.7 (CH_2-5′), 71.5 (CH-3′), 77.4 (CH-2′), 84.78 (CH-4′), 84.81 (CH-1′), 126.3, 128.1, and 128.6 (CH-arom), 140.0 (C-arom); MS (CI) *m*/*z* (%) 211 ([M + H^+], 25), 193 ([M + H^+] − H_2O, 100); HRMS (CI) 211.0973 [$C_{11}H_{15}O_4$ (M + H^+) requires 211.0970]; consistent with the literature data.[58b]

Method 2. Aqueous HCl (2M, 20 mL) was added to a solution of the silyloxy derivative **27a** (135 mg, 0.416 mmol) in toluene (10 mL), and the resulting heterogeneous mixture was evaporated on a rotavap (45 °C, 20 mBar) to afford a white solid, which was purified on a column of reverse phase silica gel (HPFC) (C18HS 25+M, 2.5 × 15 cm) using a gradient, starting with water and continuing with up to a mixture of water and MeOH (80:20) to obtain nucleoside **29a** (75 mg, 86%) as a white powder, whose spectral data were identical to those obtained in the previous experiment.

(−)-1′-Deoxy-1′-(3-fluorophenyl)-β-D-ribofuranose (29b). Following general procedure D, silane **27b** (118 mg, 0.34 mmol) was deprotected, and flash chromatography on a column of silica gel (3 × 10 cm) with ethyl acetate gave **29b** (50 mg, 65%) as a white solid: mp 92−93 °C (ethyl acetate); $[\alpha]_D$ −31.6 (*c* 0.35, MeOH); ^{1}H NMR (400.1 MHz, CD_3OD) δ 3.32−3.33 (bs, 3H, OH), 3.74 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 11.9 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 4.7 Hz, 1H, 5′-Ha), 3.81 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 11.9 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 3.7 Hz, 1H, 5′-Hb), 3.85 (dd, $^3J_{2'\text{-H},1'\text{-H}}$ = 6.8 Hz, $^3J_{2'\text{-H},3'\text{-H}}$ = 5.7 Hz, 1H, 2′-H), 4.00 (ddd, $^3J_{4'\text{-H},5'\text{-Ha}}$ = 4.7 Hz, $^3J_{4'\text{-H},3'\text{-H}}$ = 4.2 Hz,

$^3J_{4'\text{-H},5'\text{-Hb}}$ = 3.7 Hz, 1H, 4′-H), 4.05 (ddd, $^3J_{3'\text{-H},2'\text{-H}}$ = 5.7 Hz, $^3J_{3'\text{-H},4'\text{-H}}$ = 4.2 Hz, $^4J_{3'\text{-H},1'\text{-H}}$ = 0.5 Hz, 1H, 3′-H), 4.73 (dd, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.8 Hz, $^4J_{1'\text{-H},3'\text{-H}}$ = 0.5 Hz, 1H, 1′-H), 6.99 (dddd, $^3J_{4\text{-H,F}}$ = 9.0 Hz, $^3J_{4\text{-H},5\text{-H}}$ = 7.9 Hz, J_{HH} = 2.7 Hz, J_{HH} = 1.0 Hz, 1H, 4-H), 7.21−7.26 (m, 1H, 2-H, and 6-H), 7.33 (ddd, $^3J_{5\text{-H},6\text{-H}}$ = 8.0 Hz, $^3J_{5\text{-H},4\text{-H}}$ = 7.9 Hz, $^4J_{5\text{-H,F}}$ = 6.0 Hz, 1H, 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 63.4 (CH_2-5′), 72.6 (CH-3′), 78.9 (CH-2′), 84.5 (d, $^4J_{CF}$ = 1.6 Hz, CH-1′), 86.2 (CH-4′), 113.7 (d, $^2J_{CF}$ = 22.4 Hz, CH-2), 115.1 (d, $^2J_{CF}$ = 21.5 Hz, CH-4), 122.8 (d, $^4J_{CF}$ = 2.7 Hz, CH-6), 130.7 (d, $^3J_{CF}$ = 8.3 Hz, CH-5), 143.0 (d, $^3J_{CF}$ = 6.8 Hz, C-1), 164.3 (d, $^1J_{CF}$ = 244.3 Hz, CF-3); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.8, all in agreement with the literature data;[67] MS (CI) m/z (%) 229 ([M + H$^+$], 55), 211 ([M + H$^+$] − H_2O, 100) HRMS (CI) 229.0878 [$C_{11}H_{14}FO_4$ (M + H$^+$) requires 229.0876]. Anal. Calcd for $C_{11}H_{13}FO_4$: C, 57.89; H, 5.74. Found: C, 57.61; H, 5.75.

(+)-1′-Deoxy-1′-phenyl-β- L-ribofuranose (30a). Method 1. Following general procedure D, silane **28a** (77 mg, 0.24 mmol) was deprotected and a flash chromatography on a column of silica gel (3 × 10 cm) with ethyl acetate gave **30a** (36 mg, 72%) as a white crystalline solid: mp 112−113 °C (ethyl acetate), (lit.[58b] gives mp 121−122 °C for the D-enantiomer); [α]$_D$ +25.0 (*c* 0.48, MeOH); ^{1}H NMR (400.1 MHz, CD_3OD) δ 3.73 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 12.1 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 4.8 Hz, 1H, 5′-Ha), 3.79 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 12.1 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 3.9 Hz, 1H, 5′-Hb), 3.88 (dd, $^3J_{2'\text{-H},1'\text{-H}}$ = 6.4 Hz, $^3J_{2'\text{-H},3'\text{-H}}$ = 5.8 Hz, 1H, 2′-H), 3.95 (ddd, $^3J_{4'\text{-H},3'\text{-H}}$ = 4.8 Hz, $^3J_{4'\text{-H},5'\text{-Ha}}$ = 4.8 Hz, $^3J_{4'\text{-H},5'\text{-Hb}}$ = 3.9 Hz, 1H, 4′-H), 4.03 (dd, $^3J_{3'\text{-H},2'\text{-H}}$ = 5.8 Hz, $^3J_{3'\text{-H},4'\text{-H}}$ = 4.8 Hz, 1H, 3′-H), 4.69 (d, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.4 Hz, 1H, 1′-H), 5.28 (s, 3H, OH), 7.22−7.32 (m, 3H, H-arom), 7.36−7.39 (m, 2H, H-arom); ^{13}C NMR (100.6 MHz, CD_3OD) δ 62.7 (CH_2-5′), 71.5 (CH-3′), 77.4 (CH-2′), 84.8 (CH-4′), 84.8 (CH-1′), 126.3, 128.1, and 128.6 (CH-arom), 140.0 (C-arom); MS (CI) m/z (%) 211 ([M + H$^+$], 80), 193 ([M + H$^+$] − H_2O, 100); HRMS (CI) 211.0972 [$C_{11}H_{15}O_4$ (M + H$^+$) requires 211.0970]; consistent with the literature data for the D-enantiomer.[58b]

Method 2. Aqueous HCl (2M, 16 mL) was added to a solution of the silyloxy derivative **28a** (87 mg, 0.268 mmol) in toluene (8 mL), and the resulting heterogeneous mixture was evaporated on a rotavap (45 °C, 20 mBar) to afford a white solid, which was purified on a column of reverse phase silica gel (HPFC) (C18HS 25+M, 2.5 × 15 cm) using gradient, starting with water and continuing with up to a mixture of water and MeOH (80:20) to obtain ribonucleoside **30a** (44 mg, 79%) as a white powder, whose spectral data were identical to those obtained in the previous experiment.

