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Glycal Metallanitrenes for 2-Amino Sugar Synthesis: Amidoglycosylation of Gulal-, Allal-, Glucal-, and Galactal 3-Carbamates

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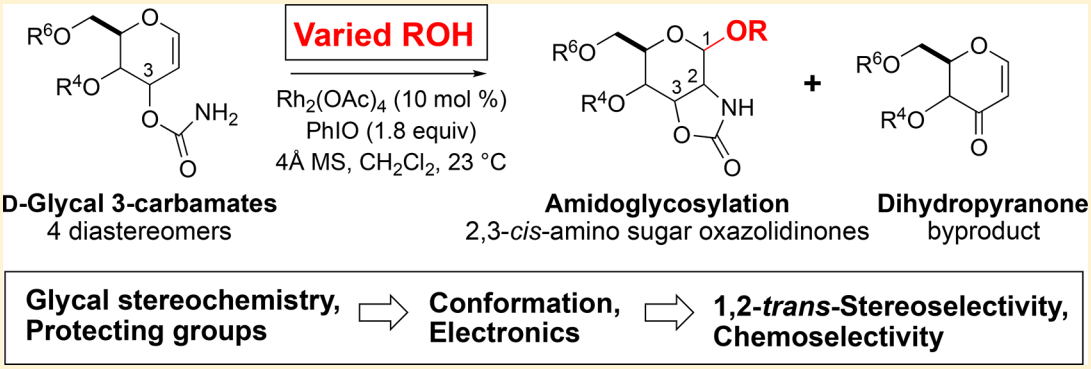
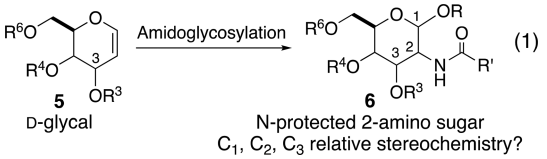
Supporting Information



ABSTRACT: The rhodium(II)-catalyzed oxidative cyclization of glycal 3-carbamates with in situ incorporation of an alcohol nucleophile at the anomeric position provides access to a range of 2-amino sugars having 1,2-trans-2,3-cis stereochemistry, a structural motif present in compounds of medicinal and biological significance such as the streptothricin group of antibiotics and the Chitinase inhibitor allosamidin. All of the diastereomeric D-glycal 3-carbamates have been investigated, revealing significant differences in anomeric stereoselectivity depending on substrate stereochemistry and protecting groups. In addition, some substrates were prone to forming C3-oxidized dihydropyranone byproducts under the reaction conditions. Allal- and gulal 3-carbamates provided uniformly high stereo- and chemoselectivity, while for glucal substrates, acyclic, electron-withdrawing protecting groups at the 4*O* and 6*O* positions were required. Galactal 3-carbamates have been the most challenging substrates; formation of their amidoglycosylation products is most effective with an electron-withdrawing 6*O*-Ts substituent and a sterically demanding 4*O*-TBS group. These results suggest a mechanism whereby conformational and electronic factors determine the partitioning of an intermediate acyl nitrenoid between alkene addition, leading to amidoglycosylation, and C3−H insertion, providing the dihydropyranone byproduct. Along the amidoglycosylation pathway, high anomeric selectivity results when a glycosyl aziridine intermediate is favored over an aziridine-opened oxocarbenium donor.

INTRODUCTION

The biological[1] and medicinal[2] significance of 2-amino sugars has stimulated the development of methods for their chemical synthesis.[3] Examples shown in Figure 1 include the streptothricin antibiotics (**1**)[4] and the Chitinase inhibitor allosamidin (**2**),[5] as well as 2-amino sugar building blocks such as **3**[6] and **4**[7] equipped with functionality useful for glycodiversification of bioactive compounds.[8] Glycals are attractive starting materials[9] for accessing 2-amino sugars as they provide a reactive enol ether alkene for incorporation of nitrogen functionality at C2 and introduction of substituents at the anomeric position.[10] An oxidative amino- or amidoalkoxylation can accomplish both substitutions simultaneously, constituting an overall amidoglycosylation reaction (**5** → **6**, eq 1).



(1)

Two stereochemical elements require consideration in such a process. First is the relative C1/C2 stereochemistry of product **6** set in the double-bond addition. One strategy for controlling this stereochemistry involves initial formation of a transient glycosyl aziridine, which undergoes S_N2 ring opening by an acceptor to give 1,2-trans stereochemistry. Glycosyl

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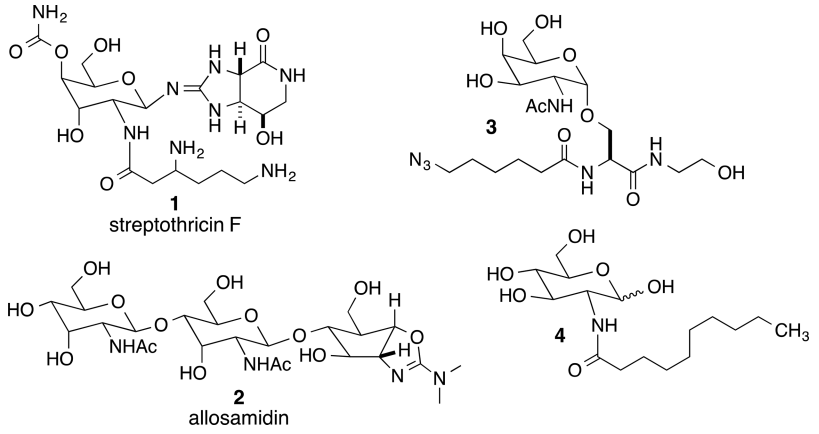
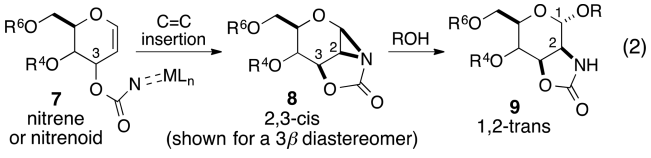


Figure 1. Bioactive natural products and building blocks containing 2-amino sugars.

aziridines have been generated from glycals by direct nitrene- or nitrenoid-mediated nitrogen atom transfer[11] and by azide cycloaddition, followed by loss of nitrogen from the resulting triazoline.[10h] The second stereochemical element is glycal face selectivity for nitrogen incorporation. The stereocenter at the allylic C3 site of the glycal substrate (**5**) is particularly influential, with intermolecular addition of nitrogen to the double bond typically occurring trans to the C3 substituent. For example, intermolecular nitrenoid additions to glycals reported by Murakami gave 2,3-trans products.[11f] Access to the 2,3-cis motif in 2-amino sugar synthesis necessary for preparation of compounds such as **1** and **2** therefore requires different strategies.[10c,f,g] Danishefsky and co-workers developed an ingenious glycal sulfonamidoglycosylation approach, where the aziridine was generated via trans-diaxial halosulfonamidation, followed by internal displacement of halide from the 2-halo-1-sulfonamido sugar.[10c]

An alternative strategy takes advantage of the glycal C3 hydroxyl group as a directing element for intramolecular installation of nitrogen at the C2 position, establishing the 2,3-cis arrangement. For example, Nicolaou and co-workers developed an IBX-mediated oxidative cyclization of glycal-derived N-aryl carbamates that proceeds via N-centered radicals.[12] Donohoe's tethered aminohydroxylation approach is conceptually related, and has been applied to 3-amino sugar synthesis.[13] Cardona and Goti have also recently reported a related osmium-catalyzed approach from glycals that can afford a route to either 2- or 3-amino sugars.[14]

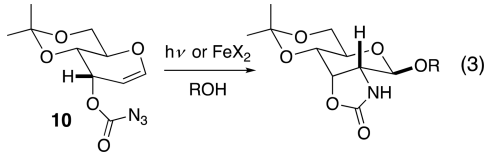
Our contribution has been to use alkene insertion reactions of glycal 3-carbamoyl nitrenes and nitrenoids (**7**) as a means for 2-amino sugar synthesis (eq 2). The intramolecular process



(2)

establishes the otherwise elusive 2,3-cis stereo array and leads to a presumed glycosyl aziridine intermediate (e.g., **8**), though this has proved too labile to isolate. We expected that, as long as the aziridine was maintained, in situ glycosylation would occur with inversion, leading to oxazolidinone-protected 2-amino glycoside products bearing the 1,2-trans relationship as in **9**.

In our initial foray in this area we used allal 3-azidoformate **10** (eq 3) to generate the acyl nitrene for intramolecular



(3)

aziridination.[15] While amidoglycosylation occurred photochemically with high 1,2-trans stereoselectivity, the intermediacy of a free nitrene led to limited efficiency.[16] The azidoformate (**10**) was also a substrate for an amidohalogenation–glycosylation sequence promoted by iron(II) chloride, bromide, or iodide,[17] likely via an N-centered radical intermediate.[18]

Our most versatile approach for nitrene-mediated amidoglycosylation, and the subject of this article, has adapted the Du Bois conditions for C–H insertion of carbamate-derived rhodium acyl nitrenoids[19] to intramolecular C=C insertion within glycal 3-carbamate frameworks (Scheme 1).[20] Under typical Du Bois conditions with diacetoxyiodobenzene as the oxidant,[21] acetate outcompetes the glycosyl acceptor as the nucleophile unless we use very large amounts (>20 equiv) of the acceptor. Fortunately, the use of iodosobenzene (PhIO)[22] as an alternative acetate-free iodine(III) source has remedied this shortcoming.

Our initial studies with allal-[20] and glucal[23] 3-carbamates identified the influence of substrate stereochemistry on the reaction outcome (Scheme 1, substrates **12** and **13**). Allal 3-carbamates with 4*O*,6*O* acetonide or benzylidene protecting groups gave clean amidoglycosylation (**12a** or **12e** → **16**) with excellent 1,2-trans anomeric stereocontrol and no C3-oxidation byproducts (**20**). However, glucal 3-carbamates **13a** and **13d** with similar cyclic 4*O*,6*O* protection resulted in anomeric mixtures of **17** along with dihydropyranone byproducts **20**. Upon further investigation with substrates **13**, we found that nonpolar solvents and acyclic 4*O*,6*O* protection produced **17** with high 1,2-trans stereoselectivity and that acyclic, electron-withdrawing protecting groups (Ac or Ts) also gave high chemoselectivity for **17** over byproduct **20**.[24]

In this article, we report new experiments with gulal- and galactal 3-carbamates (**11** and **14**, Scheme 1) as well as an allal 3-carbamate (**12b**) with acyclic 4*O*,6*O* protection. Moreover, in additional new examples with all the D-glycal carbamates **11**–**14**, we now demonstrate a variety of alcohol nucleophiles that introduce structural diversity and provide functional handles for further elaboration or subsequent cleavage of the anomeric group to unveil the free reducing sugar. These results support a mechanistic model wherein anomeric selectivity

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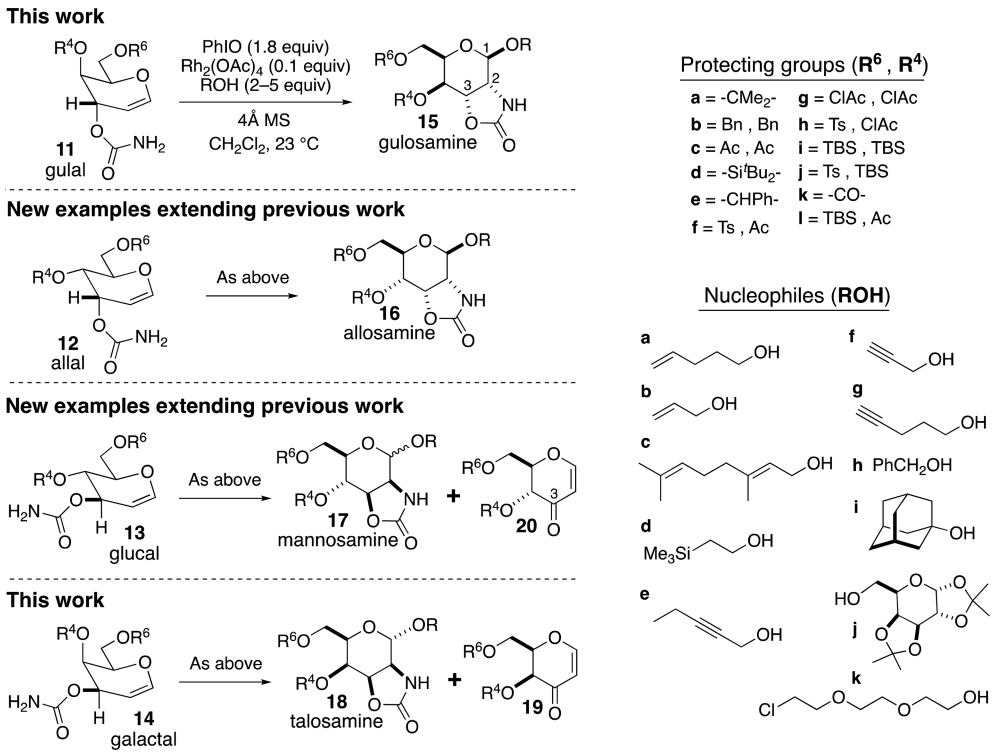
Scheme 1. One-Pot Amidoglycosylation with D-Glycal 3-Carbamates 11−14, Giving Amino Sugar Derivatives 15−18 and Formation of Dihydropyranone Byproducts 19 and 20



depends on the feasibility of a glycosyl aziridine intermediate and chemoselectivity arises from partitioning of an acyl nitrenoid intermediate between C=C addition and C−H insertion. Our studies now span the dirhodium(II)-catalyzed amidoglycosylation chemistry of all the diastereomeric D-glycal 3-carbamates (Scheme 1) and provide a robust basis for further application of this methodology to the synthesis of stereochemically diverse, oxazolidinone-containing 2-amino sugar building blocks.

RESULTS

Synthesis of Gulal-, Allal-, and Galactal 3-Carbamates. In extending our amidoglycosylation chemistry to gulal and galactal substrates, we were mindful of the strong influence of 4*O*,6*O* protection on stereo- and chemoselectivity in reactions of glucal 3-carbamates.[24] We therefore sought to compare 4*O*,6*O* groups having a range of electronic, steric, and conformational properties: (1) acyclic, electron-withdrawing (Ac, ClAc, Ts); (2) acyclic, electron-rich (Bn); (3) sterically demanding (TBS); and (3) cyclic (acetonide, benzylidene, di-*tert*-butylsilylene).

We adapted Danishefsky's application[25] of the Mislow−Evans[26] rearrangement to prepare gulal- and allal 3-carbamates from galactal and glucal starting materials, respectively. Ferrier rearrangement of tri-*O*-acetyl-D-galactal provided α-thiophenyl pseudoglycal **21**[25,27] en route to variously protected gulals (Scheme 2a). Danishefsky and co-workers have described oxidation of sulfur in **21** with *m*-CPBA, followed by the allylic sulfoxide to sulfenate rearrangement[25] and, with other substrates, use of DMDO for the rearrangement-triggering oxidation.[10d] We found DMDO to be the more generally efficient oxidant for our syntheses of gulal- and allal 3-carbamates. Oxidation of thioether **21** with DMDO led to [2,3] rearrangement of the allylic sulfoxide, and the resulting C3 sulfenate ester was trapped by O−S bond cleavage with the thiophilic nucleophile diethylamine, providing 4,6-di-*O*-acetyl-D-gulal (**24c**) in good yield. To prepare gulals with other protecting groups, we carried out methanolysis of **21** to provide diol **22**,[25,27] which was converted to either the isopropylidene (**23a**) or the dibenzyl (**23b**) derivative. The oxidation−rearrangement sequence[28] provided gulals **24a** and **24b** having the α-oriented C3 hydroxyl.

We treated gulals **24** with trichloroacetylisocyanate to introduce the primary 3*O*-carbamoyl group. The classic Kocovsky conditions, using neutral alumina to cleave the trichloroacetyl carbamate intermediate,[29] were ideal for the diacetyl-protected system, giving primary carbamate **11c** in high yield. Alternatively, substrates with base-stable protecting groups (**24a** and **24b**) were subjected to methanolysis to afford the respective gulal 3-carbamates **11a** and **11b**. Additionally, to complement our earlier studies with allal 3-carbamates bearing cyclic 4*O*,6*O* protection (acetonide, benzylidene),[20,24] we prepared dibenzyl-protected allal carbamate **12b** via the same route as for **11b** but starting with tri-*O*-acetyl-D-glucal and proceeding via Mislow−Evans rearrangement of **25**[30] to **26**[31] (Scheme 2b).

The galactal 3-carbamates **14a**, **14b**, and **14d** were prepared in high yields from the corresponding 4*O*,6*O*-protected D-galactals **27a**,[32] **27b**,[33] and **27d**,[34] as shown in Scheme 3. In preparing other, differently protected galactal 3-carbamates **14** (Scheme 4), we used a route similar to Nicolaou's approach to *N*-aryl-3-carbamoyl glycals[12b] that we also employed in preparing 4*O*,6*O*-protected glucal 3-carbamates.[24] In the presence of catalytic DBU, silylene-protected **27d** reacted with 2,4-dimethoxybenzyl isocyanate, to introduce the N-protected carbamate in **28**. Desilylation, followed by protection of the resulting diol **29** provided derivatives **31**, bearing protecting groups with varying electronic and steric properties. During the

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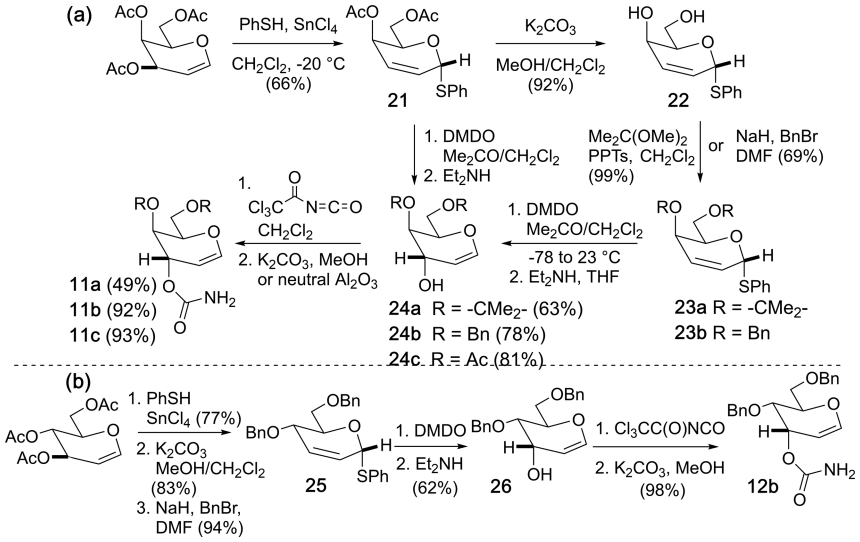
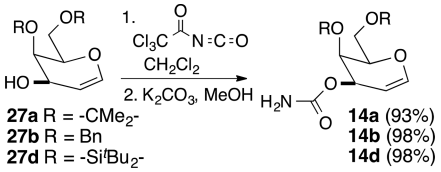
Scheme 2. Synthesis of (a) Gulal 3-Carbamates and (b) a Conformationally Flexible Allal 3-Carbamate



Scheme 3. Synthesis of Acetonide-, Benzyl-, and Silylene-Protected Galactal 3-Carbamates



removal of the 2,4-dimethoxybenzyl (DMB) group with DDQ in aqueous chloroform, starting material was consumed in about 1 h, generally accompanied by formation of two more polar products, the desired primary carbamate **14** and a transient bisaminal byproduct **32**.[35] With continued vigorous stirring of the biphasic reaction mixture, hydrolysis of **32** to **14** occurred over 2−4 h.