(+)-1′-Deoxy-1′-(3-fluorophenyl)-β-L-ribofuranose (30b). Following general procedure D, silane **28b** (666 mg, 1.94 mmol) was deprotected, and flash chromatography on a column of silica gel (3 × 10 cm) with ethyl acetate gave **30b** (276 mg, 62%) as a white solid: mp 92−93 °C (ethyl acetate); [α]$_D$ +27.1 (*c* 0.48, MeOH); ^{1}H NMR (400.1 MHz, CD_3OD) δ 3.32−3.33 (bs, 3H, OH), 3.74 (dd, $^2J_{5'\text{-Ha},5'\text{-Hb}}$ = 11.9 Hz, $^3J_{5'\text{-Ha},4'\text{-H}}$ = 4.7 Hz, 1H, 5′-Ha), 3.81 (dd, $^2J_{5'\text{-Hb},5'\text{-Ha}}$ = 11.9 Hz, $^3J_{5'\text{-Hb},4'\text{-H}}$ = 3.7 Hz, 1H, 5′-Hb), 3.85 (dd, $^3J_{2'\text{-H},1'\text{-H}}$ = 6.8 Hz, $^3J_{2'\text{-H},3'\text{-H}}$ = 5.7 Hz, 1H, 2′-H), 4.00 (ddd, $^3J_{4'\text{-H},5'\text{-Ha}}$ = 4.7 Hz, $^3J_{4'\text{-H},3'\text{-H}}$ = 4.2 Hz, $^3J_{4'\text{-H},5'\text{-Hb}}$ = 3.7 Hz, 1H, 4′-H), 4.05 (ddd, $^3J_{3'\text{-H},2'\text{-H}}$ = 5.7 Hz, $^3J_{3'\text{-H},4'\text{-H}}$ = 4.2 Hz, $^4J_{3'\text{-H},1'\text{-H}}$ = 0.5 Hz, 1H, 3′-H), 4.73 (dd, $^3J_{1'\text{-H},2'\text{-H}}$ = 6.8 Hz, $^4J_{1'\text{-H},3'\text{-H}}$ = 0.5 Hz, 1H, 1′-H), 6.99 (dddd, $^3J_{4\text{-H,F}}$ = 9.0 Hz, $^3J_{4\text{-H},5\text{-H}}$ = 7.9 Hz, J_{HH} = 2.7 Hz, J_{HH} = 1.0 Hz, 1H, 4-H), 7.21−7.26 (m, 1H, 2-H, and 6-H), 7.33 (ddd, $^3J_{5\text{-H},6\text{-H}}$ = 8.0 Hz, $^3J_{5\text{-H},4\text{-H}}$ = 7.9 Hz, $^4J_{5\text{-H,F}}$ = 6.0 Hz, 1H, 5-H); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 63.4 (CH_2-5′), 72.6 (CH-3′), 78.9 (CH-2′), 84.5 (d, $^4J_{CF}$ = 1.6 Hz, CH-1′), 86.2 (CH-4′), 113.7 (d, $^2J_{CF}$ = 22.4 Hz, CH-2), 115.1 (d, $^2J_{CF}$ = 21.5 Hz, CH-4), 122.8 (d, $^4J_{CF}$ = 2.7 Hz, CH-6), 130.7 (d, $^3J_{CF}$ = 8.3 Hz, CH-5), 143.0 (d, $^3J_{CF}$ = 6.8 Hz, C-1), 164.3 (d, $^1J_{CF}$ = 244.3 Hz, CF-3); ^{19}F NMR (376.5 MHz, $CDCl_3$) δ −113.8; IR (NaCl, neat) ν 3376 (s, OH), 2932 (s), 2883 (s), 2501 (s), 1615 (s), 1591 (s), 1488 (s), 1450 (s) cm^{-1}; MS (CI) m/z (%) 229 ([M + H$^+$], 50), 211 ([M + H$^+$] − H_2O, 100); HRMS (CI) 229.0875 [$C_{11}H_{14}FO_4$ (M + H$^+$) requires 229.0876].

(+)-1′-Deoxy-1′-phenyl-β-D-lyxofuranose (32). Aqueous HCl (2 M, 14 mL) was added to a solution of the silyloxy derivative **31** (87 mg, 0.268 mmol) in toluene (7 mL), and the resulting heterogeneous mixture was evaporated on a rotavap (45 °C, 20 mBar) to afford a white solid, which was purified on a column of reverse phase silica gel (HPFC) (C18HS 25+M, 2.5 × 15 cm) using a gradient, starting with water and continuing with up to a mixture of water and MeOH (80:20) to obtain nucleoside **32** (56 mg, 79%) as a white powder: [α]$_D$ +51.4 (*c* 0.23, MeOH); ^{1}H NMR (500 MHz, DMSO-d_6) δ 3.59 (ddd, 1H, J_{gem} = 11.6, $J_{5b\text{-H,OH}}$ = 4.9, $J_{5b\text{-H,4-H}}$ = 4.6, H-5b), 3.67 (ddd, 1H, J_{gem} = 11.6, $J_{5a\text{-H,OH}}$ = 5.4, $J_{5a\text{-H,4-H}}$ = 3.8, H-5a), 3.97 (ddd, 1H, $J_{4\text{-H,3-H}}$ = 7.1, $J_{4\text{-H,5-H}}$ = 4.6, 3.8, H-4), 4.03 (ddd, 1H, $J_{2\text{-H,OH}}$ = 7.6, $J_{2\text{-H,3-H}}$ = 4.7, $J_{2\text{-H,1-H}}$ = 4.2, H-2), 4.39 (ddd, 1H, $J_{3\text{-H,4-H}}$ = 7.1, $J_{3\text{-H,OH}}$ = 5.5, $J_{3\text{-H,2-H}}$ = 4.7, H-3), 4.73 (d, 1H, $J_{OH,2\text{-H}}$ = 7.6, OH-2), 4.79 (d, 1H, $J_{1\text{-H,2-H}}$ = 4.2, H-1), 4.88 (d, 1H, $J_{OH,3\text{-H}}$ = 5.5, OH-3), 4.99 (dd, 1H, $J_{OH,5\text{-H}}$ = 5.4, 4.9, OH-5), 7.21 (m, 1H, H-*p*-Ph), 7.28 (m, 2H, H-*m*-Ph), 7.35 (m, 2H, H-*o*-Ph); ^{13}C NMR (125.7 MHz, DMSO-d_6) δ 60.3 (CH_2-5), 72.4 (CH-3), 72.9 (CH-2), 80.1 (CH-4), 81.7 (CH-1), 126.9 (CH-*p*-Ph), 127.5 (CH-*m*-Ph), 127.7 (CH-*o*-Ph), 139.1 (C-*i*-Ph); IR (KBr) ν 3296, 3064, 3031, 1604, 1587, 1495, 1455, 1310, 1210, 1178, 1130, 1062, 1029, 1001, 909, 737, 700 cm^{-1}; HRMS (ESI) 233.0785 [$C_{11}H_{14}O_4Na$ (M + Na) requires 233.0784].

■ ASSOCIATED CONTENT

Supporting Information. Procedures for racemic products, copies of ^{1}H NMR and ^{13}C NMR spectra, and HPLC/GC traces. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: (M.H.) hocek@uochb.cas.cz; (A.V.M.) a.malkov@lboro.ac.uk; (P.K.) pavelk@chem.gla.ac.uk.

Present Addresses

[¶]NovaEnergo Ltd., Nám. 14. října 1307/2, 15000 Prague, Czech Republic.

[§]Exchange Erasmus student from Department of Chemistry, Charles University, 12840 Prague 2, Czech Republic.

[▽]Department of Chemistry, Loughborough University, Loughborough, Leicestershire LE11 3UT, UK.

■ ACKNOWLEDGMENT

We thank the University of Glasgow for a fellowship to J.Š. and O.K., The Erasmus exchange program for a scholarship to V.K., the Academy of Sciences of the Czech Republic (Z4 055 905), the Ministry of Education (LC 512), and the Grant Agency of the ASCR (IAA400550902) for additional support, and Eastman for a generous gift of the pure enantiomers, from which the enantiomeric diols **4** were readily obtained. We also thank the late Dr. Andy Parkin of the University of Glasgow for the X-ray analysis.

■ DEDICATION

[†]Dedicated to Professor Antonín Holý on the occasion of his 75th birthday and in appreciation of his life work in the area of nucleosides and antiviral drugs.

REFERENCES

(1) Reviews: (a) Wang, L.; Schultz, P. G. *Chem. Commun.* **2002**, 1. (b) Henry, A. A.; Romesberg, F. E. *Curr. Opin. Chem. Biol.* **2003**, *7*, 727. (c) Kool, E. T.; Morales, J. C.; Guckian, K. M. *Angew. Chem., Int. Ed.* **2000**, *39*, 990. (d) Kool, E. T. *Acc. Chem. Res.* **2002**, *35*, 936.

(2) (a) Ogawa, A. K.; Abou-Zied, O. K.; Tsui, V.; Jimenez, R.; Case, D. A.; Romesberg, F. E. *J. Am. Chem. Soc.* **2000**, *122*, 9917. (b) Wu, Y. Q.; Ogawa, A. K.; Berger, M.; McMinn, D. L.; Schultz, P. G.; Romesberg, F. E. *J. Am. Chem. Soc.* **2000**, *122*, 7621. (c) Guckian, K. M.; Krugh, T. R.; Kool, E. T. *J. Am. Chem. Soc.* **2000**, *122*, 6841. (d) Parsch, J.; Engels, J. W. *J. Am. Chem. Soc.* **2002**, *124*, 5664. (e) Lai, J. S.; Qu, J.; Kool, E. T. *Angew. Chem., Int. Ed.* **2003**, *42*, 5973. (f) Lai, J. S.; Kool, E. T. *J. Am. Chem. Soc.* **2004**, *126*, 3040.

(3) (a) Henry, A. A.; Olsen, A. G.; Matsuda, S.; Yu, C.; Geierstanger, B. H.; Romesberg, F. E. *J. Am. Chem. Soc.* **2004**, *126*, 6923. (b) Henry, A. A.; Yu, C. Z.; Romesberg, F. E. *J. Am. Chem. Soc.* **2003**, *125*, 9638. (c) Hwang, G. T.; Romesberg, F. E. *Nucleic Acids Res.* **2006**, *34*, 2037. (d) Matsuda, S.; Henry, A. A.; Romesberg, F. E. *J. Am. Chem. Soc.* **2006**, *128*, 6369. (e) Kim, Y.; Leconte, A. M.; Hari, Y.; Romesberg, F. E. *Angew. Chem., Int. Ed.* **2006**, *45*, 7809. (f) Matsuda, S.; Fillo, J. D.; Henry, A. A.; Rai, P.; Wilkens, S. J.; Dwyer, T. J.; Geierstanger, B. H.; Wemmer, D. E.; Schultz, P. G.; Spraggon, G.; Romesberg, F. E. *J. Am. Chem. Soc.* **2007**, *129*, 10466. (g) Matsuda, S.; Leconte, A. M.; Romesberg, F. E. *J. Am. Chem. Soc.* **2007**, *129*, 5551. (h) Hari, Y.; Hwang, G. T.; Leconte, A. M.; Joubert, N.; Hocek, M.; Romesberg, F. E. *ChemBioChem* **2008**, *9*, 2796.

(4) (a) Leconte, A. M.; Hwang, G. T.; Matsuda, S.; Capek, P.; Hari, Y.; Romesberg, F. E. *J. Am. Chem. Soc.* **2008**, *130*, 2336. (b) Seo, Y. J.; Romesberg, F. E. *ChemBioChem* **2009**, *10*, 2394. (c) Malyshev, D.; Seo, Y. J.; Ordoukhanian, P.; Romesberg, F. E. *J. Am. Chem. Soc.* **2009**, *131*, 14620.

(5) (a) Wu, Q. P.; Simons, C. *Synthesis* **2004**, 1533. (b) Wellington, K. W.; Benner, S. A. *Nucleosides Nucleotides Nucleic Acids* **2006**, *25*, 1309. (c) Adamo, M. F. A; Pergoli, R. *Curr. Org. Chem.* **2008**, *12*, 1544. (d) Štambaský, J.; Hocek, M.; Kočovský, P. *Chem. Rev.* **2009**, *109*, 6729.

(6) (a) Matsuda, S.; Romesberg, F. E. *J. Am. Chem. Soc.* **2004**, *126*, 14419. (b) Mathis, G.; Hunziker, J. *Angew. Chem., Int. Ed.* **2002**, *41*, 3203. (c) Brotschi, C.; Häberli, A.; Leumann, C. J. *Angew. Chem., Int. Ed.* **2001**, *40*, 3012. (d) Brotschi, C.; Mathis, G.; Leumann, C. J. *Chem.—Eur. J.* **2005**, *11*, 1911. (e) Zahn, A.; Brotschi, C.; Leumann, C. J. *Chem.—Eur. J.* **2005**, *11*, 2125. (f) Reese, C. B.; Wu, Q. *Org. Biomol. Chem.* **2003**, *1*, 3160.

(7) (a) Chaudhuri, N. C.; Kool, E. T. *Tetrahedron Lett.* **1995**, *36*, 1795. (b) Ren, R. X.-F.; Chaudhuri, N. C.; Paris, P. L.; Rumney, S., IV; Kool, E. T. *J. Am. Chem. Soc.* **1996**, *118*, 7671. (c) Griesang, N.; Richert, C. *Tetrahedron Lett.* **2002**, *43*, 8755. (d) Aketani, S.; Tanaka, K.; Yamamoto, K.; Ishihama, A.; Cao, H.; Tengeiji, A.; Hiraoka, S.; Shiro, M.; Shinoya, M. *J. Med. Chem.* **2002**, *45*, 5594. (e) Beuck, C.; Singh, I.; Bhattacharya, A.; Hecker, W.; Parmar, W. S.; Seitz, O.; Elmar Weinhold, E. *Angew. Chem., Int. Ed.* **2003**, *42*, 3958. (f) Hainke, S.; Singh, I.; Hemmings, J.; Seitz, O. *J. Org. Chem.* **2007**, *72*, 881.

(8) (a) Yokoyama, M.; Nomura, M.; Togo, H.; Seki, H. *J. Chem. Soc., Perkin Trans. 1* **1996**, 2145. (b) He, W.; Togo, H.; Yokoyama, M. *Tetrahedron Lett.* **1997**, *38*, 5541. (c) Hainke, S.; Arndt, S.; Seitz, O. *Org. Biomol. Chem.* **2005**, *3*, 4233. For a similar reactivity of pyranoglycals, see: (d) Malkov, A. V.; Farn, B. P.; Hussain, N.; Kočovský, P. *Collect. Czech. Chem. Commun.* **2001**, *66*, 1735.

(9) (a) Wang, Z. X.; Wiebe, L. I.; De Clercq, E.; Balzarini, J.; Knaus, E. E. *Can. J. Chem.* **2000**, *78*, 1081. (b) Häberli, A.; Leumann, C. J. *Org. Lett.* **2001**, *3*, 489. (c) Sun, Z.; Ahmed, S.; McLaughlin, L. W. *J. Org. Chem.* **2006**, *71*, 2922.