Conformations of Glycal 3-Carbamates. Our initial studies with glucal 3-carbamates[23,24] and conformationally locked allal 3-carbamates[20,24] suggested that substrates undergoing chemo- and stereoselective amidoglycosylations favored the conformation having a pseudoaxial 3*O*-carbamoyl group. For example, conformational changes in the glucal 3-carbamate framework (**13**) occurred upon introduction of acyclic, electron-withdrawing 4*O* and 6*O* groups, as in **13c** and **13f**, two substrates with increased selectivity. In these glucals, the conformational differences were best reflected in the $J_{H4,H5}$ values (Table 1). Smaller values of $J_{H4,H5}$ (cf. **13c** and **13f** versus **13a** and **13d**) indicated a shift in conformational weighting away from the **13**-($^4H_5$) arrangement toward the inverted **13**-($^5H_4$) form, having the pseudoaxial carbamate.[36,37] As summarized in Table 1, similar ^{1}H NMR coupling constant analysis was used to evaluate an analogous effect with gulal-, galactal-, and conformationally unconstrained allal 3-carbamates.[38]

In the gulal 3-carbamates (**11**), we focused on $J_{H3,H4}$ since H3 and H4 are trans-diequatorial in the $^4H_5$ conformer but diaxial in the inverted $^5H_4$ arrangement. As shown in Table 1, the gulal carbamates all exhibited small $J_{H3,H4}$ values, consistent with a predominant **11**-($^4H_5$) conformation. Additionally,

Scheme 4. Preparation of Variously Protected Galactal 3-carbamates

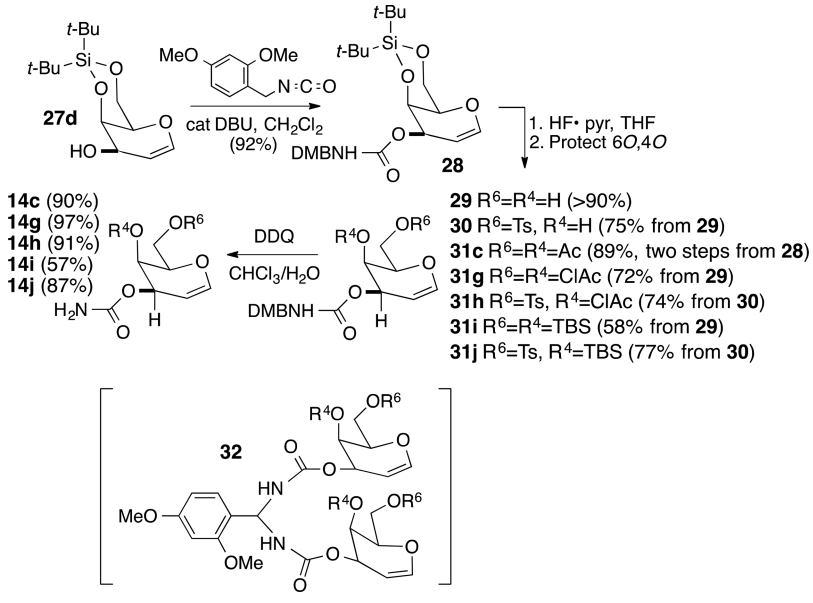


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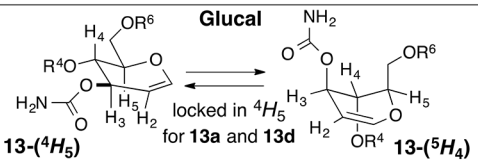
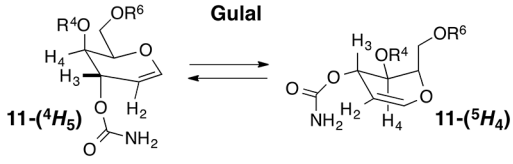
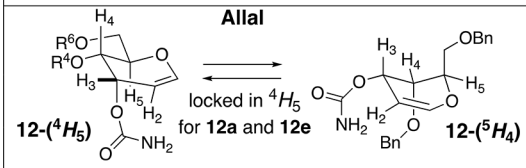
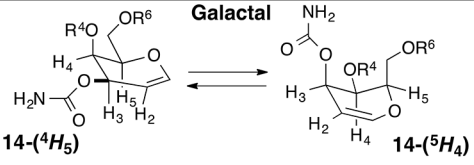
Table 1. Conformational Analysis of D-Glycal 3-carbamates[a]

D-Glycal 3-carbamate	Glycal	R⁶	R⁴	$^4J_{H1,H3}$	$^3J_{H2,H3}$	$^4J_{H2,H4}$	$^3J_{H3,H4}$	$^3J_{H4,H5}$
	**13a**[b]	-CMe$_2$-		1.5	1.7	none	8.0	9.9
	13d	-Si^{t}Bu$_2$-		1.6	1.9	none	7.6	10.0
	13b	Bn	Bn	1.2	2.7	none	6.3	8.8
	13c	Ac	Ac	none	3.0	none	6.0	7.5
	13f[c]	Ts	Ac	none	2.5	1.4	5.5	6.7
	**11a**	-CMe$_2$-		none	5.3	1.5	2.0	nd
	11b	Bn	Bn	none	5.4	1.8	1.9	1.4
	11c	Ac	Ac	none	5.5	1.4	2.4	nd
	**12a**	-CMe$_2$-		none (none)[b]	6.0 (6.0)[b]	none (none)[b]	2.4 (3.9)[b]	nd (10.1)[b]
	12e	-CHPh-		none	6.0	none	4.0	10.4
	12b	Bn	Bn	none	6.0	none	3.8	10.7
	**14a**	-CMe$_2$-		2.1	1.7	1.7	4.9	nd
	14d	-Si^{t}Bu$_2$-		2.0	1.9	1.9	4.5	0.8
	14b[d]	Bn	Bn	1.4	3.0	1.3	3.8	2.5
	14c	Ac	Ac	none	2.1	2.1	4.7	2.2
	14g	ClAc	ClAc	1.5	2.9	1.3	nd	nd
	14h[e]	Ts	ClAc	1.5	2.9	1.3	nd	1.9
	14i[f]	TBS	TBS	1.4	3.1	1.0	4.2	2.6
	14j	Ts	TBS	0.7	4.9	none	4.6	nd

[a]All J values determined in $CDCl_3$ unless otherwise indicated; nd = not determined; the highlighted J values are discussed in the text. [b]In DMSO-d_6. [c]In C_6D_6. [d]Also observed $^4J_{H3,H5}$ = 1.4 Hz. [e]Also observed $^4J_{H3,H5}$ = 1.2 Hz. [f]Also observed $^4J_{H3,H5}$ = 1.2 Hz.

we observed four-bond coupling between H2 and H4 for gulals **11**, in accord with their W relationship in the $^4H_5$ conformer.[37b,39] Finally, we compared the $J_{H2,H3}$ values of the gulal 3-carbamates to allal 3-carbamates **12a** and **12e** locked in the $^4H_5$ conformation, since the gulal 3-carbamate conformer **11**-($^4H_5$) should have a similar H2/H3 relationship. In fact, the $J_{H2,H3}$ values for gulals **11** and allals **12** showed good agreement. In all respects, the NMR data support a predominant $^4H_5$ conformation **11**-($^4H_5$) for the gulal 3-carbamates, orienting the 3*O*-carbamoyl group pseudo axial. This conformation is stabilized by the "allylic effect", i.e., the vinylogous anomeric preference for having the C3−O bond pseudoaxial, and by the antiperiplanar relationship of C3−O and C4−O dipoles.[40]

For dibenzyl-protected allal 3-carbamate **12b**, $J_{H4,H5}$ and $J_{H2,H3}$ were diagnostic of conformation. These coupling constants were nearly identical for the acyclic-protected dibenzyl system **12b** and the $^4H_5$-locked acetonide- and benzylidene-protected allal 3-carbamates **12a** and **12e**. In particular, the $J_{H4,H5}$ value for **12b** indicated a trans-diaxial relationship as also found in **12a** and **12e**. We did not observe W-coupling between H2 and H4 in allals **12**, also consistent with conformer **12**-($^4H_5$) rather than **12**-($^5H_4$).

In galactal 3-carbamates **14**, the vicinal coupling constants among H3, H4, and H5 are of equatorial-axial type in both **14**-($^4H_5$) and **14**-($^5H_4$). Therefore, we focused on the $J_{H2,H3}$ values, which for most of the galactal derivatives **14** were similar to those of $^4H_5$-locked glucal 3-carbamates **13a** and **13d**. In addition, the galactal conformer **14**-($^4H_5$) has a W relationship between H2 and H4, but the inverted form **14**-($^5H_4$) does not. For all but one of galactal 3-carbamates **14**, we detected such a four-bond W-coupling, $J_{H2,H4}$. These results indicate a preferred conformation **14**-($^4H_5$) for almost all the galactal 3-carbamates. The exception was 6*O*-Ts,4*O*-TBS-protected galactal 3-carbamate **14j**, where the $J_{H2,H4}$ W-coupling disappeared and the $J_{H2,H3}$ value was the largest among the galactals studied, suggesting a conformational shift toward the **14j**-($^5H_4$) arrangement with the carbamate group in a pseudoaxial position. Indeed, galactal 3-carbamate **14j** turned out to be the most chemoselective in amidoglycosylation reactions (vide infra).

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Amidoglycosylation Reactions of All Glycal Diastereomers with 4-Penten-1-ol. Having synthesized the full range of diastereomeric glycal 3-carbamates **11**−**14** (**Gly**, Table 2), we applied uniform conditions (1.8 equiv of PhIO, 0.1 equiv of $Rh_2(OAc)_4$, 4 Å molecular sieves, ∼0.1 M glycal carbamate in CH_2Cl_2) for the oxidative cyclization process using 4-penten-1-ol (5 equiv) as the nucleophile (glycosyl acceptor **a**, Scheme 1 and Table 2). This alcohol nucleophile provides synthetically versatile *n*-pentenyl glycoside[41] products and allowed us to compare selectivities with our prior studies on allal- and glucal 3-carbamates.[23,24] For each reaction, we measured chemo- and stereoselectivity from the NMR spectra of the crude reaction mixture. Because we isolated and characterized a number of the possible dihydropyranone byproducts **19** and **20** (**DHP**, Table 2) in our new work with galactal 3-carbamates (vide infra) and in prior studies with glucal 3-carbamates,[24] we could easily identify any **DHP** in NMR spectra of the crude reaction mixtures. Meanwhile, the anomeric ratios for the **AG** products (**15**−**18**, Table 2) were determined by integration of the H1 resonances when these did not overlap with other signals in ^{1}H NMR spectra. To complement the ^{1}H NMR integration data, and as an alternative when ^{1}H NMR signal overlap made it difficult to measure the anomeric ratio, we also used integration of the well-separated C1 (δ 105−95) and C2 (δ 55−50) signals of the anomers.[42]

Amidoglycosylation in the gulal series to give 2-gulosamine derivatives (**15**) was 1,2-trans-selective, and no C3-oxidation byproducts formed (Table 2, entries 1−3). There was some variation in anomeric selectivity, depending on the nature of the protecting groups. Higher stereoselectivity occurred with the acetonide protection in **11a** and with electron-withdrawing, acyclic protection in diacetyl gulal 3-carbamate **11c** (entries 1 and 3), while the dibenzyl-protected **11b** gave lower anomer selectivity (entry 2). Because we had NMR data for all three dihydropyranones **19a**, **19b**, and **19c** from our galactal 3-carbamate studies (vide infra), we would have been able to detect even traces of these compounds had they formed in the reactions of gulal carbamates **11**, but they did not.

The oxazolidinone ring fusion in our amidoglycosylation products affects the pyranose ring conformation, making coupling constant analysis of stereochemistry ambiguous. We therefore took care in establishing the anomeric stereochemistry of 2-amidogulose products **15**, beginning with NOESY studies of both anomers of diacetyl-protected products **15ca**. A NOESY correlation between H1 and H5 was present for the major anomer, but not for the minor anomer, implying that the major anomer was the β diastereomer (1,2-trans product **15ca-*β***, Figure 2). The characteristic H1/H5 NOESY cross peak also appeared with the major acetonide-protected product **15aa**, again indicating the 1,2-trans stereochemistry. Because the minor diastereomer of **15aa** was not isolated in sufficient quantity for NOESY analysis, we further characterized the major product by *N*-Boc protection to **33** (Scheme 5) and subsequent oxazolidinone opening[43] to give **34**, having a $J_{H1,H2}$ value (8.6 Hz), consistent with the β-anomeric stereochemistry.

For dibenzyl-protected **15ba**, we compared spectral data with **15ca** and **15aa** (Figure 2). Both anomers of **15ba** were isolated, and there was a good match in the relative positions of resonances for H1 (major product had the upfield signal), C1 (major product had the downfield signal), C2 (major product had the downfield signal), and $J_{H1,H2}$ (major product had the larger coupling constant). This analysis, in conjunction with the NOESY and ring-opening studies on **15ca** and **15aa**, confirmed 1,2-trans amidoglycosylation selectivity for all three gulal 3-carbamate substrates studied.

In the allal series, we observed high 1,2-trans anomeric stereoselectivity as well as excellent chemoselectivity (Table 2, entries 4−6). Notably, the more conformationally flexible dibenzyl-protected allal 3-carbamate **12b** was highly 1,2-trans selective, analogous to the benzylidene- and acetonide-protected allals **12a** and **12e**, and gave only the merest trace of DHP **20b**. As in the gulal-derived case, $J_{H1,H2}$ was not a conclusive indicator of anomeric stereochemistry in the ring-fused product **16ba**, so we prepared oxazolidinone-opened **36** by hydrolysis of Boc-protected derivative **35** (Scheme 5). The trans-diaxial $J_{H1,H2}$ value in **36** (8.3 Hz) confirmed the β-anomeric configuration.

For the glucal carbamates **13** there was a pronounced dependence of stereo- and chemoselectivity on the 4*O* and 6*O* protecting groups. Conformationally locked substrates **13a** and **13d** provided low anomer selectivity and significant formation of corresponding dihydropyranones **20** (Table 2, entries 7 and 8). Switching to acyclic protection in 4,6-di-*O*-benzyl substrate **13b** (entry 9) resulted in a dramatic increase in 1,2-trans selectivity but gave the same amount of dihydropyranone byproduct. A less polar solvent further increased anomeric selectivity from **13b**, but again without inhibiting formation of byproduct **20b** (entry 10). In the glucal-derived oxazolidinone-containing 2-mannosamine products **17**, the 1,2-trans α-anomeric products have a distinguishing H1 singlet ($J_{H1,H2} \approx 0$ Hz) in contrast to an H1 doublet ($J_{H1,H2} = 2-3$ Hz) for the minor β anomers.[23,24]

Ultimately, we achieved high anomer selectivity and chemoselectivity in the glucal 3-carbamate series **13** by using acyclic, electron-withdrawing Ac and Ts groups at 4*O* and 6*O*. For best results, these groups were required at both positions (compare entries 11 and 12 versus entries 14 and 16). Conformationally restricted carbonate **13k** gave low selectivity despite the electron-withdrawing character of the protecting group (entry 15), suggesting that *both* electronic and conformational factors are required for high stereo- and chemoselection.

Galactal 3-carbamates **14** have proved the most difficult to harness for dirhodium(II)-catalyzed amidoglycosylation. With either the acetonide- or silylene-protected carbamates (**14a** and **14d**), we isolated only the corresponding dihydropyranones **19**, in addition to unreacted starting material (Table 2, entries 17 and 18). It was with dibenzyl-protected **14b** that we obtained the first hint that galactal 3-carbamate amidoglycosylation was feasible under these conditions (entry 19). We isolated a small quantity of a single anomer of product **18ba**, along with dihydropyranone **19b** as the main product.

The diacetyl-protected **14c** was a more promising galactal 3-carbamate for amidoglycosylation. Under our standard conditions, about equal amounts of amidoglycosylation and C3−H oxidation occurred (Table 2, entry 20), and we detected only a single anomer of the 2-amidotalose product **18ca**. NOESY analysis of **18ca** (Figure 3) showed diagnostic contacts between the NH and H1 protons and between H5 and H1′a on the *n*-pentenyl chain. There was no cross-peak between H1 and H5. Finally, the anomeric ^{1}H resonance appeared as a singlet ($J_{H1,H2} \approx 0$ Hz), consistent with an α-glycoside conformation as shown in Figure 3 with near-orthogonal placement of H1 and H2 and reminiscent to the $J_{H1,H2} \approx 0$ Hz observed in the α-2-amidomannosides **17** derived from glucal 3-carbamates **13**.