(10) Singh, I.; Seitz, O. *Org. Lett.* **2006**, *8*, 4319.

(11) (a) Hocek, M.; Pohl, R.; Klepetářová, B. *Eur. J. Org. Chem.* **2005**, 4525. (b) Štefko, M.; Pohl, R.; Klepetářová, B.; Hocek, M. *Eur. J. Org. Chem.* **2008**, 1689. (c) Joubert, N.; Urban, M.; Pohl, R.; Hocek, M. *Synthesis* **2008**, 1918. (d) Štefko, M.; Pohl, R.; Hocek, M. *Tetrahedron* **2009**, *65*, 4471.

(12) (a) Urban, M.; Pohl, R.; Klepetářová, B.; Hocek, M. *J. Org. Chem.* **2006**, *71*, 7322. (b) Joubert, N.; Pohl, R.; Klepetářová, B.; Hocek, M. *J. Org. Chem.* **2007**, *72*, 6797. (c) Štefko, M.; Slavětínská, L.; Klepetářová, B.; Hocek, M. *J. Org. Chem.* **2010**, *75*, 442. (d) Kubelka, T.; Slavětínská, L.; Klepetářová, B.; Hocek, M. *Eur. J. Org. Chem.* **2010**, 2666. (e) Štefko, M.; Slavětínská, L.; Klepetářová, B.; Hocek, M. *J. Org. Chem.* **2011**, *76*, 6619.

(13) Bárta, J.; Pohl, R.; Klepetářová, B.; Ernsting, N. P.; Hocek, M. *J. Org. Chem.* **2008**, *73*, 3798.

(14) Štambaský, J.; Malkov, A. V.; Kočovský, P. *Collect. Czech. Chem. Commun.* **2008**, *73*, 705.

(15) Štambaský, J.; Malkov, A. V.; Kočovský, P. *J. Org. Chem.* **2008**, *73*, 9148.

(16) For Pd-catalyzed allylic substitution, see: (a) Negishi, E., Ed. *Handbook of Palladium Chemistry for Organic Synthesis*; J. Wiley: New York, 2002; Vol 2, p 1663. For an overview of our contribution to Pd-catalyzed allylic substitution, see: (b) Kočovský, P. *J. Organomet. Chem.* **2003**, *687*, 256. For an overview of catalysis by other metals, see: (c) Kočovský, P.; Malkov, A. V.; Vyskočil, Š.; Lloyd-Jones, G. C. *Pure Appl. Chem.* **1999**, *71*, 1425. (d) Kočovský, P.; Malkov, A. V. *Pure Appl. Chem.* **2008**, *80*, 953.

(17) In principle, the two isomeric substrates **1** and **3** should produce the same η^3-complex **2** (M = Pd; ref 16). However, there are cases where the nucleophilic attack occurs preferentially at the carbon to which the leaving group was originally attached, a phenomenon known as the "memory effect": (a) Fiaud, J. C.; Malleron, J. L. *Tetrahedron Lett.* **1981**, *22*, 1399. (b) Trost, B. M.; Schmuff, N. R. *Tetrahedron Lett.* **1981**, *22*, 2999. (c) Trost, B. M.; Bunt, R. C. *J. Am. Chem. Soc.* **1996**, *118*, 235. (d) Hayashi, T.; Kawatsura, M.; Uozumi, Y. *J. Am. Chem. Soc.* **1998**, *120*, 1681. (e) Vyskočil, Š.; Smrčina, M.; Hanuš, V.; Polášek, M.; Kočovský, P. *J. Org. Chem.* **1998**, *63*, 7738. (f) Kočovský, P.; Vyskočil, Š.; Císařová, I.; Sejbal, J.; Tišlerová, I.; Smrčina, M.; Lloyd-Jones, G. C.; Stephen, S. C.; Butts, C. P.; Murray, M.; Langer, V. *J. Am. Chem. Soc.* **1999**, *121*, 7714. (g) Lloyd-Jones, G. C.; Stephen, S. C. *Chem.—Eur. J.* **1998**, *4*, 2539. (h) Lloyd-Jones, G. C.; Stephen, S. C. *Chem. Commun.* **1998**, 2321. (i) Butts, C. P.; Crosby, J.; Lloyd-Jones, G. C.; Stephen, S. C. *Chem. Commun.* **1997**, 1707. (j) Blacker, A. J.; Clarke, M. L.; Loft, M. S.; Williams, J. M. J. *Org. Lett.* **1999**, *1*, 1969. (k) Burckhardt; Baumann, U. M.; Togni, A. *Tetrahedron: Asymmetry* **1997**, *8*, 155. (l) Lloyd-Jones, G. C.; Stephen, S. C.; Murray, M.; Butts, C. P.; Vyskočil, Š.; Kočovský, P. *Chem.—Eur. J.* **2000**, *6*, 4348. (m) Fairlamb, I. J. S.; Lloyd-Jones, G. C.; Vyskočil, Š.; Kočovský, P. *Chem.—Eur. J.* **2002**, *8*, 4443. (n) Gouriou, L.; Lloyd-Jones, G. C.; Vyskočil, Š.; Kočovský, P. *J. Organomet. Chem.* **2003**, *687*, 525. (o) Fristrup, P.; Ahlquist, M.; Tanner, D.; Norrby, P.-O. *J. Phys. Chem. A* **2008**, *112*, 12862.

(18) For overviews, see ref 16 and the following: (a) Trost, B. M.; Van Vranken, D. L. *Chem. Rev.* **1996**, *96*, 395. (b) Helmchen, G.; Pfaltz, A. *Acc. Chem. Res.* **2000**, *33*, 336. (c) Helmchen, G.; Kudis, S.; Sennhenn, P.; Steinhagen, H. *Pure Appl. Chem.* **1997**, *69*, 513.

(19) In the Pd-catalyzed allylic substitution, the η^3-complex **2** is formed via inversion of configuration (ref 16). For the retention pathway, see: (a) Starý, I.; Kočovský, P. *J. Am. Chem. Soc.* **1989**, *111*, 4981. (b) Starý, I.; Zajíček, J.; Kočovský, P. *Tetrahedron* **1992**, *48*, 7229. (c) Farthing, C. N.; Kočovský, P. *J. Am. Chem. Soc.* **1998**, *120*, 6661 and refs cited therein. See also: (d) Kurosawa, H.; Ogoshi, S.; Kawasaki, Y.; Murai, S.; Miyoshi, M.; Ikeda, I. *J. Am. Chem. Soc.* **1990**, *112*, 2813. (e) Kurosawa, H.; Kajimaru, H.; Ogoshi, S.; Yoneda, H.; Miki, K.; Kasai, N.; Murai, S.; Ikeda, I. *J. Am. Chem. Soc.* **1992**, *114*, 8417. (f) Krafft, M. E.; Wilson, A. M.; Fu, Z.; Procter, M. J.; Dasse, O. A. *J. Org. Chem.* **1998**, *63*, 1748. (g) Cook, G. R.; Yu, H.; Sankaranarayanan, S.; Shanker, P. S. *J. Am. Chem. Soc.* **2003**, *125*, 5115. (h) Nehri, K.; Franzén, J.; Bäckvall, J.-E. *Chem.—Eur. J.* **2005**, *11*, 6937.

(20) In the Mo-catalyzed allylic substitution, the η^3-complex **2** has been shown to arise via retention of configuration: (a) Dvořák, D.; Starý, I.; Kočovský, P. *J. Am. Chem. Soc.* **1995**, *117*, 6130. (b) Lloyd-Jones, G. C.; Krska, S. W.; Hughes, D. L.; Gouriou, L.; Bonnet, V. D.; Jack, K.; Sun, Y.; Reamer, R. A. *J. Am. Chem. Soc.* **2004**, *126*, 702.

(21) The stereochemistry of the formation of the molybdenum complex **2** (M = Mo) from a chiral substrate **3**, carried out in the presence of a chiral ligand, is controlled predominantly by the ligand. An isomerization in the case of a "mismatched" combination of **3** and L* has

been demonstrated, so that even a racemic substrate **3** can be converted into a substitution product with high enantioselectivity: Malkov, A. V.; Starý, I.; Gouriou, L.; Lloyd-Jones, G. C.; Langer, V.; Spoor, P.; Vinader, V.; Kočovský, P. *Chem.—Eur. J.* **2006**, *12*, 6910.

(22) For overviews, see: (a) Trost, B. M. *Tetrahedron* **1977**, *33*, 371. (b) Trost, B. M. *Acc. Chem. Res.* **1980**, *13*, 385. (c) Tsuji, J. *Tetrahedron* **1986**, *42*, 4361. Tsuji, J.; Minami, I. *Acc. Chem. Res.* **1987**, *20*, 140.

(23) The regioselectivity of the Pd-catalyzed reaction can be reversed in favor of the branched product by certain ligands: Prétôt, R.; Pfaltz, A. *Angew. Chem., Int. Ed.* **1998**, *37*, 323.

(24) (a) Trost, B. M.; Lautens, M. *J. Am. Chem. Soc.* **1982**, *104*, 5543. (b) Trost, B. M.; Merlic, C. A. *J. Am. Chem. Soc.* **1990**, *112*, 9590 and references given therein. (c) Sjögren, M. P. T.; Frisell, H.; Åkermark, B.; Norrby, P. O.; Eriksson, L.; Vitagliano, A. *Organometallics* **1997**, *16*, 942.

(25) (a) Trost, B. M.; Hung, M.-H. *J. Am. Chem. Soc.* **1983**, *105*, 7757. (b) Lehmann, J.; Lloyd-Jones, G. C. *Tetrahedron* **1995**, *51*, 8863. (c) Frisell, H.; Åkermark, B. *Organometallics* **1995**, *14*, 561.

(26) The behavior of W complexes actually appears to be dependent on the steric bulk of the nucleophile and the R^1 group: the less sterically cumbersome partners also afford the branched products, but with the increased steric congestion the reaction is characterized by the shift toward linear products.[25]

(27) (a) Bruneau, C.; Renaud, J.-L.; Demerseman, B. *Pure Appl. Chem.* **2008**, *80*, 861. (b) Zhu, H.-J.; Demerseman, B.; Toupet, L.; Xi, Z.-F.; Bruneau, C. *Adv. Synth. Catal.* **2008**, *350*, 1601.

(28) Rh-Catalyzed formation of the C−C bonds: (a) Evans, P. A.; Nelson, J. D. *Tetrahedron Lett.* **1998**, *38*, 1725. (b) Evans, P. A.; Nelson, J. D. *J. Am. Chem. Soc.* **1998**, *120*, 5581. (c) Evans, P. A.; Brandt, T. A. *Org. Lett.* **1999**, *1*, 1563. (d) Evans, P. A.; Kennedy, L. J. *Org. Lett.* **2000**, *2*, 2213. (e) Evans, P. A.; Kennedy, L. J. *J. Am. Chem. Soc.* **2001**, *123*, 1234. (f) Evans, P. A.; Robinson, J. E. *J. Am. Chem. Soc.* **2001**, *123*, 4609. (g) Evans, P. A.; Uraguchi, D. *J. Am. Chem. Soc.* **2003**, *125*, 7158. (h) Evans, P. A.; Leahy, D. K. *J. Am. Chem. Soc.* **2003**, *125*, 8974. (i) Evans, P. A.; Lawler, M. J. *J. Am. Chem. Soc.* **2004**, *126*, 8642. Formation of the C−N bonds: (j) Evans, P. A.; Robinson, J. E. *Org. Lett.* **1999**, *1*, 1929. (k) Evans, P. A.; Robinson, J. E.; Nelson, J. D. *J. Am. Chem. Soc.* **1999**, *121*, 6761. (l) Evans, P. A.; Robinson, J. E.; Moffett, K. K. *Org. Lett.* **2001**, *3*, 3269. (m) Evans, P. A.; Lai, K. W.; Zhang, H.-R.; Huffman, J. C. *Chem. Commun.* **2006**, 844. Formation of the C−O bonds: (n) Evans, P. A.; Leahy, D. K. *J. Am. Chem. Soc.* **2000**, *122*, 5012. (o) Evans, P. A.; Leahy, D. L. *J. Am. Chem. Soc.* **2002**, *124*, 7882. (p) Evans, P. A.; Leahy, D. K.; Slieker, L. M. *Tetrahedron: Asymmetry* **2003**, *14*, 3613. (q) Evans, P. A.; Leahy, D. L.; Andrews, W. J.; Uraguchi, D. *Angew. Chem., Int. Ed.* **2004**, *43*, 4788.

(29) For the development of the methodology for the Ir-catalyzed C−C bonds formation, see: (a) Graening, T.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 17192. (b) Weix, D. J.; Hartwig, J. F. *J. Am. Chem. Soc.* **2007**, *129*, 7720. Formation of C−N bonds: (c) Ohmura, T.; Hartwig, J. F. *J. Am. Chem. Soc.* **2002**, *124*, 15164. (d) Shu, C.; Leitner, A.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2004**, *43*, 4797. (e) Leitner, A.; Shu, C.-T.; Hartwig, J. F. *Proc. Natl. Acad. Sci.* **2004**, *101*, 5830. (f) Leitner, A.; Shekhar, S.; Pouy, M. J.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 15506. (g) Pouy, M.; Leitner, A.; Weix, D. J.; Ueno, S.; Hartwig, J. F. *Org. Lett.* **2007**, *9*, 3949. (h) Yamashita, Y.; Gopalarathnam, A.; Hartwig, J. F. *J. Am. Chem. Soc.* **2007**, *129*, 7508. (i) Marković, D.; Hartwig, J. F. *J. Am. Chem. Soc.* **2007**, *129*, 11680. Formation of the C−O bonds: (j) López, F.; Ohmura, T.; Hartwig, J. F. *J. Am. Chem. Soc.* **2003**, *125*, 3426. (k) Keiner, C. A.; Shu, C.; Incarvito, C.; Hartwig, J. F. *J. Am. Chem. Soc.* **2003**, *125*, 14272. (l) Shu, C.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2004**, *43*, 4794. (m) Ueno, S.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2008**, *47*, 1928. For the activation of the catalyst by an in situ formation of the corresponding metallacycle, see: (n) Leitner, A.; Shu, C.; Hartwig, J. F. *Org. Lett.* **2005**, *7*, 1093. For a recent overview, see: Hartwig, J. F.; Stanley, L. M. *Acc. Chem. Res.* **2010**, *43*, 1461.