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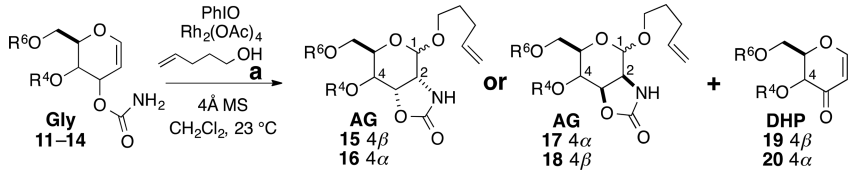
Table 2. Amidoglycosylation of Glycal 3-Carbamates with 4-Penten-1-ol Acceptor[a]



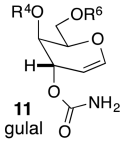
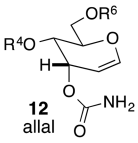
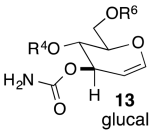
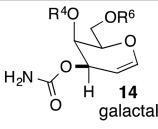
Entry	D-glycal 3-carbamate	Gly	R^6	R^4	AG	AG 1,2-trans: 1,2-cis[b]	% yield 1,2-trans AG[c]	DHP	AG:DHP[b]
1		**11a**	-CMe_2-		**15aa**	8.8:1	66	**19a**	**AG** only
2		**11b**	Bn	Bn	**15ba**	4.5:1	55	**19b**	**AG** only
3		**11c**	Ac	Ac	**15ca**	8.2:1[d]	65[d]	**19c**	**AG** only
4		**12a**	-CMe_2-		**16aa**	1,2-trans only	74	**20a**	**AG** only
5[e]		**12e**	-CHPh-		**16ea**	1,2-trans only	80	**20e**	**AG** only
6		**12b**	Bn	Bn	**16ba**	>30:1	67	**20b**	30:1
7[e]		**13a**	-CMe_2-		**17aa**	1.3:1	40	**20a**	3.1:1
8		**13d**	-Si^tBu_2-		**17da**	2.2:1	33	**20d**	3.2:1
9		**13b**	Bn	Bn	**17ba**	12:1	61	**20b**	2.9:1
10[f]		**13b**	Bn	Bn	**17ba**	22:1	54	**20b**	3.0:1
11		**13c**	Ac	Ac	**17ca**	1,2-trans only	69	**20c**	15:1
12		**13f**	Ts	Ac	**17fa**	1,2-trans only	69	**20f**	14:1
13		**13i**	TBS	TBS	**17ia**	5.8:1	46[g]	**20i**	2.4:1
14		**13j**	Ts	TBS	**17ja**	12:1	67	**20j**	8.1:1
15		**13k**	-CO-		**17ka**	2.9:1	32	**20k**	2.4:1
16		**13l**	TBS	Ac	**17la**	25:1	68	**20l**	6.6:1
17		**14a**	-CMe_2-		**18aa**	No **AG**	No **AG**	**19a**	**DHP** only[h]
18		**14d**	-Si^tBu_2-		**18da**	No **AG**	No **AG**	**19d**	**DHP** only[i]
19		**14b**	Bn	Bn	**18ba**	1,2-trans only	14	**19b**	0.24-0.46:1[j]
20		**14c**	Ac	Ac	**18ca**	1,2-trans only	25	**19c**	0.73:1[k]

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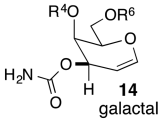
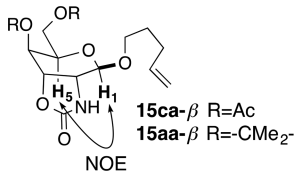
Table 2. continued

Entry	D-glycal 3-carbamate	Gly	R^6	R^4	AG	AG 1,2-trans: 1,2-cis[b]	% yield 1,2-trans AG[c]	DHP	AG:DHP[b]
21	 **14** galactal	**14g**	ClAc	ClAc	**18ga**	1,2-trans only	39	**19g**	1.5:1
22		**14h**	Ts	ClAc	**18ha**	1,2-trans only	39	**19h**	1.5:1[l]
23		**14i**	TBS	TBS	**18ia**	1,2-trans only	32	**19i**	1.6:1[m]
24		**14j**	Ts	TBS	**18ja**	1,2-trans only	55	**19j**	5.6:1

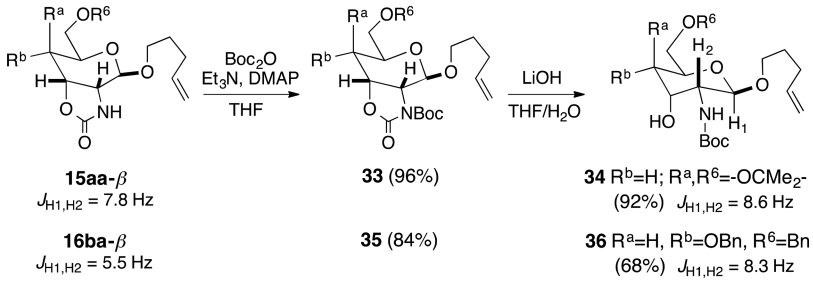
[a]Typical reaction conditions: 1.8 equiv of PhIO, 0.1 equiv of $Rh_2(OAc)_4$, 5 equiv of 4-penten-1-ol, 4 Å molecular sieves (300 wt %), ~0.1 M glycal carbamate in CH_2Cl_2. [b]Crude reaction mixtures were analyzed by ^1H and/or ^{13}C NMR to measure conversion, anomer ratio, and dihydropyranone formation. [c]Isolated yield after chromatography. [d]Average of two runs. [e]Data in entries 5 and 7−16 are from ref 24. [f]Solvent was hexanes/CH_2Cl_2 (1/1). [g]The anomers were inseparable by chromatography; the yield of the α component was calculated from the relative integration of α and β anomer ^1H NMR signals in the purified mixture. [h]**19a**/**14a** = 2.2:1. [i]**19d**/**14d** = 3.6:1. [j]Range from ^1H and ^{13}C NMR analysis over four runs. Remaining starting material **14b** (10−15%) also detected. [k]Some **14c** remained: **18ca**/**19c**/**14c** = 38:52:10. [l]Starting material **14h** (~10%) also remained. [m]Some **14i** remained: **18ia**/**19i**/**14i** = 52:34:14.



Compound	δH1	$J_{H1,H2}$ (Hz)	δC1	δC2
Major anomers				
15ca-β R=Ac	4.43	7.4	103.6	53.0
15aa-β R=-CMe_2-	4.35	7.8	103.2	52.7
15ba-β R=Bn	4.37	7.5	103.5	53.4
Minor anomers				
15ca-α R=Ac	4.90	4.3	94.9	50.5
15aa-α R=-CMe_2-	5.15	3.3	95.1	50.8
15ba-α R=Bn	4.87	3.6	94.7	51.6

Figure 2. Stereochemistry determination in β-2-aminogulose oxazolidinones.

Scheme 5. Oxazolidinone Opening To Confirm Stereochemistry of 2-Gulosamine and 2-Allosamine Derivatives by ^1H NMR



15aa-β $J_{H1,H2}$ = 7.8 Hz

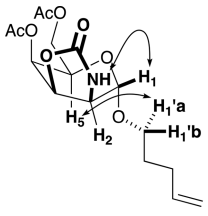
16ba-β $J_{H1,H2}$ = 5.5 Hz

33 (96%)

35 (84%)

34 R^b=H; R^a,R^6=-$OCMe_2$- (92%) $J_{H1,H2}$ = 8.6 Hz

36 R^a=H, R^b=OBn, R^6=Bn (68%) $J_{H1,H2}$ = 8.3 Hz



18ca-α
Diagnostic NOE contacts shown with arrows.
No NOE cross peak observed between H1 and H5.
Observed $J_{H1,H2}$ ≈ 0 Hz.

Figure 3. NOESY correlations in α-2-amidotalose derivative **18ca** prepared from galactal 3-carbamate **14c**.

We sought to increase the electron-withdrawing power of the 4*O* and 6*O* protecting groups in galactal 3-carbamates **14** as a means to improve chemoselectivity. However, the dividends were limited, as chloroacetyl protection, incorporating either two ClAc groups (**14g**) or one along with a 6*O* tosyl (**14h**), gave only small increases in chemoselectivity (Table 2, entries 21 and 22). Interestingly, steric perturbation as in bis-silyl-protected **14i** (entry 23) increased chemoselectivity by the same extent as the electron-withdrawing protecting groups in **14g** and **14h**. Ultimately, combination of a bulky silyl ether

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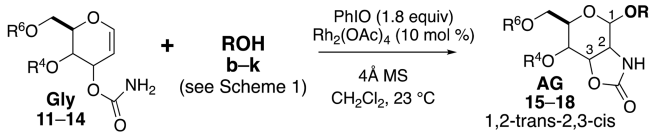
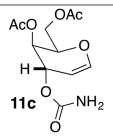
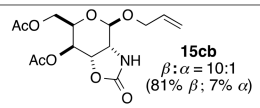
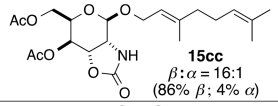
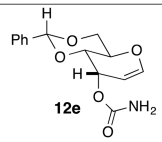
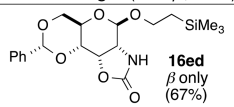
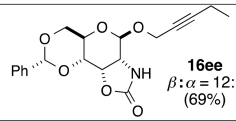
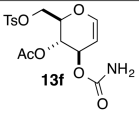
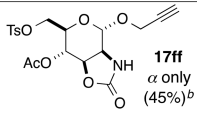
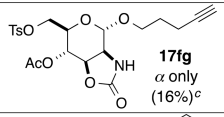
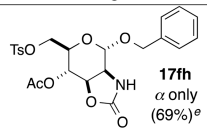
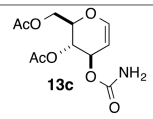
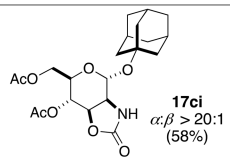
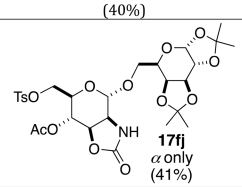
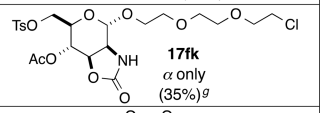
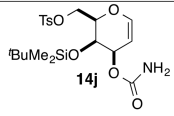
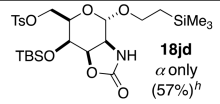
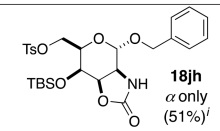
Table 3. Amidoglycosylation of D-Glycal 3-Carbamates with Other Glycosyl Acceptor Alcohols



Entry	Gly	ROH (equiv)	AG[a] (Yield)
1	 **11c**	**b** (5.1)	 **15cb** $\beta:\alpha = 10:1$ (81% β; 7% α)
2	**11c**	**c** (5.0)	 **15cc** $\beta:\alpha = 16:1$ (86% β; 4% α)
3	 **12e**	**d** (4.9)	 **16ed** β only (67%)
4	**12e**	**e** (5.0)	 **16ee** $\beta:\alpha = 12:1$ (69%)
5	 **13f**	**f** (5.1)	 **17ff** α only (45%)[b]
6	**13f**	**g** (5.0)	 **17fg** α only (16%)[c]
7[d]	**13f**	**h** (5.2)	 **17fh** α only (69%)[e]
8[f]	 **13c**	**i** (5.0)	 **17ci** $\alpha:\beta > 20:1$ (58%)
9	**13c**	**i** (2.0)	**17ci** $\alpha:\beta = 12:1$ (40%)
10	**13f**	**j** (2.0)	 **17fj** α only (41%)
11	**13f**	**k** (5.0)	 **17fk** α only (35%)[g]
12	 **14j**	**d** (4.9)	 **18jd** α only (57%)[h]
13[d]	**14j**	**h** (4.9)	 **18jh** α only (51%)[i]

[a]Crude reaction mixtures were analyzed by ^{1}H NMR to measure anomer ratios and to detect formation of dihydropyranones **19** and **20** and any remaining starting material. Yields are of products after chromatography on silica gel. [b]**17ff/20f/13f** = 14:1:12; starting material **13f** (47%) recovered. [c]**17fg/20f/13f** = 11:1:21; starting material **13f** (53%) recovered. [d]Using 3.1 equiv of PhIO. [e]**17fh/20f/13f** = 18:1:1. [f]Data in entries 8–10 are from ref 24. [g]**17fk/20f/13f** = 12:1:6. [h]**18jd/19j/14j** = 16:3:1. [i]**18jh/19j/14j** = 5:2:1.

at 4*O* and an electron-withdrawing sulfonyl group at 6*O* led to the most chemoselective and high-yielding galactal substrate **14j**, providing amidoglycosylation product **18ja** as a single 1,2-trans anomer in 55% yield and with 5.6:1 chemoselectivity (entry 24) as compared to the initial galactals **14a** and **14d** (entries 17 and 18), which provided only the unwanted **DHP** products **19** and none of the **AG** products at all.

Reactions of Selective Glycal 3-Carbamates with Other Glycosyl Acceptors. Having identified selectivity-inducing protecting groups for each of the four diastereomeric D-glycal 3-carbamate frameworks **11**–**14**, we used these substrates to explore the addition of other glycosyl acceptor alcohols (Table 3). Gratifyingly, the metallanitrene-mediated chemistry was compatible with a range of alcohol nucleophiles, enabling incorporation of varied anomeric functionality, including groups such as alkynyl, alkenyl, and chloroalkyl, that are amenable to further elaboration. Other anomeric substituents (e.g., benzyl, 2-(trimethylsilyl)ethyl) that can serve as temporary masking groups for revealing C1-OH free reducing sugars could also be introduced via the amidoglycosylation reactions of **11**–**14**.

Allylic alcohols were well tolerated as glycosyl acceptors, with gulal substrate **11c** giving β-allyl glycoside **15cb** and gulosamine geranyl glycoside **15cc** in high yield and good anomeric stereoselectivity (Table 3, entries 1 and 2). With benzylidene-protected allal **12e**, formation of a 2-(trimethylsilyl)ethyl glycoside gave only the 1,2-trans product, allosamine oxazolidinone **16ed** (entry 3). This glycosyl group is a known protecting group for the anomeric oxygen, cleavable via fluoride-induced elimination.[44] Incorporation of an internal alkyne in the glycosyl acceptor was achieved, providing 2-pentynyl glycoside **16ee** with good anomeric stereocontrol (entry 4). Dihydropyranone byproduct formation from C3–H oxidation was not observed for these gulal- or allal 3-carbamate substrates **11c** and **12e**.

Terminal alkyne-containing alcohols gave lower yields when used as acceptors in reactions with glucal 3-carbamate **13f** (Table 3, entries 5 and 6), though stereo- and chemoselectivity

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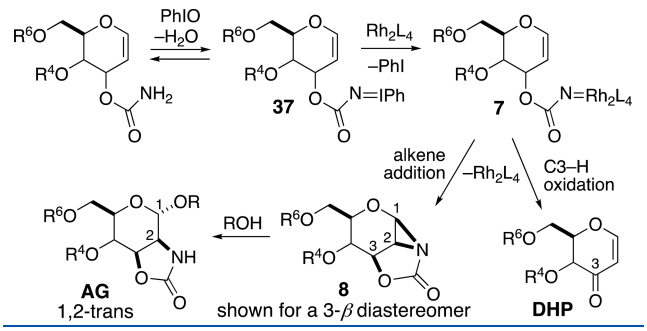
remained high. Using propargyl alcohol, 2-mannosamine derivative **17ff** formed exclusively as the α (1,2-trans) product, while 4-pentynyl glycoside **17fg** was also generated as a single anomer. In both cases, there was little dihydropyranone formation, with the low yields resulting instead from incomplete consumption of the glycal carbamate (**13f**). On the other hand, we observed good efficiency with benzyl alcohol as the acceptor, leading to selective formation of **17fh** (entry 7). Several examples from our preliminary report[24] (entries 8−10) further demonstrate the reaction scope for glucal substrates, including direct access to disaccharide **17fj**. Best yields resulted with excess acceptor alcohol (5 equiv), perhaps because of a need to activate the insoluble, oligomeric iodosobenzene oxidant.[45] A final example in the glucal series (entry 11) demonstrated installation of a diglyme-type linker with a primary halide functionality in product **17fk**. Electrophile-containing anomeric groups are of utility for attachment of carbohydrate units to molecules of biological and medicinal interest.[46]

Although the galactal 3-carbamate series (**14**) was the most prone to unwanted dihydropyranone formation by C3-oxidation, the optimally protected substrate **14j** provided talosamine derivatives **18j** bearing the all-cis C2−C5 stereoarray (Table 3, entries 12 and 13). Even with our most selective protecting group combination, formation of dihydropyranone **19j** was not completely suppressed. Nevertheless, amidoglycosylation products **18jd** and **18jh**, bearing a C6 tosylate for possible further functionalization as well as readily cleavable anomeric protecting groups, were prepared in synthetically useful yields. When using benzyl alcohol as the nucleophile (entries 7 and 13), we obtained highest conversions and best yields by increasing the amount of iodosobenzene, possibly because some of the oxidant is consumed by direct reaction with the benzyl alcohol.

DISCUSSION

General Mechanistic Considerations. Consistent with the work of Du Bois,[47] Dauban and Dodd,[48] and Che[49] among others on reactions of carbamates and sulfamates with iodine(III) oxidants in the presence of dirhodium(II) catalysts, the amidoglycosylation of glycal 3-carbamates likely involves a rhodium-complexed nitrene **7**, generated from iminoiodinane **37** (Scheme 6). Addition of the metallanitrene to the glycal

Scheme 6. Mechanistic Proposal for Amidoglycosylation via an Acyl Metallanitrene



π bond provides a glycosyl aziridine (e.g., **8** in the 3-β series), possibly with the metal still complexed at nitrogen (not shown).[50] As long as the N−anomeric contact is present, the acceptor adds in S_N2 fashion, leading to the 1,2-trans amidoglycosylation (**AG**) product. Dihydropyranone (**DHP**) byproduct formation, meanwhile, also originates from the metallanitrene intermediate **7**, as supported by our previous studies that utilized an alternative *N*-tosyloxycarbamate nitrene precursor (which obviates the need for a hypervalent iodine oxidant) and gave the same distribution of amidoglycosylation and C3−H oxidation products with rhodium catalysis as compared to the standard primary carbamate using PhIO.[51]

Control experiments with glucal 3-carbamates **13a** and **13d** indicated no amidoglycosylation or dihydropyranone formation in the absence of dirhodium(II) catalyst.[24,51] With the acetonide-protected allal 3-carbamate **12a**, a low yield (16%) of amidoglycosylation was obtained in the absence of catalyst.[20] As our current studies have revealed, the allal carbamates are the most favorable substrates, and the iminoiodinane intermediate may be electrophilic enough to react directly with the enol ether π bond.