(30) For further examples of the Ir-catalyzed formation of the C−C bonds, see, for example: (a) Bartels, B.; García-Yerba, C.; Helmchen, G. *Eur. J. Org. Chem.* **2003**, 1097. (b) García-Yerba, C.; Jansen, J. P.; Rominger, F.; Helmchen., G. *Organometallics* **2004**, *23*, 5459. (c) Lipowsky, G.; Miller, N.; Helmchen, G. *Angew. Chem., Int. Ed.* **2004**, *43*, 4595. (d) Streiff, S.; Welter, C.; Schelwies, M.; Lipowsky, G.; Miller, N.; Helmchen, G. *Chem. Commun.* **2005**, 2957. (e) Dahnz, A.; Helmchen, G. *Synlett* **2006**, 697. (f) Schelwies, M.; Dübon, P.; Helmchen, G. *Angew. Chem., Int. Ed.* **2006**, *45*, 2466. (g) Gnamm, C.; Forster, S.; Miller, N.; Brodner, K.; Helmchen, G. *Synlett* **2007**, 790. (h) Dübon, P.; Schelwies, M.; Helmchen, G. *Chem.—Eur. J.* **2008**, *14*, 6722. For a detailed mechanistic study of the stereochemistry of the catalytic reaction with stabilized C-nucleophiles, see: (i) Bartles, B.; García-Yerba, C.; Rominger, F.; Helmchen, G. *Eur. J. Org. Chem.* **2002**, 2569. Formation of the C−N bonds: (j) Lipowsky, G.; Helmchen, G. *Chem. Commun.* **2004**, 116. (k) Welter, C.; Koch, O.; Lipowsky, G.; Helmchen, G. *Chem. Commun.* **2004**, 896. (l) Weihofen., R.; Tverskoy, E.; Helmchen, G. *Angew. Chem., Int. Ed.* **2006**, *45*, 5546. (m) Spies, S.; Berthold, S.; Weihofen, R.; Helmchen, G. *Org. Biomol. Chem.* **2007**, *5*, 2357. (n) Gnamm, C.; Franck, G.; Miller, N.; Stork, T.; Brodner, K.; Helmchen, G. *Synthesis* **2008**, 3331. (o) Spies, S.; Welte, C.; Franck, G; Taquet, J.-P.; Helmchen, G. *Angew. Chem., Int. Ed.* **2008**, *47*, 7652. Formation of the C−O bond: (p) Welter, C.; Dahnz, A.; Brunner, B.; Streiff, S.; Dübon, P.; Helmchen, G. *Org. Lett.* **2005**, *7*, 1239. For a feature article, see: (q) Helmchen, G.; Dahnz, A.; Dübon, P.; Schelwies, M.; Weihofen, R. *Chem. Commun.* **2007**, 675. For an overview, see: (r) Helmchen, G.; Ernst, M.; Paradies, G. *Pure Appl. Chem.* **2004**, *76*, 495.

(31) Bohrsch, V.; Blechert, S. *Chem. Commun.* **2006**, 1968.

(32) (a) Roustan, J. L.; Mérour, J. Y.; Houlihan, F. *Tetrahedron Lett.* **1979**, *39*, 3721. (b) Dieter, J.; Nicholas, K. M. *J. Organomet. Chem.* **1981**, *212*, 107. (c) Ladoulis, S. J.; Nicholas, K. M. *J. Organomet. Chem.* **1985**, *285*, C13. (d) Silverman, G. S.; Strickland, S.; Nicholas, K. M. *Organometallics* **1986**, *5*, 2117. (e) Xu, Y.; Zhou, B. *J. Org. Chem.* **1987**, *52*, 974. (f) Zhou, B.; Xu, Y. *J. Org. Chem.* **1988**, *53*, 4419. For a review, see: (g) Bolm, C.; Legros, J.; Le Paih, J.; Zani, L. *Chem. Rev.* **2004**, *104*, 6217.

(33) Bergmeier, S. C.; Stanchina, D. M. *J. Org. Chem.* **1999**, *64*, 2852.

(34) For the first report on this way of preparation of Boc-protected alcohols, see:Stoner, E. J.; Peterson, M. J.; Allen, M. S.; DeMattei, J. A.; Haight, A. R.; Leanna, M. R.; Patel, S. R.; Plata, D. J.; Premchandran, R. H.; Rasmussen, M. *J. Org. Chem.* **2003**, *68*, 8847.

(35) These carbonates are rather sensitive compounds that readily undergo allylic rearrangement. For a detailed discussion of the problems associated with their preparation, see ref 15.

(36) Fiaud, J.-C.; Legros, J.-Y. *J. Org. Chem.* **1987**, *52*, 1907.

(37) For further comparison: the Rh-catalyzed substitution with stabilized C-nucleophiles is known to afford products of overall retention of configuration,[28] so that double inversion can be assumed. This mechanism is further supported by the observation that organometallics, such as PhZnBr, give products of overall inversion,[28g] which can be rationalized by inversion in the first step, followed by transmetalation and intramolecular delivery via retention, mirroring the behavior of Pd and Ni catalysts.[16]

(38) The relative configuration of the major diastereoisomer of **12** obtained in the presence of ligand **11** was deduced from the configuration of the product of the subsequent ring-closing metathesis, which proved to be trans (Scheme 6).

(39) (a) No significant improvement was observed here when the "activated" catalyst[29n] was used. The catalyst was "activated" by heating $[Ir(COD)Cl]_2$ and ligand (R_a,R_c,R_c)-**11** with propylamine at 50 °C for 20 min to generate the corresponding metalacyclic species,[29n] followed by evaporation of the volatile materials before the addition of the reaction solvent and the two reagents. (b) Attempted reaction in the absence of the iridium exhibited very low conversion (≤10%). (c) Conversion of the bisallyl ethers **12ca** and **12da** to the respective products was based on the ^{1}H NMR spectroscopy integrals of the worked-up reaction mixture (based on the carbonate). These two compounds were not isolated.

(40) In fact, formation of the rearranged product **13** is proportional to the time that is used for the generation of the alkoxide from the monoprotected diol **5a**. Thus, if **5a** is first left with *n*-BuLi for a longer period of time before CuI is added, the initially generated secondary alkoxide tends to slowly rearrange to the primary isomer, which then,

after transmetalation with CuI, reacts in the subsequent Ir-catalyzed reaction with the allylic partner, so that **13** becomes a visible impurity in the product. On the other hand, shortening the time allowed between the alkoxide generation and its subsequent reaction with the allylic partner to the minimum, prevents the formation of **13** entirely. For an optimized protocol, see the Experimental Section.

(41) The relative configuration was confirmed for the product of ring-closing metathesis (Scheme 6).

(42) The ratios were established by chiral HPLC; see the Experimental Section for details.

(43) By contrast, inferior results were obtained with ligand (S_a,S_c,S_c)-**10**: Although the diastereoselectivity was still high [94% dr for (*R*)-**5a** and 96% dr for (*S*)-**5a**], the formation of the rearranged product **13** and other unidentified byproducts rose to unacceptable levels (24% in both series), as revealed by the ^{1}H NMR spectra of the crude products.[40]

(44) The lower temperature (−40 °C) is required here to suppress the formation of the byproduct; at 0 °C, 15% of **13** was formed.

(45) The mechanism of the formation of 1,3-diphenylpropene **14** is rather obscure. Hartwig reported on an interesting migration of one of the phenyls of the $OCPh_3$ group in the σ-complex [Rh]−O−CPh_3 to form the new complex [Rh]−Ph and Ph_2C═O: Zhao, P.; Incarvito, C. D.; Hartwig, J. F. *J. Am. Chem. Soc.* **2006**, *128*, 3124. In view of this observation, it can be speculated that the allylic complex [Rh]−(C_3H_4Ph), initially generated from **9**, loses the allyl group with a concomitant migration of the phenyl to the coordination sphere of the metal, generating [Rh]−Ph. The reaction of the latter complex with another molecule of the substrate **9** would then effect a standard allylic substitution, where the Ph would migrate from the metal to the organic ligand, giving rise to **14**. It is noteworthy that we did not observe the formation of this byproduct in the case of the Ir-based catalyst, unless a phosphine ligand (such as BINAP) was added to the reaction mixture.