Anomeric Stereoselectivity. In general, we attribute high 1,2-trans amidoglycosylation selectivity to S_N2 opening of a glycosyl aziridine intermediate, whereas diminished anomeric stereoselectivity results from a competitive oxocarbenium-mediated S_N1 pathway. As discussed below, we have observed that high 1,2-trans stereoselectivity correlates with conformational and electronic factors expected to favor a stereospecific glycosyl aziridine donor over a less or perhaps differentially selective (i.e., 1,2-cis selective) oxocarbenium electrophile.[52] Nitrogen-directed addition to a zwitterionic intermediate, for example, could lead to the 1,2-cis product, as reported by Padwa for a related indolyl carbamate system.[21a,b]

A 1,2-trans-selective glycosyl aziridine donor (e.g., **8**, Scheme 6) is best accommodated when the C3−O bond is pseudoaxial. If the sugar ring lacks the flexibility to orient the C3−O bond appropriately, keeping the N−anomeric contact entails enough strain to disfavor the glycosyl aziridine. This effect became evident in reactions of glucal substrates **13**. With 4,6-*O*-isopropylidene (**13a**) or di-*tert*-butylsilylene (**13d**) protecting groups, we obtained low anomeric selectivity (Table 2, entries 7 and 8). In these cases, the system is conformationally fixed, and inspection of molecular models reveals that, upon C2 amidation from glucal nitrenoid **38** (Scheme 7), the corresponding glycosyl aziridine **39** suffers from eclipsing interactions along the C3−C4 bond. This torsional strain is released in aziridine-opened zwitterion **40**, which we predict is the preferred intermediate for **13a** and **13d** given the diminished 1,2-trans selectivity. By contrast, conformationally flexible glucal 3-carbamates, such as the 4,6-di-*O*-benzyl-protected **13b**, gave much better stereoselectivity (Table 2, entries 9 and 10). Here, ring inversion better enables the covalent aziridine donor **39′** (intermediates numbered with a prime have the pseudoaxial C3−O bond), favoring it over an oxocarbenium glycosyl donor, particularly in less polar solvent mixtures (e.g., hexanes/CH_2Cl_2 as in Table 2, entry 10). Electron-withdrawing protecting groups as in **13c** and **13f** should further disfavor a C1 cation versus the glycosyl aziridine, while they also promote an increased propensity in glucal substrates **13** for the conformationally inverted $^5H_4$ arrangement, akin to that shown for the derived nitrenoid **38′** (cf. Table 1 and Scheme 7). These electronic and conformational factors are consistent with the high 1,2-trans anomer selectivity observed with **13c** and **13f** (Table 2, entries 11 and 12, and Table 3, entries 5−11).

Allal-derived systems **12** are highly stereoselective (Table 2, entries 4−6, and Table 3, entries 3 and 4) and appear to enable a glycosyl aziridine intermediate particularly well. In the case of conformationally rigid acetonide- (**12a**) and benzylidene-protected

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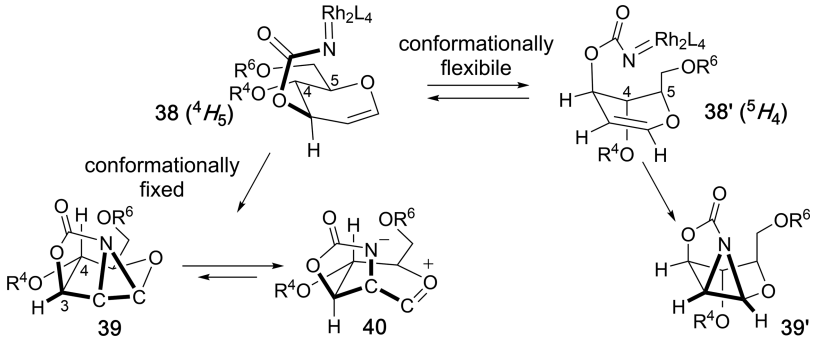
Scheme 7. Influence of Conformational Flexibility on Glucal-Derived 2-Amido Glycosyl Donors



(**12e**) allal 3-carbamates, the C3−O bond is fixed in the pseudoaxial position. Even when the conformational lock is opened, as in dibenzyl-protected allal 3-carbamate **12b**, the glycosyl aziridine donor (**41′**, Figure 4) is favorable because

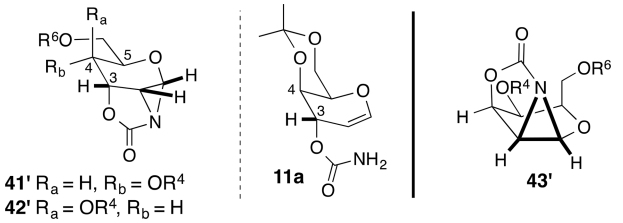


Figure 4. Allal-, gulal-, and galactal-derived glycosyl aziridine donors.

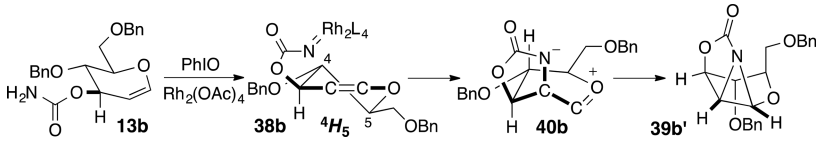
with the C4 and C5 substituents in the equatorial positions the C3−O bond is pseudoaxial, leading to highly 1,2-trans-selective glycosylation.

The situation is somewhat less propitious in the gulal 3-carbamate series (**11**). Although our NMR studies on **11** showed that the $^4H_5$ conformation is favored in the ground state (see Table 1), this places the C4 substituent axial in addition to the pseudoaxial C3 carbamoyl group. Even if alkene insertion from a pseudoaxial acyl nitrenoid leads directly to the glycosyl aziridine (**42′**, Figure 4), this intermediate may be more prone to opening prior to nucleophilic addition, eroding 1,2-trans selectivity. Comparing **11b** (dibenzyl) and **11c** (diacetyl) gulal 3-carbamates (Table 2, entries 2 and 3), we obtained higher stereoselectivity with the more electron-withdrawing acetyl groups, which would destabilize an oxocarbenium donor relative to the glycosyl aziridine. The acetonide-protected substrate **11a** (Table 2, entry 1) gave anomer selectivity comparable to the diacetyl-protected **11c**, presumably reflecting an intermediate **42′** that accommodates the acetonide ring in a chair conformation while avoiding a 1,3-diaxial interaction between an acetonide methyl and the C4−C3 bond in the pyranose ring. This acetonide chair conformation was evident in the starting gulal **11a**, as the acetonide methyls had well-separated ^{13}C NMR chemical shifts (δ 29.2 and 18.4).[53] Finally, the high 1,2-trans stereoselectivity with galactal 3-carbamates **14** probably reflects the intermediacy of a glycosyl aziridine donor **43′** (Figure 4), a species that should be at least as favorable as the corresponding aziridine formed in the gulal series (cf. **39′**, Scheme 7).

In our model, an energetically favorable glycosyl aziridine is the key to high anomeric stereoselectivity, but this intermediate need not arise in a concerted fashion. Instead, a zwitterion could form first, closing to the aziridine prior to glycosylation. Initial glycal C2 amidation could therefore occur from a conformer with the 3*O*-carbamoyl nitrenoid in either the pseudoaxial (direct aziridination) or pseudoequatorial position (stepwise aziridine formation). For example, benzyl-protected glucal **13b**, which our NMR measurements showed favors the $^4H_5$ conformer, nevertheless gave high 1,2-trans stereocontrol. This could arise either through the minor conformer **38b′** as shown in Scheme 7 or, alternatively, by a conformational change following C2−N bond formation to enable aziridine closure as indicated in Scheme 8 (**38b** → **40b** → **39b′**). In short, while it may be optimal to have the pseudoaxial C3−O bond in the ground state (e.g., gulal- and allal 3-carbamates), this is not necessary for good anomeric selectivity.

Chemoselectivity. Literature precedent suggests two mechanistic options for conversion of acyl nitrenoid **7** to the dihydropyranone (**DHP**, Scheme 9). Nitrene insertion into the activated (vinylogously α-ethereal)[54] C3−H bond could produce a four-membered cyclic carbamate (**44**) which fragments,[55] extruding either isocyanic acid to give the carbonyl directly or carbon dioxide to reach an imine that would readily hydrolyze to the dihydropyranone product. This is the mechanism that Du Bois has suggested for the formation of ketones encountered in some C−H insertion attempts from secondary alcohol-derived carbamates.[56] A mechanistic alternative is hydride transfer to the rhodium acyl nitrenoid (**7** → **45**), followed by regeneration of the catalyst and formation of the carbonyl. Doyle has reported a related ketone-forming reaction of rhodium carbenoids, proposed to occur by hydride transfer to the acyl carbenoid carbonyl.[57] Studies from Clark's group, meanwhile, have suggested hydride transfer to the carbenoid carbon or to the rhodium center.[58] Several other groups have noted the formation of carbonyl byproducts in reactions of nitrenoids derived from primary carbamates, including cases where deuterium substitution was used to curtail the unwanted oxidation.[18b,59]

Scheme 8. Stepwise Aziridine Formation from a Conformationally Flexible Glucal Precursor



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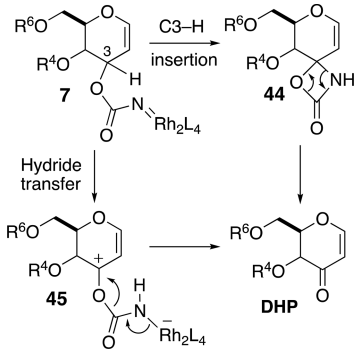
Both the direct insertion and hydride-transfer possibilities of Scheme 9 can be viewed as part of the same mechanistic

Scheme 9. Possible Mechanisms for C3−H Oxidation via Metallanitrene 7



continuum, involving buildup of positive charge at C3. Rhodium nitrenoids are electrophilic, favoring reaction at electron-rich C−H bonds in an insertion process that develops positive character at carbon in the transition state.[47] In our substrates, the glycal C3 position is particularly prone to oxidation because a C3 cation or partial positive charge is well accommodated, especially in stereoelectronically favorable cases (vide infra). Accordingly, electron-withdrawing protecting groups deactivate the C3−H bond toward oxidation,[60] as for our glucal- and galactal substrates (**13** and **14**), where the most chemoselective systems have electron-withdrawing groups (e.g., Ac, Ts) at one or both of the 4*O* and 6*O* positions.

A vinylogous anomeric effect[61] likely contributes to the particular susceptibility of a pseudoaxial C3−H bond toward oxidation. Although they relate to the glycal 3-carbamates and not the rhodium acyl nitrenoids themselves, our NMR conformational studies suggest that both the allal- and gulal 3-carbamate systems, which disfavor C3 carbonyl formation, prefer a $^4H_5$ conformation with the 3*O*-carbamoyl group pseudo axial (**11**-($^4H_5$) and **12**-($^4H_5$), Table 1), placing the C3−H bond in the stereoelectronically deactivated pseudoequatorial position. In the glucal 3-carbamates, the conformation varied, depending on 4*O*,6*O* protection, and substrates having the largest deviation away from the $^4H_5$ conformer (which has the pseudoaxial C3−H; see **13c** and **13f**, Table 1) gave the smallest amount of dihydropyranones **20c** and **20f** in amidoglycosylation studies (Table 2, entries 11 and 12). There is synergy at work: a pseudoaxial 3*O*-carbamoyl group makes amidoglycosylation easier and dihydropyranone formation harder.

By contrast, the galactal 3-carbamates **14**, which gave large amounts of dihydropyranones, for the most part favor the $^4H_5$ conformation having the pseudoequatorial 3*O*-carbamoyl group and the pseudoaxial C3 hydrogen, as characterized by a long-range $^4J_{H2,H4}$ (see Table 1 and depicted for the corresponding nitrenoid **46** in Figure 5). However, the most

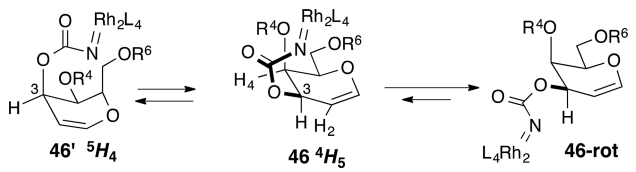


Figure 5. Metallanitrene positioning in galactal 3-carbamate.

chemoselective galactal substrate **14j** (R^6 = Ts, R^4 = TBS) did not show this long-range W coupling, suggesting a shift toward the $^5H_4$ conformation, which could be displayed in the nitrenoid **46′** as well. The promotion of amidoglycosylation relative to C3−H oxidation with **14j** reflects both the more optimal geometry in **46′** for nitrenoid addition to the alkene and the stereoelectronic deactivation of a now pseudoequatorial C3−H bond.[62]

Another possible influence on chemoselectivity, particularly in the galactal case, is positioning of the rhodium-complexed nitrene through rotations about the C3−O and O−C(O) bonds. Along the path toward alkene amidation from **46** (Figure 5), nonbonding interactions arise between the axial group at C4 and the nitrenoid, and subsequent C2−N bond formation develops a 1,3-diaxial interaction. On the other hand, if the nitrenoid moiety is turned away from the axial C4 substituent (as in rotamer **46-rot**), it should favorably engage the pseudoaxial C3−H bond to afford the dihydropyranone product.

The difficulty of C=C addition for the galactal 3-carbamate-derived rhodium nitrenoids would therefore arise from both an increased propensity for C3−H insertion and an impediment to C=C insertion from the preferred $^4H_5$ conformation (**46**). Meanwhile, the inverted $^5H_4$ galactal arrangement (**46′**), having the pseudoequatorial C3−H bond and placing the C4 substituent out of the way of C=C addition, would favor amidoglycosylation versus C3 oxidation, as fulfilled, albeit imperfectly, by galactal 3-carbamate **14j**. Studies are continuing in our group to emphasize this reaction channel for the galactals, including through catalyst control of chemoselectivity by varying the metal and ligands.[63,64]

CONCLUSIONS

Amidoglycosylation studies using the full range of diastereomeric D-glycal 3-carbamates and dirhodium(II) acetate catalysis have revealed the profound effect of glycal stereochemistry on stereo- and chemoselectivity. The allals gave excellent anomeric stereocontrol with either cyclic or dibenzyl 4*O*,6*O* protection and without any appreciable formation of C3-oxidized dihydropyranone byproducts. The gulals showed somewhat lower stereoselectivity with benzyl protecting groups, but good 1,2-trans anomer control in the diacetyl- and acetonide-protected cases, coupled with excellent chemoselectivity as dihydropyranones were not formed. Glucal 3-carbamates locked in a $^4H_5$ conformation (pseudoequatorial 3*O*-carbamoyl group) gave low anomeric selectivities and led to considerable formation of dihydropyranone byproducts. However, conformationally flexible glucal systems gave high stereoselectivity, and both stereo- and chemoselectivity improved with electron-withdrawing 4*O*,6*O* protection. The use of electron-withdrawing protecting groups also helped favor amidoglycosylation versus C3 oxidation with galactal 3-carbamates, but the tendency toward dihydropyranone formation was particularly strong. Ultimately, the combination of an electron-withdrawing C6-OTs group and a bulky C4-OTBS substituent gave best results for the galactal 3-carbamate case, an outcome tied to the system's conformational preference.

We interpret these results in terms of a rhodium acyl nitrenoid intermediate that can lead to either C=C addition or C3−H oxidation. Positioning of the acyl nitrenoid for alkene addition is aided by a pseudoaxial orientation, and high 1,2-trans selectivity implies a glycosyl aziridine donor. When an

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aziridine intermediate is too strained, a zwitterionic oxocarbenium intermediate competes, lowering anomeric selectivity. The extent of C3−H oxidation, giving dihydropyranone byproducts, depends on inductive and stereoelectronic factors and can be curtailed by using appropriate protecting groups.

Metallanitrene-mediated alkene insertion from glycal 3-carbamates provides a tandem amidoglycosylation process amenable to synthesis of 2-amino sugars having 1,2-trans-2,3-cis stereochemistry. Using this methodology we have prepared β-2-amidogulo-, β-2-amidoallo-, α-2-amidomanno-, and α-2-amidotalopyranosides that include functionality (e.g., alkynyl, alkenyl, primary chloride, tosyl) for further synthetic elaboration. These compounds are potential building blocks for carbohydrate chemistry, including glycodiversification. In addition, our studies have outlined general aspects of the reactivity of rhodium acyl nitrenoids, findings that have applicability beyond the realm of 2-amino sugar synthesis.

EXPERIMENTAL SECTION

General Methods. ^{1}H NMR chemical shifts are reported in parts per million (δ) relative to tetramethylsilane (TMS, δ 0.00), using as a reference either added TMS or an appropriate signal for residual solvent protons. ^{13}C NMR chemical shifts are reported in parts per million, using the center peak of the solvent signal as a reference (δ 77.0 for $CDCl_3$). ^{13}C NMR peak multiplicities, where reported, were inferred using either DEPT 135 or edited HSQC experiments. The designation "o" (for odd number of attached hydrogens) denotes a CH or CH_3 carbon. Where ^{1}H and ^{13}C NMR peak assignments are given, these were made unambiguously by a combination of ^{1}H/^{1}H COSY, ^{1}H/^{13}C HSQC, and ^{1}H/^{13}C HMBC experiments. Atom numbering for NMR peak assignments is shown on the structures included on copies of spectra in the Supporting Information. Infrared spectra were recorded on an FT-IR instrument, including using an attenuated total reflection (ATR) accessory. Melting points were obtained using a capillary melting point apparatus and are uncorrected. High-resolution mass spectra (HRMS) were obtained from the Columbia University Chemistry Department Mass Spectrometry Facility either with a four-sector tandem JEOL system or on a Waters Xevo G2-XS QTOF mass spectrometer.

Iodosobenzene (PhIO) was prepared according to the literature procedure[65] and was stored in the dark at −20 °C under nitrogen. Solutions of dimethyldioxirane (DMDO) in acetone were prepared according to the literature procedure.[66] Oven-dried (135 °C) 4 Å molecular sieves were further activated by flame-drying under vacuum (0.5 mmHg) just prior to use. Methylene chloride was either distilled from CaH_2 or used as received from Sigma-Aldrich (anhydrous, Sure Seal). Anhydrous tetrahydrofuran (inhibitor-free, Sure Seal) was purchased from Sigma-Aldrich. Other reagents were obtained commercially and were used as received. Reactions were carried out in oven- or flame-dried glassware under an atmosphere of dry nitrogen. The amidoglycosylation products were sometimes difficult to visualize on TLC. A useful system to char the TLC plates involved preheating the eluted TLC plate, dipping the plate in a solution of Coleman's Permangante [$KMnO_4$ (3 g), K_2CO_3 (20 g), 5% NaOH (5 mL), H_2O (300 mL)], and then gently warming the TLC plate.

Synthesis of Gulal 3-Carbamates 11. *Thiophenyl 4,6-Di-O-acetyl-2,3-dideoxy-α-D-threo-hex-2-enopyranoside (21).*[25,27] Tri-*O*-acetyl-D-galactal (5.0 g, 18.4 mmol) was dissolved in CH_2Cl_2 (50 mL), and thiophenol (1.88 mL, 18.4 mmol) was added. The solution was cooled to −20 °C, and $SnCl_4$ (0.92 mL of a 1.0 M solution in CH_2Cl_2, 0.92 mmol) was added dropwise over 5 min. After 1 h at −20 °C, the reaction was quenched by addition of satd aq $NaHCO_3$ (30 mL), and the mixture was allowed to warm to room temperature. The layers were separated, and the organic layer was dried ($MgSO_4$), filtered, and concentrated. The crude was chromatographed (250 mL SiO_2, 10 → 15 → 25 → 40% EtOAc/hexanes), affording thiophenyl pseudoglycal **21** (3.9 g, 66%) as a white solid: mp 87−90 °C (lit. 92−93 °C); R_f = 0.38 (30% EtOAc/hexanes); IR (thin film) 1739 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.64−7.52 (m, 2H), 7.37−7.23 (m, 3H), 6.23 (dd, J = 10.0, 3.3 Hz, 1H), 6.11 (ddd, J = 9.9, 5.3, 1.6 Hz, 1H); 5.86 (dd, J = 3.1, 1.7 Hz, 1H), 5.14 (dd, J = 5.3, 2.5 Hz, 1H), 4.71 (ddd, J = 6.3, 6.3, 2.5 Hz, 1H), 4.35−4.20 (m, 2H), 2.09 (s, 3H), 2.04 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.6 (s), 170.3 (s), 134.6 (s), 131.7 (o), 131.3 (o), 128.9 (o), 127.6 (o), 124.4 (o), 83.4 (o), 67.2 (o), 63.3 (o), 62.6 (t), 20.8 (o), 20.7 (o); HRMS (FAB) m/z calcd for $C_{16}H_{19}O_5S$ (M + H)$^+$ 323.0953, found 323.0941.

Thiophenyl 2,3-Dideoxy-α-D-threo-hex-2-enopyranoside (22).[25,27,28b] The diacetate **21** (3.89 g, 12.1 mmol) was dissolved in MeOH/CH_2Cl_2 (28 mL/15 mL) at room temperature. Potassium carbonate (1.67 g, 12.1 mmol) was added and the mixture was well stirred during 30 min. Saturated aq NH_4Cl (20 mL) was added, and the mixture was extracted with CH_2Cl_2 (3 × 20 mL). The combined organic layers were dried ($MgSO_4$), filtered, and concentrated. The crude was purified by chromatography (SiO_2, 60% EtOAc/hexanes), yielding diol **22** (2.63 g, 92%) as a fluffy, white solid: mp 108−110 °C; R_f = 0.22 (50% EtOAc/hexanes); IR (thin film) 3280 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.60−7.46 (m, 2H), 7.38−7.21 (m, 3H), 6.16−6.03 (m, 2H), 5.80 (s, 1H), 4.36 (ddd, J = 5.4, 5.4, 2.1 Hz, 1H), 4.07−3.78 (m, 3H), 2.57 (d, J = 8.7 Hz, 1H), 2.55 (t, J = 5.5 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 134.6 (s), 131.9 (o), 129.3 (o), 129.0 (o), 128.4 (o), 127.6 (o), 83.9 (o), 70.8 (o), 62.8 (o), 62.5 (t); HRMS (EI) m/z calcd for $C_{12}H_{14}O_3S$ (M^+) 238.0664, found 238.0667.

Thiophenyl 4,6-O-Isopropylidene-2,3-dideoxy-α-D-threo-hex-2-enopyranoside (23a). To a solution of diol **22** (2.64 g, 11.1 mmol) in CH_2Cl_2 (55 mL) at room temperature was added 2,2-dimethoxypropane (2.73 mL, 22.2 mmol) followed by pyridinium *p*-toluenesulfonate (557 mg, 2.22 mmol). After 2 h, the reaction mixture was concentrated and chromatographed directly (200 mL SiO_2, 20% EtOAc/hexanes), affording acetonide **23a** (3.056 g, 99%) as a yellow syrup. Alternatively, an aqueous workup of the reaction mixture, using satd aq $NaHCO_3$, could be done prior to chromatography, producing comparable results: R_f = 0.36 (20% EtOAc/hexanes); IR (thin film) 3053, 1583 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.58−7.47 (m, 2H), 7.36−7.18 (m, 3H), 6.22 (dd, J = 9.9, 3.6 Hz, 1H), 6.00 (ddd, J = 9.8, 5.3, 1.6 Hz, 1H), 5.97 (m, 1H), 4.26 (dd, J = 13.0, 3.4 Hz, 1H), 4.22−4.11 (m, 2H), 3.94 (dd, J = 13.0, 2.0 Hz, 1H), 1.52 (s, 3H), 1.46 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 135.4 (s), 130.8 (o), 130.6 (o), 128.9 (o), 127.0 (o), 125.6 (o), 98.8 (s), 83.6 (o), 62.6 (o),* 62.6 (t),* 60.8 (o), 28.8 (o), 19.2 (o), the signals at δ 62.6 coincided but were differentiated in the DEPT 135 experiment; HRMS (FAB) m/z calcd for $C_{15}H_{17}O_3S$ (M − H)$^+$ 277.0898, found 277.0904.[67]

Thiophenyl 4,6-Di-O-benzyl-2,3-dideoxy-α-D-threo-hex-2-enopyranoside (23b). To a suspension of sodium hydride (86.6 mg of a 60% w/w suspension in oil, 2.17 mmol) in DMF (1 mL) at 0 °C was added a solution of diol **22** (148 mg, 0.622 mmol) in DMF (3 mL). The mixture was stirred for 15 min at 0 °C followed by addition of benzyl bromide (0.18 mL, 1.5 mmol). The cold bath was removed and stirring continued for 2 h at room temperature. The reaction was quenched with satd aq NH_4Cl (8 mL) and the mixture extracted with Et_2O (1 × 25 mL and 3 × 10 mL). The combined organic layers were washed with brine (1 × 10 mL), dried ($MgSO_4$), filtered, and concentrated. The crude was chromatographed (40 mL SiO_2, 10% EtOAc/hexanes) providing dibenzyl-protected α-thiophenyl pseudoglycal **23b** as a white solid (179 mg, 69%). R_f = 0.63 (30% EtOAc/hexanes); mp 74−77 °C; R_f = 0.63 (30% EtOAc/hexanes); IR (thin film) 3059, 3030, 1582 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.62−7.53 (m, 2H), 7.38−7.15 (m, 13H), 6.16 (dd, J = 10.0, 3.1 Hz, 1H), 6.08 (ddd, J = 10.0, 5.0, 1.4 Hz, 1H), 5.85 (dd, J = 3.0, 1.4 Hz, 1H), 4.68−4.51 (m, 5H), 3.92−3.77 (m, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 138.3 (s), 138.2 (s), 135.0 (s), 131.8 (o), 130.3 (o), 128.7 (o), 128.29 (o), 128.26 (o), 127.7 (o), 127.61 (o),* 127.57 (o),* 127.5 (o), 127.2 (o), 126.1 (o), 83.8 (o), 73.3 (t), 70.8 (t), 70.0 (o), 69.4 (t), 67.7 (o), *these ^{13}C NMR signals were best resolved by processing the FID with no line broadening (lb = 0); HRMS (FAB) m/z calcd for $C_{26}H_{27}O_3S$ (M + H)$^+$ 419.1681, found 419.1682.

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General Procedure for Oxidation and Rearrangement of α-Thiophenyl Pseudoglycals to Gulal Derivatives Using Dimethyldioxirane. A solution of the thiophenyl pseudoglycal (~2 mmol) in CH_2Cl_2 (6 mL) was cooled to −78 °C and a solution of DMDO (~0.08 M in acetone) was added via glass pipet (steel needles and cannula were avoided because they hastened decomposition of the DMDO). Consumption of the starting material was monitored by TLC and once the reaction was judged complete (excess DMDO was typically required) the cold bath was removed and the reaction mixture was allowed to warm to room temperature and concentrated (rotary evaporator then high vacuum line for 15−30 min). The crude was dissolved in THF (6 mL), diethylamine (1.4 mL) was added, and the mixture was stirred for 1 h at room temperature. The reaction mixture was concentrated, and the crude was chromatographed (SiO_2, EtOAc/hexanes).

*4,6-O-Isopropylidene-D-gulal (**24a**).* Prepared from **23a** (573 mg, 2.06 mmol) via the general procedure using DMDO. Chromatography (200 mL SiO_2, 60 → 65 → 70% EtOAc/hexanes) provided acetonide-protected gulal **24a** (240 mg, 63%). R_f = 0.27 (60% EtOAc/hexanes); IR (thin film) 3428, 1648 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.62 (d, J = 6.2 Hz, 1H), 5.00 (ddd, J = 6.5, 5.0, 1.5 Hz, 1H), 4.17−3.98 (m, 3H), 3.85 (dd, J = 5.1, 1.6 Hz, 1H), 3.72 (d, J = 1.5 Hz, 1H), 1.86 (br s, 1H), 1.51 (s, 3H), 1.42 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.8 (o), 99.3 (o), 98.6 (s), 68.1 (o), 64.5 (o), 62.9 (t), 62.1 (o), 29.3 (o), 18.5 (o); HRMS (FAB) m/z calcd for $C_9H_{15}O_4$ $(M + H)^+$ 187.0970, found 187.0975.

*4,6-Di-O-benzyl-D-gulal (**24b**).* Prepared from **23b** (350 mg, 0.836 mmol) via the general procedure using DMDO. Chromatography (200 mL SiO_2, 40% EtOAc/hexanes) provided dibenzyl-protected gulal **24b** (214 mg, 78%) as a light-yellow oil. R_f = 0.31 (40% EtOAc/hexanes); IR (thin film) 3406, 3063, 3031, 1643 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.38−7.22 (m, 10H), 6.57 (d, J = 6.1 Hz, 1H), 4.95 (ddd, J = 6.5, 4.8, 1.7 Hz, 1H), 4.56 (AB, J_{AB} = 12.0 Hz, $\Delta\nu_{AB}$ = 45.6 Hz, 2H), 4.51 (AB, J_{AB} = 12.0 Hz, $\Delta\nu_{AB}$ = 29.1 Hz, 2H), 4.09 (ddd, J = 6.9, 5.4, 1.5 Hz, 1H), 4.01 (ddd, J = 4.9, 4.9, 2.6 Hz, 1H), 3.77 (dd, J = 9.9, 7.0 Hz, 1H), 3.63−3.52 (m, 2H), 1.71 (br, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.6, 137.8, 137.7, 128.4, 128.0, 127.9, 127.8, 127.7, 100.5, 74.7, 73.4, 72.3, 68.9, 60.8; HRMS (FAB) m/z calcd for $C_{20}H_{22}O_4Na$ $(M + Na)^+$ 349.1416, found 349.1403.

*4,6-Di-O-acetyl-D-gulal (**24c**).*[25,27,28b] Prepared from **21** (698.2 mg, 2.17 mmol) via the general procedure using DMDO. Chromatography (200 mL SiO_2, 20 → 30 → 40 → 60 → 70 → 80% EtOAc/hexanes) provided gulal **24c** (404 mg, 81%) as a solid: mp 98−99 °C; R_f = 0.29 (50% EtOAc/hexanes); IR (thin film) 3437, 1734, 1712, 1645 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.60 (d, J = 6.2 Hz, 1H), 4.99 (ddd, J = 6.5, 4.9, 1.6 Hz, 1H), 4.92 (s, 1H), 4.30−4.21 (m, 3H), 3.97 (ddd, J = 4.9, 4.9, 2.4 Hz, 1H), 2.33 (br, 1H), 2.11 (s, 3H), 2.09 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.7 (s), 170.3 (s), 146.5 (o), 100.2 (o), 69.8 (o), 69.4 (o), 62.7 (t), 61.1 (o), 20.83 (o), 20.77 (o); HRMS (FAB) m/z calcd for $C_{10}H_{14}O_6Na$ $(M + Na)^+$ 253.0688, found 253.0685.

General Procedure for Modified Kocovsky Carbamate Synthesis Using Basic Methanolysis of the Intermediate Trichloroacetyl Carbamate. To a 0 °C solution of the allylic alcohol (~0.6 mmol) in CH_2Cl_2 (5 mL) was added trichloroacetyl isocyanate (1.5 equiv). The solution was stirred at 0 °C during 10 min, and the ice bath was removed, allowing the mixture to warm to room temperature. The starting alcohol was typically consumed (TLC) within 20−30 min. The reaction mixture was recooled to 0 °C and K_2CO_3 (3 equiv, powdered) was added, followed immediately by MeOH (5 mL). The mixture was stirred at 0 °C during 10 min and then warmed to room temperature. Methanolysis to the desired primary carbamate was typically complete within 2−3 h. The mixture was poured into satd aq NH_4Cl (30 mL) and extracted with CH_2Cl_2 (3 × 25 mL). The combined organic layers were dried ($MgSO_4$), filtered, and concentrated. The crude was chromatographed (SiO_2, EtOAc/hex), providing the primary carbamate product.

*3-O-Carbamoyl-4,6-O-isopropylidene-D-gulal (**11a**).* Prepared from **24a** (216 mg, 1.16 mmol) via the general procedure for modified Kocovsky carbamate synthesis. Chromatography (150 mL SiO_2, 60 → 70% EtOAc/hexanes) gave acetonide-protected gulal carbamate **11a** (131 mg, 49%) as a white solid: mp 125−128 °C; R_f = 0.38 (60% EtOAc/hexanes); IR (thin film) 3455, 3357, 3194, 1718, 1713, 1649, 1602 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.67 (d, J = 6.2 Hz, 1H, H1), 4.96 (ddd, J = 6.5, 5.1, 1.5 Hz, 1H, H2), 4.83 (dd, J = 5.4, 2.0 Hz, 1H, H3), 4.68 (br s, 2H, NH_2), 4.14−4.01 (m, 3H, H4, H6a,b), 3.67 (m, 1H, H5), 1.51 (s, 3H, $C(CH_3)_2$), 1.43 (s, 3H, $C(CH_3)_2$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.7 (s, $C(O)NH_2$), 147.9 (o, C1), 98.8 (s, $C(CH_3)_2$), 96.1 (o, C2), 66.2 (o, C4), 65.1 (o, overlapping C3 and C5), 62.7 (t, C6), 29.2 (o, $C(CH_3)_2$), 18.4 (o, $C(CH_3)_2$); HRMS (ESI) m/z calcd for $C_{10}H_{15}NO_5Na$ $(M + Na)^+$ 252.0848, found 252.0845.