(46) By contrast, the reaction of racemic arylpropenyl carbonates with dimethyl sodiomalonate, catalyzed by chiral molybdenum complexes, is known to be stereoconvergent, i.e., both enantiomers are converted into the same enantiomer of the product, demonstrating epimerization of the intermediate Mo-complex.[21] Note, however, that other Mo-complexes may react nonselectively: (a) Malkov, A. V.; Baxendale, I. R.; Dvořák, D.; Mansfield, D. J.; Kočovský, P. *J. Org. Chem.* **1999**, *64*, 2737. (b) Malkov, A. V.; Davis, S. L.; Baxendale, I. R.; Mitchell, W. L.; Kočovský, P. *J. Org. Chem.* **1999**, *64*, 2751. (c) Kočovský, P.; Ahmed, G.; Šrogl, J.; Malkov, A. V.; Steele, J. *J. Org. Chem.* **1999**, *64*, 2765. (d) Malkov, A. V.; Spoor, P.; Vinader, V.; Kočovský, P. *J. Org. Chem.* **1999**, *64*, 5308. (e) Malkov, A. V.; Baxendale, I. R.; Mansfield, D. J.; Kočovský, P. *J. Chem. Soc., Perkin Trans. 1* **2001**, 1234. For the control of enantioselectivity by chiral ligands, see ref 21 and the following: (f) Trost, B. M.; Hachiya, I. *J. Am. Chem. Soc.* **1998**, *120*, 1104. (g) Trost, B. M.; Hildbrand, S.; Dogra, K. *J. Am. Chem. Soc.* **1999**, *121*, 10416. (h) Glorius, F.; Pfaltz, A. *Org. Lett.* **1999**, *1*, 141. (i) Belda, O.; Kaiser, N.-F.; Bremberg, U.; Larhed, M.; Hallberg, A.; Moberg, C. *J. Org. Chem.* **2000**, *65*, 5868. (j) Kaiser, N.-F.; Bremberg, U.; Larhed, M.; Moberg, C.; Hallberg, A. *Angew. Chem., Int. Ed.* **2000**, *39*, 3596. (k) Malkov, A. V.; Spoor, P.; Vinader, V.; Kočovský, P. *Tetrahedron Lett.* **2001**, *42*, 509. For a kinetic resolution of racemic allylic substrate on the Mo-catalyzed allylic substitution, see: (l) Hughes, D. L.; Palucki, M.; Yasuda, N.; Reamer, R. A.; Reider, P. J. *J. Org. Chem.* **2002**, *67*, 2762.

(47) Note that **15a,b** and **18a,b** are enantiomers, and the same relation applies to the pair of **16a,b** and **17a,b**.

(48) For reviews, see: (a) *Handbook of Olefin Metathesis*; Grubbs, R. H., Ed.; Wiley−VCH: Weinheim, 2003. (b) Schrock, R. R.; Hoveyda, A. H. *Angew. Chem., Int. Ed.* **2003**, *38*, 4555. (c) Trnka, T. M.; Grubbs, R. H. *Acc. Chem. Res.* **2001**, *34*, 18–29. (d) Fürstner, A. *Angew. Chem., Int. Ed.* **2000**, *39*, 3012.

(49) The optimization was carried out with 1:1 diastereoisomeric mixtures of the bisallyl ethers obtained from the reaction of (±)-**5a** or (±)-**5b** with (±)-**9a** (Scheme 4). No difference was observed as a function of the silyl protecting group, and both diastereoisomeric ethers reacted with a similar rate, as confirmed later with pure diastereoisomers. However, removal of the TBS group from the cyclized products turned out to be substantially easier than that of its TBDPS counterpart, so that only the TBS derivatives were used in the experiments involving pure diastereoisomers.

(50) Kumamoto, H.; Tanaka, H. *J. Org. Chem.* **2003**, *67*, 3541.

(51) (a) The racemic 1:1 mixture of diastereoisomers of the TBDPS (rather than TBS) derivatives, obtained from the reaction of (±)-**5b** and (±)-**9a** (Scheme 4), followed by ring-closing metathesis, was used for optimization of the reagent and conditions. Thus for instance, the standard treatment with Bu_4NF (TBAF, 3.5 equiv, 20 °C, 16 h) gave the corresponding alcohol in 44% yield along with a number of decomposition products, which made the separation tedious. By contrast, Py·HF (3 equiv, 20 °C, 16 h) failed completely. On the other hand, with 11 equiv of the latter reagent (20 °C, 16 h), the alcohol was obtained in 52%. Finally, $Et_3N·3HF$ (3 equiv, 20 °C, 16 h) afforded the alcohol in 56% yield. (b) It is pertinent to note that unlike their silylated precursors, the diastereoisomeric free alcohols can be readily separated by flash chromatography. Therefore, in principle, an enantiopure diastereoisomeric mixture, e.g., **15a**/**16a**, obtained from (*S*)-**5a** and (±)-**9a** via the Ir(I)-catalyzed allylic substitution, can also be used if both anomers of *C*-nucleosides are the target. The ring-closing metathesis of the latter mixture would produce a ∼1:1 mixture of **19a**/**20a**, deprotection of which, followed by chromatography, would provide pure, readily separable enantiomers **23a** and **24a**.

(52) (a) Riddler, S. A.; Anderson, R. E.; Mellors, J. W. *Antiviral Res.* **1995**, *27*, 189. (b) Hurst, M.; Noble, S. *Drugs* **1999**, *58*, 919. (c) Martin, J. C.; Hitchcock, M. J. M.; DeClercq, E.; Prusow, W. H. *Antiviral Res.* **2010**, *85*, 34.

(53) Hudlický, T.; Rinner, U.; Gonzalez, D.; Akgun, H.; Schilling, S.; Siengalewicz, P.; Martinot, T. A.; Pettit, G. R. *J. Org. Chem.* **2002**, *67*, 8726.

(54) For a recent review on RuO_4-catalyzed oxidations, see: Plietker, B. *Synthesis* **2005**, 2453.

(55) Beligny, S.; Eibauer, S.; Maechling, S.; Blechert, S. *Angew. Chem., Int. Ed.* **2006**, *45*, 1900.

(56) Plietker, B.; Niggemann, M. *J. Org. Chem.* **2005**, *70*, 2402.

(57) Note however that the O-deprotection with HCl can only be carried out at the stage of diols **27**/**28**, as the olefins **19**/**22** would decompose under these conditions.

(58) For examples of the use of *C*-ribonucleosides for RNA studies, see: (a) Matulic-Adamic, J.; Biegelman, L. *Tetrahedron Lett.* **1996**, *37*, 6973. (b) Matulic-Adamic, J.; Biegelman, L.; Portmann, S.; Egli, M.; Usman, N. *J. Org. Chem.* **1996**, *61*, 3909. (c) Matulic-Adamic, J.; Biegelman, L. *Tetrahedron Lett.* **1997**, *38*, 203. (d) Matulic-Adamic, J.; Biegelman, L. *Tetrahedron Lett.* **1997**, *38*, 1669. (e) Burgin, A. B.; Ginzales, C.; Matulic-Adamic, J.; Karpiesky, A. M.; Usman, N.; McSwiggen, J. A.; Beigelman, L. *Biochemistry* **1996**, *35*, 14090. (f) Lu, J.; Li, N.-S.; Koo, S. C.; Piccirilli, J. A. *J. Org. Chem.* **2009**, *74*, 8021.