*3-O-Carbamoyl-4,6-di-O-benzyl-D-gulal (**11b**).* Prepared from **24b** (213 mg, 0.653 mmol) via the general procedure for modified Kocovsky carbamate synthesis. Chromatography (75 mL SiO_2, 35 → 40% EtOAc/hexanes) provided di-O-benzyl-protected gulal carbamate **11b** (222 mg, 92%) as a white solid: mp 47−51 °C; R_f = 0.28 (35% EtOAc/hexanes); IR (thin film) 3469, 3351, 3197, 3064, 3030, 1721, 1646, 1600 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.38−7.23 (m, 10H, ArH), 6.65 (d, J = 6.1 Hz, 1H, H1), 5.07 (dd, J = 5.3, 2.0 Hz, 1H, H3), 4.93 (ddd, J = 6.0, 5.4, 1.8 Hz, 1H, H2), 4.76 (d, J = 12.0 Hz, 1H, $PhCH_2$), 4.75 (br s, 2H, NH_2), 4.54 (d, J = 12.1 Hz, 1H, $PhCH_2$), 4.45 (AB, J_{AB} = 12.0 Hz, $\Delta\nu_{AB}$ = 24.4 Hz, 2H, $PhCH_2$), 3.99 (ddd, J = 6.2, 6.2, 1.0 Hz, 1H, H5), 3.72 (dd, J = 9.8, 6.7 Hz, 1H, H6a), 3.66 (ddd, J = 1.8, 1.8, 1.8 Hz, 1H, H4), 3.49 (dd, J = 9.8, 5.7 Hz, 1H, H6b); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.8 (s, $C(O)NH_2$), 148.0 (o, C1), 137.7 (s, C_i), 137.5 (s, C_i), 128.4 (o, C_{Ar}),* 128.3 (o, 2 × C_{Ar}),* 127.9 (o, 2 × C_{Ar}), 127.8 (o, C_{Ar}), 97.0 (o, C2), 73.5 (t, $PhCH_2$), 72.9 (o, C5), 72.1 (o, C4), 71.8 (t, $PhCH_2$), 68.9 (t, C6), 63.2 (o, C3), *these ^{13}C NMR signals were best resolved by processing the FID with no line broadening (lb = 0); HRMS (FAB) m/z calcd for $C_{21}H_{22}NO_5$ $(M - H)^+$ 368.1498, found 368.1517.[67]

*3-O-Carbamoyl-4,6-di-O-acetyl-D-gulal (**11c**).* In this case, because of the acetyl protecting groups, we followed the approach of Kocovsky[29a] and Sugai[29b] with alumina-mediated hydrolysis of the *N*-trichloroacetyl carbamate intermediate. The activity of neutral alumina (Bio-Rad Neutral Alumina AG 7, 100−200 mesh, Activity grade 1) was adjusted by adding 300 μL of water to 10 g of the alumina and mixing thoroughly. The moistened alumina was stored in a tightly capped vial. To a solution of diacetyl-protected gulal **24c** (260 mg, 1.13 mmol) in CH_2Cl_2 (3.5 mL) at room temperature was added trichloroacetyl isocyanate (200 μL, 1.69 mmol). After 25 min, TLC indicated complete consumption of starting material, and enough of the alumina, prepared as described above, was added to just absorb all the solvent. After standing for 20 min, the alumina was suspended in EtOAc and stirred 20 min. The mixture was filtered through a pad of Celite, and the filtrate was concentrated. The crude was chromatographed (150 mL SiO_2, 60% EtOAc/hexanes), affording primary carbamate **11c** (287 mg, 93%) as a solid: mp 134−136 °C, R_f = 0.22 (60% EtOAc/hexanes); IR (thin film) 3472, 3449, 3357, 1745, 1733, 1696, 1645, 1605 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.63 (d, J = 6.1 Hz, 1H, H1), 5.09 (m, 1H, H4), 5.05 (ddd, J = 5.7, 5.7, 1.4 Hz, 1H, H2), 4.86 (dd, J = 5.2, 2.4 Hz, 1H, H3), 4.79 (br s, 2H, NH_2), 4.32−4.10 (m, 3H, H5, H6a,b), 2.11 (s, 3H, $C(O)CH_3$), 2.10 (s, 3H, $C(O)CH_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.6 (s, $C(O)CH_3$), 169.7 (s, $C(O)CH_3$), 155.2 (s, $C(O)NH_2$), 147.5 (o, C1), 97.7 (o, C2), 70.6 (o, C5), 66.3 (o, C4), 63.9 (o, C3), 62.5 (t, C6), 20.8 (o, $C(O)CH_3$), 20.7 (o, $C(O)CH_3$); HRMS (FAB) m/z calcd for $C_{11}H_{15}NO_7$ (M^+) 273.0849, found 273.0847.

Synthesis of Allal 3-Carbamate 12b. *Thiophenyl 4,6-Di-O-benzyl-2,3-dideoxy-α-D-erythro-hex-2-enopyranoside (**25**).*[30] To a 0 °C solution of the corresponding diol[68] (488 mg, 2.05 mmol) in DMF (6 mL) was added NaH (246 mg of a 60% w/w dispersion in oil, 6.15 mmol). After 15 min, benzyl bromide (0.56 mL, 4.68 mmol) was added, and the mixture was allowed to warm to room temperature and stirred 3 h. The reaction was quenched by addition of satd aq NH_4Cl (8 mL) and extracted with Et_2O (1 × 25 mL, 3 × 10 mL). The combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated. Chromatography (150 mL SiO_2) provided dibenzyl ether **25** (808 mg, 94%) as an oil: R_f = 0.64

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(30% EtOAc/hexanes); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.60−7.49 (m, 2H), 7.40−7.17 (m, 13H), 6.08−5.93 (m, 2H), 5.77 (s, 1H), 4.57 (AB, J_{AB} = 12.1 Hz, $\Delta\nu_{AB}$ = 41.6 Hz, 2H), 4.55 (AB, J_{AB} = 11.4 Hz, $\Delta\nu_{AB}$ = 44.4 Hz, 2H), 4.33 (ddd, J = 9.2, 3.6, 2.5 Hz, 1H), 4.25 (dd, J = 9.3, 1.4 Hz, 1H), 3.85−3.69 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 138.1 (s), 137.9 (s), 135.5 (s), 131.5 (o), 129.1 (o), 128.8 (o), 128.4 (o), 128.3 (o), 127.9 (o), 127.8 (o), 127.6 (o), 127.24 (o), 127.16 (o), 84.0 (o), 73.2 (t), 71.2 (t), 70.2 (o), 69.6 (o), 68.9 (t).

*4,6-Di-O-benzyl-D-allal (**26**).*[31] Prepared from **25** (799 mg, 1.91 mmol) via the general rearrangement procedure using DMDO. Chromatography (200 mL SiO_2, 35 → 40% EtOAc/hexanes) provided allal **26** (383 mg, 62%): R_f = 0.33 (40% EtOAc/hexanes); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.40−7.20 (m, 10H), 6.46 (d, J = 5.9 Hz, 1H), 4.92 (dd, J = 5.8, 5.8 Hz, 1H), 4.61 (AB, J_{AB} = 11.5 Hz, $\Delta\nu_{AB}$ = 12.2 Hz, 2H), 4.60 (AB, J_{AB} = 12.2 Hz, $\Delta\nu_{AB}$ = 23.9 Hz, 2H), 4.17 (dd, J = 5.1, 4.0 Hz, 1H), 4.08 (ddd, J = 10.2, 2.8, 2.8 Hz, 1H), 3.84−3.75 (m, 3H), 2.54 (br s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 146.6 (o), 137.9 (s), 137.4 (s), 128.5 (o), 128.3 (o), 128.1 (o), 127.9 (o), 127.8 (o), 127.7 (o), 100.0 (o), 74.1 (o), 73.5 (t), 72.12 (t),* 72.09 (o),* 68.5 (t), 59.8 (o), *these ^{13}C NMR resonances were resolved upon reprocessing the FID with lb = 0 and also in the DEPT 135 experiment.

*3O-Carbamoyl-4,6-di-O-benzyl-D-allal (**12b**).* Prepared from allylic alcohol **26** (383 mg, 1.17 mmol) via the general procedure for modified Kocovsky carbamate synthesis (i.e., with MeOH, K_2CO_3 treatment). Chromatography (150 mL SiO_2, 30 → 40% EtOAc/hexanes) gave dibenzyl-protected allal carbamate **12b** (324 mg, 75%) as a white solid: mp 118−119 °C; R_f = 0.29 (30% EtOAc/hexanes); IR (thin film) 3431, 3352, 3296, 3219, 1652, 1642, 1622 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.33−7.13 (m, 10H, ArH), 6.46 (d, J = 5.8 Hz, 1H, H1), 5.37 (dd, J = 6.0, 3.8 Hz, 1H, H3), 4.85 (dd, J = 5.9, 5.9 Hz, 1H, H2), 4.65 (br s, 2H, NH_2), 4.52 (AB, J_{AB} = 10.8 Hz, $\Delta\nu_{AB}$ = 94.9 Hz, 2H, PhCH_2O), 4.52 (AB, J_{AB} = 12.1 Hz, $\Delta\nu_{AB}$ = 18.0 Hz, 2H, PhCH_2O), 4.03 (ddd, J = 10.7, 3.3, 2.5 Hz, 1H, H5), 3.81 (dd, J = 10.7, 3.8 Hz, 1H, H4), 3.78−3.66 (m, 2H, H6); ^{13}C NMR (75 MHz, $CDCl_3$) δ 156.4 (s, OC(O)NH_2), 148.0 (o, C1), 137.9 (s, C_{Ph}), 137.3 (s, C_{Ph}), 128.38 (o, C_{Ph}),* 128.37 (o, C_{Ph}),* 128.3 (o, C_{Ph}), 127.9 (o, C_{Ph}), 127.8 (o, C_{Ph}), 127.7 (o, C_{Ph}), 97.2 (o, C2), 73.6 (t, PhCH_2O), 73.1 (o, C5), 72.6 (o, C4), 72.0 (t, PhCH_2O), 68.5 (t, C6), 62.4 (o, C3), *these ^{13}C NMR resonances were resolved upon reprocessing the FID with lb = 0; HRMS (FAB) m/z calcd for $C_{21}H_{22}NO_5$ $(M - H)^+$ 368.1498, found 368.1486.[67]

Allal 3-carbamates **12a** and **12e** were prepared and characterized as described in ref 20. Additional ^{1}H and ^{13}C NMR spectra for acetonide-protected allal 3-carbamate **12a** were obtained in acetone-d_6 to aid in J-value analysis. The additional tabulated data and spectra for **12a** are included in the Supporting Information.

Synthesis of Galactal 3-Carbamates 14. *3O-Carbamoyl-4,6-O-isopropylidene-D-galactal (**14a**).* Prepared from **27a**[32] (63.4 mg, 0.340 mmol) via the general procedure for modified Kocovsky carbamate synthesis (i.e., MeOH, K_2CO_3 treatment). Chromatography (40 mL SiO_2, 60% EtOAc/hexanes) provided galactal carbamate **14a** (72.6 mg, 93%) as a white solid: mp 127−130 °C; R_f = 0.19 (60% EtOAc/hexanes); IR (thin film) 3457, 3361, 3200, 1718, 1710, 1702 (shoulder), 1656, 1605 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.50 (dd, J = 6.4, 2.1 Hz, 1H, H1), 5.37 (m, 1H, H3), 4.96 (br s, 2H, NH_2), 4.69 (ddd, J = 6.4, 1.7, 1.7 Hz, 1H, H2), 4.52 (apparent slightly br d, J = 4.9 Hz, 1H, H4), 4.03 (AB of ABX, J_{AB} = 12.8 Hz, J_{AX} = 2.0 Hz, J_{BX} = 1.4 Hz, $\Delta\nu_{AB}$ = 19.1 Hz, 2H, H6), 3.83 (apparent slightly br s, 1H, H5), 1.50 (s, 3H, CH_3), 1.48 (s, 3H, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 156.2 (s, OC(O)NH_2), 145.5 (o, C1), 99.1 (s, $C(CH_3)_2$), 97.3 (o, C2), 67.7 (o, C5), 66.1 (o, C3), 62.98 (t, C6),* 62.96 (o, C4),* 29.4 (o, $C(CH_3)_2$), 18.5 (o, $C(CH_3)_2$), *these ^{13}C NMR resonances were cleanly resolved upon reprocessing the FID with lb = 0; HRMS (EI) m/z calcd for $C_9H_{12}NO_5$ $(M\text{-}CH_3)^+$ 214.0715, found 214.0714.

*3O-Carbamoyl-4,6-di-O-benzyl-D-galactal (**14b**).* Prepared from **27b**[33] (201 mg, 0.616 mmol) via the general procedure for modified Kocovsky carbamate synthesis (i.e., MeOH, K_2CO_3 treatment). Chromatography (80 mL SiO_2, 45% EtOAc/hexanes) provided galactal carbamate **14b** (222 mg, 98%) as a white solid: mp 78−81 °C; R_f = 0.21 (40% EtOAc/hexanes); IR (thin film) 3465, 3352, 3065, 3030, 1714, 1649, 1601 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.40−7.20 (m, 10H, Ar-H), 6.43 (dd, J = 6.2, 1.4 Hz, 1H, H1), 5.39 (dddd, J = 4.2, 2.8, 1.4, 1.4 Hz, 1H, H3), 4.83−4.68 (m, 3H, H2, NH_2), 4.65 (AB, J_{AB} = 11.9 Hz, $\Delta\nu_{AB}$ = 70.1 Hz, 2H, −OCH_2Ph), 4.46 (AB, J_{AB} = 11.9 Hz, $\Delta\nu_{AB}$ = 24.0 Hz, 2H, −OCH_2Ph), 4.22 (m, 1H, H5), 4.03 (ddd, J = 3.9, 2.4, 1.4 Hz, 1H, H4), 3.64 (AB of ABX, J_{AB} = 10.1 Hz, J_{AX} = 7.4 Hz, J_{BX} = 5.0 Hz, $\Delta\nu_{AB}$ = 45.9 Hz 2H, H6); ^{1}H NMR (300 MHz, $CDCl_3$) of a more dilute sample (~10 mg/mL) removed the overlap of the H2 and NH2 resonances, revealing the H2 signal (δ 4.75) as a ddd (J = 6.2, 3.1, 1.2 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 156.3 (s, OC(O)NH_2), 145.5 (o, C1), 137.9 (s, C_{Ph}), 137.8 (s, C_{Ph}), 128.35 (o, C_{Ph}),* 128.32 (o, C_{Ph}),* 128.1 (o, C_{Ph}), 127.80 (o, C_{Ph}),* 127.76 (o, C_{Ph}),* 127.7 (o, C_{Ph}), 98.9 (o, C2), 75.4 (o, C5), 73.7 (t, OCH_2Ph), 73.3 (t, OCH_2Ph), 70.5 (o, C4), 68.0 (t, C6), 66.5 (o, C3); *these ^{13}C NMR signals were resolved by processing the FID with lb = 0; HRMS (FAB) m/z calcd for $C_{21}H_{24}NO_5$ $(M + H)^+$ 370.1654, found 370.1646. Anal. Calcd for $C_{21}H_{23}NO_5$: C, 68.28; H, 6.28; N, 3.79. Found C, 67.87; H, 6.58; N, 3.57. Selected ^{1}H NMR homonuclear decoupling results for **14b** are in the Supporting Information.

*3O-Carbamoyl-4,6-O-di-tert-butylsilylene-D-galactal (**14d**).* Prepared from **27d**[34] (217 mg, 0.757 mmol) via the general procedure for modified Kocovsky carbamate synthesis. Chromatography (80 mL SiO_2, 30 → 35 → 40% EtOAc/hexanes) provided galactal carbamate **14d** (244 mg, 98%) as a viscous, clear, colorless oil that became a white solid after full removal of solvent on the vacuum line: mp 125−127 °C; R_f = 0.25 (30% EtOAc/hexanes); IR (thin film) 3454, 3386, 3341, 3197, 1716, 1652, 1598 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.40 (dd, J = 6.4, 2.0 Hz, 1H, H1), 5.23 (m, 1H, H3), 4.80 (m, 1H, H4), 4.74 (br s, 2H, NH_2), 4.66 (ddd, J = 6.4, 1.8, 1.8 Hz, 1H, H2), 4.26 (AB of ABX, J_{AB} = 12.6 Hz, J_{AX} = 2.0 Hz, J_{BX} = 1.7 Hz, $\Delta\nu_{AB}$ = 12.0 Hz, 2H, H6), 3.89 (apparent broadened s, 1H, H5), 1.05 (s, 9H, Si[C(CH_3)$_3$]$_2$), 1.03 (s, 9H, Si[C(CH_3)$_3$]$_2$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 156.4 (s, OC(O)NH_2), 145.6 (o, C1), 98.5 (o, C2), 73.2 (o, C5), 68.0 (o, C3), 67.3 (t, C6), 65.7 (o, C4), 27.6 (o, Si[C(CH_3)$_3$]$_2$), 27.0 (o, Si[C(CH_3)$_3$]$_2$), 23.3 (s, Si[C(CH_3)$_3$]$_2$), 20.8 (s, Si[C(CH_3)$_3$]$_2$); HRMS (FAB) m/z calcd for $C_{15}H_{28}NO_5Si$ $(M + H)^+$ 330.1737, found 330.1725. Selected ^{1}H NMR homonuclear decoupling results for **14d** are in the Supporting Information.

*4,6-O-Di-tert-butylsilylene-3O-(N-2,4-dimethoxybenzyl)-carbamoyl-D-galactal (**28**).* Di-*tert*-butylsilylene-protected galactal **27d**[34] (1.21 g, 4.22 mmol) was dissolved in CH_2Cl_2 (5.0 mL) and 2,4-dimethoxybenzyl isocyanate (0.78 mL, 4.7 mmol) was added, followed by DBU (0.19 mL, 1.3 mmol). After 2 h at 25 °C, TLC indicated complete consumption of starting material. The reaction mixture was diluted with CH_2Cl_2 and washed with 10% $NaHCO_3$ (30 mL). The aqueous layer was back-extracted with CH_2Cl_2 (3 × 30 mL), and the combined organic layers were washed with brine (30 mL), dried ($MgSO_4$), filtered, and concentrated. The crude was chromatographed (5 → 10 → 15 → 20% EtOAc/hexanes, 60 mL SiO_2), providing the dimethoxybenzyl carbamate **28** as a white, crystalline solid (1.87 g, 92%): mp 121.5−123.5 °C; R_f = 0.25 (20% EtOAc/hexanes); IR (thin film) 3382, 1715, 1654, 1614, 1590 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.18 (d, J = 7.9 Hz, 1H), 6.58−6.33 (m, 3H), 5.35 (br t, J = 5.7 Hz, 1H), 5.23 (apparent br s, 1H), 4.76 (d, J = 2.9 Hz, 1H), 4.64 (d, J = 6.3 Hz, 1H), 4.33−4.17 (m, 4H), 3.89 (br s, 1H), 3.81 (s, 3H), 3.80 (s, 3H), 1.00 (s, 9H), 0.98 (s, 9H); ^{1}H NMR signals for a minor rotamer (~15−20%) were observed as a shoulder downfield of the signal at δ 5.23, as a br peak at δ 5.03, as a shoulder just downfield of the δ 4.64 resonance, and as a br s at δ 1.04; ^{13}C NMR (75 MHz, $CDCl_3$) δ 160.4 (s), 158.4 (s), 155.9 (s), 145.3 (o), 130.1 (o), 119.2 (s), 103.7 (o), 98.9 (o), 98.5 (o), 73.2 (o), 67.6 (o), 67.3 (t), 65.8 (o), 55.4 (o), 55.2 (o), 40.4 (t), 27.6 (o), 27.0 (o), 23.2 (s), 20.8 (s); HRMS (FAB) m/z calcd for $C_{24}H_{38}NO_7Si$ $(M + H)^+$ 480.2418, found 480.2435.

*3-O-(N-2,4-Dimethoxybenzyl)carbamoyl-D-galactal (**29**).* To a 0 °C solution of carbamate **28** (1.87 g, 3.89 mmol) in THF (25 mL) in a plastic vial was added HF·pyr (18 drops from a plastic dropper).

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The reaction mixture was stirred 5 min at 0 °C and at 25 °C until TLC indicated complete conversion of starting material to a single more polar product (1 h 15 min). The mixture was cooled to 0 °C, neutralized by careful addition of satd aq $NaHCO_3$ (40 mL), and extracted with EtOAc (3 × 50 mL). The combined organic layers were washed with H_2O (2 × 40 mL) and brine (40 mL), dried ($MgSO_4$), filtered, and concentrated. The crude diol product **29**, a white solid, could be purified by chromatography (90% EtOAc/hexanes, SiO_2) but due to its high polarity was more conveniently used directly in the next reaction without purification: mp 118.5−120.5 °C; R_f = 0.25 (90% EtOAc/hexanes); IR (thin film) 3428, 3334, 1677, 1658, 1615, 1588 cm^{-1}; ^1H NMR (300 MHz, acetone-d_6) δ 7.17 (d, J = 8.3 Hz, 1H), 6.53 (d, J = 2.2 Hz, 1H), 6.46 (dd, J = 8.3, 2.3 Hz, 1H), 6.37 (dd, J = 6.3, 1.2 Hz, 1H), 6.34 (br, 1H), 5.25 (dd, J = 2.0, 2.0 Hz, 1H), 4.59 (ddd, J = 6.4, 1.9, 1.9 Hz, 1H), 4.23 (apparent d, J = 6.0 Hz, 2H), 4.17 (br, 1H), 3.98 (br t, J = 5.8 Hz, 1H), 3.94−3.70 (m, 4H), 3.83 (s, 3H), 3.78 (s, 3H); ^1H NMR signal for minor rotamer (∼10%) at δ 6.05; ^{13}C NMR (75 MHz, acetone-d_6) δ 161.4 (s), 159.2 (s), 156.9 (s), 146.0 (o), 130.1 (o), 120.4 (s), 105.0 (o), 100.3 (o), 99.1 (o), 78.4 (o), 68.3 (o), 64.4 (o), 61.8 (t), 55.8 (o), 55.7 (o), 40.3 (t); HRMS (FAB) m/z calcd for $C_{16}H_{21}NO_7$ (M^+) 339.1318, found 339.1320.

*4,6-Di-O-acetyl-3-O-(N-2,4-dimethoxybenzyl)carbamoyl-D-galactal (**31c**).* The crude diol **29** (∼1.32 g, 3.87 mmol) was suspended in CH_2Cl_2 (25 mL), and pyridine (2.5 mL, 31 mmol), acetic anhydride (1.46 mL, 15.5 mmol), and *N*,*N*-dimethyl-4-aminopyridine (120 mg, 0.97 mmol) were added, in that order. After 2 h at 25 °C, the reaction mixture was diluted with CH_2Cl_2 (40 mL) and washed with satd aq $NaHCO_3$ (40 mL). The aqueous layer was back-extracted with CH_2Cl_2, and the combined organic layers were dried ($MgSO_4$), filtered, and concentrated. The crude material was chromatographed (60% EtOAc/hexanes, 100 mL SiO_2), providing the diacetyl-protected **31c** as a yellowish, viscous oil (1.48 g, 89% for two steps from silylene-protected **28**): R_f = 0.40 (60% EtOAc/hexanes); IR (thin film) 3378, 1745, 1724, 1649, 1614, 1590 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.18 (d, J = 7.9 Hz, 1H), 6.52−6.35 (m, 3H), 5.55−5.38 (m, 2H), 5.20 (br t, J = 5.6 Hz, 1H), 4.77 (m, 1H), 4.39−4.13 (m, 5H), 3.82 (s, 3H), 3.79 (s, 3H), 2.08 (s, 3H), 2.06 (s, 3H); ^1H NMR signals for minor rotamer (∼20%) at δ 7.11 (br d, J = 9.4 Hz), broad peak at δ 5.04, and a shoulder on the downfield side of the resonance at δ 4.77; ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.6 (s), 169.9 (s), 160.5 (s), 158.4 (s), 155.3 (s), 145.0 (o), 130.2 (o), 118.8 (s), 103.7 (o), 99.4 (o), 98.5 (o), 72.8 (o), 64.5 (o), 63.9 (o), 61.9 (t), 55.3 (o), 55.2 (o), 40.5 (t), 20.7 (o), 20.6 (o); HRMS (FAB) m/z calcd for $C_{20}H_{25}NO_9$ (M^+) 423.1529, found 423.1544.

*4,6-Di-O-chloroacetyl-3-O-(N-2,4-dimethoxybenzyl)carbamoyl-D-galactal (**31g**).* Diol **29** (301 mg, 0.887 mmol) was suspended in CH_2Cl_2 (2 mL), and pyridine (574 μL, 0.561 mmol), chloroacetic anhydride (607 mg, 3.55 mmol), and *N*,*N*-dimethyl-4-aminopyridine (54.6 mg, 0.444 mmol) were added, in that order. The reaction mixture was concentrated on the rotovap and for 1 h under high vacuum (∼0.5 Torr). The crude material was chromatographed directly (40 → 50 → 60% EtOAc/hexanes, 200 mL SiO_2), affording bis(chloroacetyl) ester **31g** (315 mg, 72%) as a white foam: R_f = 0.50 (60% EtOAc/hexanes); IR (thin film) 3409, 1764, 1724, 1654, 1648, 1615, 1590 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.18 (d, J = 8.0 Hz, 1H), 6.49−6.37 (m, 3H), 5.49 (m, 2H), 5.19 (t, J = 5.6 Hz, 1H), 4.80 (dd, J = 5.6, 2.6 Hz, 1H), 4.42−4.34 (m, 1H), 4.39 (AB of ABX, J_{AB} = 10.9 Hz, J_{AX} = 7.5 Hz, J_{BX} = 4.1 Hz, $\Delta\nu_{AB}$ = 53.1 Hz, 2H), 4.09 (apparent s, 2H), 4.00 (apparent s, 2H), 3.82 (s, 3H), 3.80 (s, 3H); ^1H NMR signals for minor rotamer (∼15%) appeared as broad peaks at δ 7.09 and δ 5.02 as well as a shoulder on the downfield side of the resonance at δ 4.80; ^{13}C NMR (75 MHz, $CDCl_3$) δ 167.0 (s), 166.5 (s), 160.7 (s), 158.5 (s), 155.2 (s), 145.0 (o), 130.3 (o), 118.8 (s), 103.8 (o), 99.3 (o), 98.6 (o), 72.2 (o), 66.5 (o), 63.4 (o), 63.1 (t), 55.4 (o), 55.3 (o), 40.7 (t), 40.6 (t), 40.5 (t); HRMS (FAB) m/z calcd for $C_{20}H_{23}NO_9{}^{35}Cl_2$ (M^+) 491.0750, found 491.0744.

*3-O-(N-2,4-Dimethoxybenzyl)carbamoyl-6-O-p-toluenesulfonyl-D-galactal (**30**).* Diol **29** (329 mg, 0.969 mmol) was dissolved in pyridine (1 mL) and *p*-toluenesulfonyl chloride (278 mg, 1.46 mmol) and *N*,*N*-dimethyl-4-aminopyridine (30 mg, 0.24 mmol) were added. The mixture was stirred 6 h at room temperature, diluted with CH_2Cl_2 (10 mL), and washed with satd aq $NaHCO_3$ (15 mL). The aqueous layer was back-extracted with EtOAc (10 mL), and the combined organic layers were washed with brine (10 mL), dried ($MgSO_4$), filtered, and concentrated. The crude was chromatographed (40 → 55 → 50 → 55 → 60 → 65% EtOAc/hexanes, 150 mL SiO_2), yielding the 6*O*-tosyl derivative **30** (358 mg, 75%) as a pale yellow oil: R_f = 0.40 (60% EtOAc/hexanes); IR (thin film) 3400, 1707, 1647, 1614, 1590 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.79 (apparent d, J = 8.3 Hz, 2H), 7.33 (apparent d, J = 8.1 Hz, 2H), 7.16 (d, J = 8.0 Hz, 1H), 6.49−6.40 (m, 2H), 6.31 (dd, J = 6.2, 1.2 Hz, 1H), 5.34 (t, J = 5.8 Hz, 1H), 5.27 (m, 1H), 4.68 (ddd, J = 6.2, 2.6, 1.1 Hz, 1H), 4.33−4.08 (m, 6H), 3.83 (s, 3H), 3.80 (s, 3H), 2.54 (br s, 1H), 2.44 (s, 3H); ^1H NMR signals for minor rotamer (∼15%) at δ 7.09 (br d, J = 7.6 Hz), broad peak at δ 5.13, and a shoulder on the downfield side of the resonances at δ 6.31 and δ 4.68; ^{13}C NMR (75 MHz, $CDCl_3$) δ 160.7 (s), 158.5 (s), 155.7 (s), 145.03 (o), 144.96 (s), 132.7 (s), 130.3 (o), 129.8 (o), 128.0 (o), 118.6 (s), 103.9 (o), 98.9 (o), 98.6 (o), 73.9 (o), 67.7 (t), 66.5 (o), 64.0 (o), 55.4 (o), 55.3 (o), 40.8 (t), 21.6 (o); HRMS (FAB) m/z calcd for $C_{23}H_{27}NO_9S$ (M^+) 493.1407, found 493.1425.

*4-O-Chloroacetyl-3-O-(N-2,4-dimethoxybenzyl)carbamoyl-6-O-p-toluenesulfonyl-D-galactal (**31h**).* To a solution of alcohol **30** (108 mg, 0.219 mmol) in CH_2Cl_2 (3 mL) were added, sequentially, pyridine (71 μL, 0.88 mmol), chloracetic anhydride (78 mg, 0.44 mmol), and *N*,*N*-dimethyl-4-aminopyridine (6.6 mg, 0.055 mmol). The mixture was stirred at room temperature during 15 min, diluted with CH_2Cl_2 (20 mL), and washed with satd aq $NaHCO_3$ (15 mL) and brine (35 mL). The organic layer was dried ($MgSO_4$), filtered, and concentrated. The crude was chromatographed (50% EtOAc/hexanes, 60 mL SiO_2), yielding the 4*O*-chloroacetate ester **31h** (89.7 mg, 74%) as a light yellow oil: R_f = 0.46 (60% EtOAc/hexanes); IR (thin film) 3407, 1768, 1720, 1648, 1614, 1591 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.76 (apparent d, J = 8.3 Hz, 2H), 7.33 (apparent d, J = 8.1 Hz, 2H), 7.17 (d, J = 7.9 Hz, 1H), 6.49−6.39 (m, 2H), 6.29 (d, J = 6.2 Hz, 1H), 5.41 (apparent s, 2H), 5.20 (t, J = 5.8 Hz, 1H), 4.75 (ddd, J = 6.0, 2.0, 2.0 Hz, 1H), 4.36−4.08 (m, 5H), 3.90 (apparent s, 2H), 3.83 (s, 3H), 3.80 (s, 3H), 2.45 (s, 3H); ^1H NMR signals for minor rotamer (∼15%) at δ 7.06 (br d, J = 7.0 Hz), 6.34 (d, J = 6.4 Hz), 5.00 (br s), and a downfield shoulder on the resonance at δ 4.75; ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.2 (s), 160.6 (s), 158.5 (s), 155.1 (s), 145.2 (s), 144.8 (o), 132.5 (s), 130.2 (o), 129.9 (o), 128.0 (o), 118.8 (s), 103.8 (o), 99.2 (o), 98.6 (o), 72.0 (o), 66.44 (t), 66.36 (o), 63.2 (o), 56.05 (o),* 56.01 (o),* 40.7 (t), 40.4 (t), 21.6 (o); *these ^{13}C NMR resonances were resolved upon reprocessing the FID with lb = 0; HRMS (FAB) m/z calcd for $C_{25}H_{28}NO_{10}SCl$ (M^+) 569.1122, found 569.1143.

*4,6-Bis-O-tert-butyldimethylsilyl-3-O-(N-2,4-dimethoxybenzyl)-carbamoyl-D-galactal (**31i**).* To a solution of diol **29** (125 mg, 0.368 mmol) in DMF (1 mL) were added, sequentially, imidazole (151 mg, 2.22 mmol) and *tert*-butyldimethylsilyl chloride (226 mg, 1.50 mmol). After stirring at room temperature 5 h, additional imidazole (152 mg, 2.23 mmol) and *tert*-butyldimethylsilyl chloride (221 mg, 1.47 mmol) were added. Stirring was continued for 72 h, and the reaction mixture was diluted with CH_2Cl_2 (20 mL) and washed with satd aq $NaHCO_3$ (15 mL) and brine (15 mL). The organic layer was dried ($MgSO_4$), filtered, and concentrated. The crude material was chromatographed (10 → 15 → 20% EtOAc/hexanes, 120 mL SiO_2), yielding bis-silylated **31i** (121 mg, 58%) as a clear, colorless oil: R_f = 0.73 (40% EtOAc/hexanes); IR (thin film) 3459, 3365, 1722, 1715, 1650, 1644, 1615, 1591 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.17 (d, J = 7.9 Hz, 1H), 6.49−6.38 (m, 2H), 6.32 (dd, J = 6.1, 0.9 Hz, 1H), 5.27 (slightly broadened apparent s, 1H), 5.14 (t, J = 5.8 Hz, 1H), 4.62 (dd, J = 5.9, 2.0 Hz, 1H), 4.27 (apparent d, J = 6.0 Hz, 2H), 4.16 (slightly broadened apparent s, 1H), 3.94 (m, 1H), 3.88−3.72 (m, 2H), 3.81 (s, 3H), 3.80 (s, 3H), 0.89 (s, 9H), 0.87 (s, 9H), 0.06 (apparent s, 6H), 0.05 (s, 3H), 0.01 (s, 3H); ^1H NMR signals for minor rotamer (∼15%) appeared as broadened peaks at δ 7.11, 4.86, and 4.78;

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^{13}C NMR (75 MHz, $CDCl_3$) δ 160.5 (s), 158.5 (s), 155.9 (s), 144.6 (o), 130.2 (o), 119.1 (s), 103.7 (o), 99.3 (o), 98.5 (o), 78.1 (o), 67.1 (o), 64.8 (o), 60.8 (t), 55.4 (o), 55.2 (o), 40.8 (t), 25.9 (o), 25.8 (o), 18.3 (s), 18.2 (s), −4.8 (o), −4.9 (o), −5.2 (o), −5.3 (o); HRMS (FAB) m/z calcd for $C_{28}H_{48}NO_7Si_2$ $(M - H)^+$ 566.2969, found 566.2989.[67]

*4-O-tert-Butyldimethylsilyl-3-O-(N-2,4-dimethoxybenzyl)-carbamoyl-6-O-p-toluenesulfonyl-D-galactal (**31j**).* To a solution of alcohol **30** (192 mg, 0.389 mmol) in DMF (1 mL) was added imidazole (158 mg, 2.23 mmol), followed by *tert*-butyldimethylsilyl chloride (173 mg, 1.17 mmol). After stirring for 21 h at room temperature, additional imidazole (158 mg, 2.23 mmol) and *tert*-butyldimethylsilyl chloride (173 mg, 1.17 mmol) were added, and stirring was continued for 3 days. The reaction mixture was diluted with CH_2Cl_2 (10 mL) and washed with satd aq $NaHCO_3$ (10 mL) and brine (10 mL). The aqueous layers were back-extracted with CH_2Cl_2 (10 mL), and the combined organic layers were dried ($MgSO_4$), filtered, and concentrated. The crude was chromatographed (30 → 40% EtOAc/hexanes, 125 mL SiO_2), affording silyl ether **31j** (183 mg, 77%) as a light yellow oil: R_f = 0.67 (60% EtOAc/hexanes); IR (thin film) 3456, 3407, 1731, 1715, 1699, 1645, 1614, 1591 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.77 (apparent d, J = 8.1 Hz, 2H), 7.29 (apparent d, J = 8.0 Hz, 2H), 7.16 (d, J = 8.1 Hz, 1H), 6.51−6.38 (m, 2H), 6.11 (d, J = 6.0 Hz, 1H), 5.15 (apparent t, J = 4.2 Hz, 1H), 5.06 (t, J = 5.6 Hz, 1H), 4.74 (apparent t, J = 5.4 Hz, 1H), 4.44 (dd, J = 11.0, 8.7 Hz, 1H), 4.33−4.06 (m, 5H), 3.84 (s, 3H), 3.81 (s, 3H), 2.42 (s, 3H), 0.79 (s, 9H), 0.01 (apparent s, 6H); ^{1}H NMR signals for minor rotamer (∼15%) appeared as broadened peaks at δ 7.07, 6.18, and 4.83; ^{13}C NMR (75 MHz, $CDCl_3$) δ 160.6 (s), 158.6 (s), 155.5 (s), 144.7 (s), 144.3 (o), 133.1 (s), 130.4 (o), 129.8 (o), 128.0 (o), 119.0 (s), 103.9 (o), 99.2 (o), 98.6 (o), 74.8 (o), 67.1 (t), 66.4 (o), 64.4 (o), 55.4 (o), 55.3 (o), 40.6 (t), 25.6 (o), 21.6 (o), 17.9 (s), −5.1 (o), −5.3 (o); HRMS (FAB) m/z calcd for $C_{29}H_{40}NO_9SiS$ $(M - H)^+$ 606.2193, found 606.2172.[67]

General Procedure for Oxidative Removal of the *N*-2,4-Dimethoxylbenzyl Protecting Group. To a solution of 2,4-dimethoxybenzyl carbamate (1.0 equiv, ∼0.1−0.2 M) in $CHCl_3/H_2O$ (10/1) at 25 °C was added 2,3-dichloro-5,6-dicyanobenzoquinone (3.0 equiv), and the heterogeneous mixture was stirred vigorously. The reaction was monitored closely by TLC to ensure that a transiently formed bisaminal **32** (not isolated, but the structure was inferred by analogy to a fully characterized intermediate isolated previously in the glucal series[24]) was fully hydrolyzed to the desired primary carbamate. Full conversion to the primary carbamate was typically complete within 1−4 h. The reaction mixture was diluted with CH_2Cl_2 and washed twice with satd aq $NaHCO_3$. The organic layer was dried ($MgSO_4$), filtered, and concentrated, and the crude product was chromatographed (SiO_2, EtOAc/hexanes), providing the primary carbamate product.