(59) For related oligofluorosides, see: (a) Strässler, C.; Davis, N. E.; Kool, E. T. *Helv. Chim. Acta* **1999**, *82*, 2160. (b) Gao, J.; Strässler, C.; Tahmassebi, D.; Kool, E. T. *J. Am. Chem. Soc.* **2002**, *124*, 11590. (c) Gao, J.; Watanabe, S.; Kool, E. T. *J. Am. Chem. Soc.* **2004**, *126*, 12748. (d) Wilson, J. N.; Teo, Y. N.; Kool, E. T. *J. Am. Chem. Soc.* **2007**, *129*, 15426. (e) Cuppoletti, A.; Cho, Y.; Park, J. S.; Strassler, S.; Kool, E. T. *Bioconjugate Chem.* **2005**, *16*, 528. (f) Wilson, J. N.; Cho, Y.; Tan, S.; Cuppoletti, A.; Kool, E. T. *ChemBioChem* **2008**, *9*, 279. (g) Wilson, J. N.; Gao, J.; Kool, E. T. *Tetrahedron* **2007**, *63*, 3427. (h) Teo, N. Y.; Wilson, J. N.; Kool, E. T. *J. Am. Chem. Soc.* **2009**, *131*, 3923.

(60) For examples of biologically active L-ribonucleosides, see: (a) Wang, P. Y.; Hong, J. H.; Cooperwood, J. S.; Chu, C. K. *Antiviral Res.* **1998**, *40*, 19. (b) Gumina, G.; Song, G.-Y.; Chu, C. K. *FEMS Microb. Lett.* **2001**, *202*, 9. (c) Gumina, G.; Chong, Y.; Choo, H.; Song, G.-Y.; Chu, C. K. *Curr. Top. Med. Chem.* **2002**, *2*, 1065. (d) Bryant, M. L.; Bridges, E. G.; Placidi, L.; Faraj, A.; Loi, A. G.; Pierra, C.; Dukhan, D.; Gosselin, G.; Imbach, J. L.; Hernandez, B.; Juodawlkis, A.; Tennant, B.; Korba, B.; Cote, P.; Marion, P.; Cretton-Scott, E.; Schinazi, R. F.; Sommadossi, J. P. *Antimicrob. Agents Chemother.* **2001**, *45*, 229. (e) Mugnaini, C.; Botta, M.; Coletta, M.; Corelli, F.; Focher, F.; Marini, S.;

Renzulli, M. L.; Verri, A. *Bioorg. Med. Chem.* **2003**, *11*, 357. (f) Zhu, W.; Chong, Y. H.; Choo, H.; Mathews, J.; Schinazi, R. F.; Chu, C. K. *J. Med. Chem.* **2004**, *47*, 1631. (g) Seela, F.; Lin, W.; Kazimierczuk, Z.; Rosemeyer, H.; Glacon, V.; Peng, X.; He, Y.; Ming, X.; Andrzejewska, M.; Gorska, A.; Zhang, X.; La Colla, P. *Nucleosides Nucleotides Nucleic Acids* **2005**, *24*, 859. (h) Clinch, K.; Evans, G. B.; Fleet, G. W. J.; Furneaux, R. H.; Johnson, S. W.; Lenz, D. H.; Mee, S. P. H.; Rands, P. R.; Schramm, V. L.; Taylor Ringia, E. A.; Tyler, P. C. *Org. Biomol. Chem.* **2006**, *4*, 1131. (i) Seela, F.; Peng, Q. *Collect. Czech. Chem. Commun.* **2006**, *71*, 956. (j) Hocek, M.; Šilhár, P.; Shih, I.; Mabery, E.; Mackman, R. *Bioorg. Med. Chem. Lett.* **2006**, *16*, 5290.

(61) For de novo synthesis of carbohydrates, see refs 5d and 62. For the pioneering work of Roush, see: (a) Roush, W. R.; Brown, R. J. *J. Org. Chem.* **1982**, *47*, 1371. (b) Roush, W. R.; Harris, D. J.; Lesur, B. M. *Tetrahedron Lett.* **1983**, *24*, 2227. (c) Roush, W. R.; Brown, R. J.; DiMare, M. *J. Org. Chem.* **1983**, *48*, 5083. (d) Roush, W. R.; Straub, J. A. *Tetrahedron Lett.* **1986**, *27*, 3349. (e) Roush, W. R.; Straub, J. A.; Brown, R. J. *J. Org. Chem.* **1987**, *52*, 5127. (f) Roush, W. R.; Michaelides, M. R.; Tai, D. F.; Chong, W. K. M. *J. Am. Chem. Soc.* **1987**, *109*, 7575. (g) Roush, W. R.; Michaelides, M. R.; Tai, D. F.; Lesur, B. M.; Chong, W. K. M.; Harris, D. J. *J. Org. Chem.* **1989**, *111*, 2984. (h) Roush, W. R.; Straub, J. A.; VanNieuwenhze, M. S. *J. Org. Chem.* **1991**, *56*, 1636. (i) Roush, W. R.; Lin, X.-F.; Straub, J. A. *J. Org. Chem.* **1991**, *56*, 1649. (j) Roush, W. R.; Follows, B. C. *Tetrahedron Lett.* **1994**, *35*, 4935. (k) Roush, W. R.; Pfeifer, L. A.; Marron, T. G. *J. Org. Chem.* **1998**, *63*, 2064. (l) Roush, W. R.; Bennett, C. E.; Roberts, S. E. *J. Org. Chem.* **2001**, *66*, 6389. For an organocatalytic approach, see, for example: (m) Chowdari, N. S.; Ramachary, D. B.; Cordova, A.; Barbas, C. F. *Tetrahedron Lett.* **2002**, *43*, 9591. (n) Northrup, A. B.; MacMillan, D. W. C. *Science* **2004**, *305*, 1752. (o) Suri, J. T.; Ramachary, D. B.; Barbas, C. F. *Org. Lett.* **2005**, *7*, 1383. (p) Enders, D.; Grondal, C. *Angew. Chem., Int. Ed.* **2005**, *44*, 1210. (q) Grondal, C.; Enders, D. *Tetrahedron* **2006**, *62*, 329. (r) Suri, J. T.; Mitsumori, S.; Albertshofer, K.; Tanaka, F.; Barbas, C. F. *J. Org. Chem.* **2006**, *71*, 3822.

(62) Dallanoce, C.; Amici, M. D.; Carrea, G.; Secundo, F.; Castellano, S.; Micheli, C. D. *Tetrahedron: Asymmetry* **2000**, *11*, 2741.

(63) Aragones, S.; Bravo, F.; Diaz, Y.; Matheu, M. I.; Castillon, S. *Tetrahedron: Asymmetry* **2003**, *14*, 1847.

(64) The appearance of a bright yellow solution of the corresponding copper alkoxide is indicative of the successful transmetalation. The quality of the CuI proved to be of the key importance. The optimized CuI preparation includes drying of the perfectly ground CuI in the reaction flask at 140 °C overnight and until the reaction is setup.

(65) Correia, R.; DeShong, P. *J. Org. Chem.* **2001**, *66*, 7159.

(66) The IR absorption band in the region 1725−1740 cm^{-1} is apparently a higher order absorption band. This is a typical feature for all the protected D4 analogues **19**−**22**. Note the *medium* intensity of the band (vs the *strong* intensity of the carbonyl band). This band disappeared after deprotection.

(67) Matulic-Adamic, J.; Beigelman, L.; Portmann, S.; Egli, M.; Usman, N. *J. Org. Chem.* **1996**, *61*, 3909.