*3-O-Carbamoyl-4,6-di-O-acetyl-D-galactal (**14c**).* Prepared from **31c** (1.48 g, 3.48 mmol) following the general procedure in $CHCl_3/H_2O$ (25 mL/2.5 mL) for 2 h, enabling hydrolysis of bisaminal intermediate **32c**. Using 40% EtOAc/hexanes and eluting twice, the bisaminal **32c** ran slightly below the final product **14c** on a SiO_2-coated TLC plate. Chromatography (60% EtOAc/hexanes, 50 mL SiO_2), provided **14c** as a white crystalline solid (0.858 g, 90%): mp 86−88 °C; R_f = 0.63 (60% EtOAc/hexanes); IR (thin film) 3475, 3370, 3198, 1745, 1730 (shoulder), 1652, 1603 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.45 (d, J = 6.0 Hz, 1H, H1), 5.50−5.42 (m, 2H, H3, H4), 4.94 (br s, 2H, NH_2), 4.78 (ddd, J = 6.3, 2.1, 2.1 Hz, 1H, H2), 4.38−4.31 (m, 1H, H5), 4.32−4.18 (m, 2H, H6), 2.14 (s, 3H), 2.10 (s, 3H),; ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.6 (s, $C(O)CH_3$), 170.1 (s, $C(O)CH_3$), 155.8 (s, $OC(O)NH_2$), 145.2 (o, C1), 99.0 (o, C2), 72.7 (o, C5), 64.5 (o, C3), 64.2 (o, C4), 61.9 (t, C6), 20.73 (o, $C(O)CH_3$), 20.66 (o, $C(O)CH_3$); HRMS (FAB) m/z calcd for $C_{11}H_{15}NO_7Na$ $(M + Na)^+$ 296.0746, found 296.0748. Additional details on distinguishing the C3 and C4 resonances of **14c** by ^{1}H/^{13}C HMBC and on coupling constant analysis using ^{1}H/^{13}C coupled HSQC with third-channel homonuclear ^{1}H decoupling are in the Supporting Information.

*3-O-Carbamoyl-4,6-di-O-chloroacetyl-D-galactal (**14g**).* Deprotection of *N*-(2,4-dimethoxybenzyl) carbamate **31g** (313 mg, 0.433 mmol) was achieved using the general procedure in $CHCl_3/H_2O$ (7 mL/0.7 mL) during 3 h 30 min. Chromatography (50% EtOAc/hexanes, 125 mL SiO_2) provided primary carbamate **14g** (99.2 mg, 93%) as a clear, colorless oil, which gave a white solid upon standing in the freezer (−20 °C): mp 105−107.5 °C; R_f = 0.15 (40% EtOAc/hexanes); IR (ATR) 3493, 3386, 1760 (shoulder), 1722, 1652, 1594 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.45 (dd, J = 6.3, 1.5 Hz, 1H, H1), 5.51 (m, 2H, H3, H4, with H3 slightly upfield of H4), 4.81 (ddd, J = 6.3, 2.9, 1.3 Hz, 1H, H2), 4.73 (br s, 2H, NH_2), 4.40 (AB of ABX, J_{AB} = 9.7 Hz, J_{AX} = 7.0 Hz, J_{BX} = 3.7 Hz, $\Delta\nu_{AB}$ = 38.0 Hz, 2H, H6), 4.40 (m, 1H, H5), 4.15 (apparent s, 2H, $C(O)CH_2Cl$), 4.12 (apparent s, 2H, $C(O)CH_2Cl$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 167.0 (s, $C(O)CH_2Cl$), 166.7 (s, $C(O)CH_2Cl$), 155.5 (s, $C(O)NH_2$), 145.3 (o, C1), 98.9 (o, C2), 72.1 (o, C5), 66.0 (o, C4), 64.3 (o, C3), 63.1 (t, C6), 40.6 (t, 2 × $C(O)CH_2Cl$); HRMS (FAB) m/z calcd for $C_{11}H_{13}NO_7{}^{35}Cl_2Na$ $(M + Na)^+$ 363.9967, found 363.9979.

*3-O-Carbamoyl-4O-chloroacetyl-6-O-p-toluenesulfonyl-D-galactal (**14h**).* Oxidative removal of the *N*-(2,4-dimethoxybenzyl) protecting group from carbamate **31h** (129 mg, 0.226 mmol) followed the general procedure in $CHCl_3/H_2O$ (5 mL/0.5 mL) during 4 h. Chromatography (50 → 55 → 60% EtOAc/hexanes, 60 mL SiO_2) yielded primary carbamate **14h** (86.7 mg, 91%): R_f = 0.16 (40% EtOAc/hexanes); IR (ATR) 3491, 3388, 1765 (shoulder), 1725, 1652, 1598 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.79 (apparent d, J = 8.3 Hz, 2H, H_o), 7.37 (apparent d, J = 8.0 Hz, 2H, H_m), 6.35 (dd, J = 6.3, 1.5 Hz, 1H, H1), 5.49−5.42 (m, 2H, H3, H4), 4.80 (br s, 2H, NH_2), 4.76 (ddd, J = 6.3, 2.9, 1.3 Hz, 1H, H2), 4.36 (dddd, J = 7.1, 5.3, 1.9, 1.2 Hz, 1H, H5), 4.22 (AB of ABX, J_{AB} = 10.5 Hz, J_{AX} = 7.1 Hz, J_{BX} = 5.1 Hz, $\Delta\nu_{AB}$ = 25.8 Hz, 2H, H6), 4.06 (AB, J_{AB} = 15.0 Hz, $\Delta\nu_{AB}$ = 9.7 Hz, 2H, CH_2Cl), 2.46 (s, 3H, Ar-CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.4 (s, $OC(O)CH_2Cl$), 155.5 (s, $OC(O)NH_2$), 145.3 (s), 145.1 (o, C1), 132.2 (s), 130.0 (o, C_m), 128.0 (o, C_o), 99.0 (o, C2), 72.0 (o, C5), 66.4 (t, C6), 65.8 (o, C4), 64.1 (o, C3), 40.5 (t, CH_2Cl), 21.7 (o, Ar-CH_3); HRMS (FAB) m/z calcd for $C_{16}H_{18}NO_8SClNa$ $(M + Na)^+$ 442.0339, found 442.0365.

*4,6-O-Bis-tert-butyldimethylsilyl-3-O-carbamoyl-6-O-p-toluenesulfonyl-D-galactal (**14i**).* The primary carbamate group of **14i** was revealed using the general procedure for DDQ deprotection of 2,4-dimethoxybenzyl carbamate **31i** (118 mg, 0.207 mmol). The conversion occurred over 4 h 30 min, and chromatography (15 → 20 → 25% EtOAc/hexanes, 125 mL SiO_2) provided primary carbamate **14i** (49.3 mg, 57%) as a white solid: R_f = 0.37 (20% EtOAc/hexanes); IR (thin film) 3508, 3348, 3272, 3185, 1737, 1731, 1715, 1651, 1644, 1599 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.35 (dd, J = 6.2, 1.5 Hz, 1H, H1), 5.26 (dddd, J = 4.5, 3.0, 1.3, 1.3 Hz, 1H, H3), 4.76 (br s, 2H, NH_2), 4.67 (ddd, J = 6.2, 3.2, 1.0 Hz, 1H, H2), 4.20 (ddd, J = 3.8, 2.6, 0.9 Hz, 1H, H4), 3.97 (dddd, J = 6.8, 5.7, 2.5, 1.0 Hz, 1H, H5), 3.82 (AB of ABX, J_{AB} = 10.8 Hz, J_{AX} = 7.2 Hz, J_{BX} = 5.8 Hz, $\Delta\nu_{AB}$ = 14.1 Hz, 2H, H6), 0.91 (s, 9H, $SiC(CH_3)_3$), 0.90 (s, 9H, $SiC(CH_3)_3$), 0.10 (apparent s, 6H, $SiCH_3$), 0.07 (apparent s, 6H, $SiCH_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 156.4 (s, $OC(O)NH_2$), 145.0 (o, C1), 98.7 (o, C2), 78.2 (o, C5), 67.4 (o, C3), 64.9 (o, C4), 60.6 (t, C6), 25.9 (o, $SiC(CH_3)_3$), 25.8 (o, $SiC(CH_3)_3$), 18.3 (s, $SiC(CH_3)_3$), 18.2 (s, $SiC(CH_3)_3$), −4.7 (o, $SiCH_3$), −4.9 (o, $SiCH_3$), −5.2 (o, $SiCH_3$), −5.3 (o, $SiCH_3$); HRMS (FAB) m/z calcd for $C_{19}H_{38}NO_5Si_2$ $(M - H)^+$ 416.2289, found 416.2315.[67]

*4O-tert-Butyldimethylsilyl-3-O-carbamoyl-6-O-p-toluenesulfonyl-D-galactal (**14j**).* Following the general procedure for DDQ-mediated *N*-deprotection, 2,4-dimethoxybenzyl carbamate **31j** (153 mg, 0.251 mmol) was converted over 3 h to primary carbamate **14j**, isolated after chromatography (20 → 30 → 40% EtOAc/hexanes, 120 mL SiO_2) as a clear, colorless oil (101 mg, 87%): R_f = 0.43 (40% EtOAc/hexanes); IR (thin film) 3490, 3388, 3280, 3206, 1728, 1646, 1598 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.81 (apparent d, J = 8.4 Hz, 2H, H_o), 7.35 (apparent d, J = 8.1 Hz, 2H, H_m), 6.15 (dd, J = 6.1, 0.7 Hz, 1H, H1), 5.13 (apparent t, J = 4.6 Hz, 1H, H3), 4.78

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(dd, J = 6.0, 5.1 Hz, 1H, H2), 4.65 (br s, 2H, NH_2), 4.39 (AB of ABX, J_{AB} = 11.3 Hz, J_{AX} = 8.7 Hz, J_{BX} = 2.1 Hz, $\Delta\nu_{AB}$ = 44.4 Hz, 2H, H6), 4.24−4.12 (m, 2H, H4, H5), 2.45 (s, 3H, Ar-CH_3), 0.83 (s, 9H, SiC$(CH_3)_3$), 0.07 (s, 3H, SiCH_3), 0.04 (s, 3H, SiCH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.9 (s, OC(O)NH_2), 144.8 (s), 144.5 (o, C1), 133.0 (s), 129.8 (o, C_m), 128.0 (o, C_o), 98.7 (o, C2), 74.7 (o, C5), 66.8 (t, C6), 66.2 (o, C4), 64.8 (o, C3), 25.5 (o, SiC$(CH_3)_3$), 21.6 (o, Ar-CH_3), 17.9 (s, SiC$(CH_3)_3$), −5.1 (o, SiCH_3), −5.3 (o, SiCH_3); HRMS (FAB) m/z calcd for $C_{20}H_{31}NO_7SiSNa$ $(M + Na)^+$ 480.1488, found 480.1511.

General Procedure for Glycal Amidoglycosylation. The primary carbamate (~0.2 mmol), 4 Å molecular sieves (300 wt % relative to the carbamate, stored in a 135 °C oven and flame-dried under vacuum just prior to use), $Rh_2(OAc)_4$ (0.1 equiv), and PhIO (1.8 equiv) were combined in a 10 mL round-bottom flask. 4-Penten-1-ol (5.0 equiv) was added, followed immediately by CH_2Cl_2 (2.0 mL). The mixture was well stirred, monitoring disappearance of the starting carbamate by TLC. When starting material was consumed (reaction times 3−18 h), the reaction mixture was filtered through a tightly packed pad of Celite, rinsing with EtOAc (75 mL). The filtrate was concentrated (rotary evaporator then high vacuum overnight to remove excess 4-penten-1-ol). The crude was analyzed by ^{1}H NMR and, in some cases, ^{13}C NMR for determination of the anomeric ratio, the ratio of amidoglycosylation product to C3-oxidation byproduct, and any remaining starting material, as reported in Table 2. The crude material was purified by chromatography (SiO_2, EtOAc/hexanes).

Amidoglycosylation of Gulal 3-carbamates 11 with 4-Penten-1-ol Acceptor. *4-Pentenyl 2-Amino-2-N,3-O-carbonyl-2-deoxy-4,6-O-isopropylidene-D-gulopyranosides (**15aa**).* Starting from primary carbamate **11a** (50.1 mg, 0.219 mmol), following the general amidoglycosylation procedure, and chromatography (45 → 50 → 55% EtOAc/hexanes) provided **15aa-*β*** (45.2 mg, 66%) and a few mixed fractions containing both **15aa-*β*** and **15aa-*α***. Additional chromatography gave a small amount of pure **15aa-*α*** for full characterization. Data for the major product **15aa-*β***: R_f = 0.57 (60% EtOAc/hexanes); IR (thin film) 3296, 3071, 1770, 1640 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.81 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H, H4′), 5.69 (s, 1H, NH), 5.12−4.91 (m, 2H, H5′), 4.53 (dd, J = 6.5, 1.2 Hz, 1H, H3), 4.35 (d, J = 7.8 Hz, 1H, H1), 4.18 (apparent s, 1H, H4), 4.14 (dd, J = 13.1, 2.4 Hz, 1H, H6a), 4.07−3.92 (m, 2H, H6b, H1′a), 3.57 (dd, J = 7.4, 7.4 Hz, 1H, H2), 3.53 (m, 1H, H5), 3.44 (ddd, J = 9.4, 7.0, 7.0 Hz, 1H, H1′b), 2.12 (apparent q, J = 7.1 Hz, 2H, H3′), 1.72 (apparent pentet of d, J = 7.0, 2.1 Hz, 2H, H2′), 1.49 (s, 3H, C$(CH_3)_2$); 1.44 (s, 3H, C$(CH_3)_2$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.1 (s, OC(O)NH), 137.9 (o, C4′), 115.0 (t, C5′), 103.2 (o, C1), 99.0 (s, C$(CH_3)_2$), 78.2 (o, C3), 69.4 (t, C1′), 66.7 (o, C5), 63.7 (o, C4), 62.0 (t, C6), 52.7 (o, C2), 30.1 (t, C3′), 28.9 (o, C$(CH_3)_2$), 28.5 (t, C2′), 18.5 (o, C$(CH_3)_2$); HRMS (FAB) m/z calcd for $C_{15}H_{24}NO_6$ $(M + H)^+$ 314.1604, found 314.1619. A NOESY study of the major product (see the Supporting Information) indicated an NOE contact between H1 and H5, consistent with the β-anomeric stereochemistry in **15aa-*β***.

Data for the minor product **15aa-*α***: R_f = 0.48 (60% EtOAc/hexanes); IR (thin film) 3310, 1767, 1745, 1641 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.80 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H), 5.15 (d, J = 3.3 Hz, 1H), 5.11−4.92 (m, 3H), 4.61 (dd, J = 7.9, 2.7 Hz, 1H), 4.24 (dd, J = 2.4, 2.4 Hz, 1H), 4.02 (AB of ABX, J_{AB} = 12.9 Hz, J_{AX} = 2.2 Hz, J_{BX} = 2.0 Hz, $\Delta\nu_{AB}$ = 43.0 Hz, 2H), 3.89 (dd, J = 8.0, 3.4 Hz, 1H), 3.85 (m, 1H), 3.82 (ddd, J = 9.7, 6.5, 6.5 Hz, 1H), 3.48 (ddd, J = 9.7, 6.5, 6.5 Hz, 1H), 2.13 (apparent q, J = 7.1 Hz, 2H), 1.70 (apparent pentet, J = 6.9 Hz, 2H), 1.48 (s, 3H), 1.42 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.8 (s), 138.0 (o), 115.0 (t), 98.9 (s), 95.1 (o), 74.4 (o), 68.2 (t), 63.7 (o), 63.5 (t), 61.4 (o), 50.8 (o), 30.1 (t), 29.1 (o), 28.5 (t), 18.7 (o); HRMS (FAB) m/z calcd for $C_{15}H_{24}NO_6$ $(M + H)^+$ 314.1604, found 314.1606.

*4-Pentenyl 2-Amino-2-N,3-O-carbonyl-2-deoxy-4,6-di-O-benzyl-D-gulopyranosides (**15ba**).* Reaction of primary carbamate **11b** (52.6 mg, 0.142 mmol), following the general amidoglycosylation procedure, and chromatography (40 → 50% EtOAc/hexanes) provided anomers **15ba-*β*** (35.4 mg, 55%) and **15ba-*α*** (4.0 mg, 6%), both as colorless oils. Data for the major product **15ba-*β***: R_f = 0.41 (40% EtOAc/hexanes); IR (thin film) 3317, 3064, 3031, 1765, 1640 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.40−7.22 (m, 10H, Ar−H), 5.79 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H, H4′), 5.53 (br s, 1H, NH), 5.08−4.92 (m, 2H, H5′), 4.66 (dd, J = 6.5, 2.3 Hz, 1H, H3), 4.59 (AB, J_{AB} = 11.9 Hz, $\Delta\nu_{AB}$ = 30.5 Hz, 2H, OCH_2Ph), 4.50 (AB, J_{AB} = 11.9 Hz, $\Delta\nu_{AB}$ = 12.7 Hz, 2H, OCH_2Ph), 4.37 (d, J = 7.5 Hz, 1H, H1), 3.98−3.85 (m, 2H, H5, H1′a), 3.79 (br apparent s, 1H, H4), 3.67 (AB of ABX, J_{AB} = 9.7 Hz, J_{AX} = 6.5 Hz, J_{BX} = 5.9 Hz, $\Delta\nu_{AB}$ = 16.4 Hz, 2H, H6), 3.55 (dd, J = 7.0, 7.0 Hz, 1H, H2), 3.46 (ddd, J = 9.5, 6.8, 6.8 Hz, 1H, H1′b), 2.10 (apparent q, J = 7.2 Hz, 2H, H3′), 1.69 (apparent pentet, J = 7.1 Hz, 2H, H2′); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.2 (s, OC(O)NH), 137.9 (o, C4′), 137.8 (s, C_i), 137.0 (s, C_i), 128.5 (o, C_{Ar-H}), 128.4 (o, C_{Ar-H}), 128.2 (o, C_{Ar-H}), 127.7 (o, C_{Ar-H}), 127.6 (o, C_{Ar-H}), 115.0 (t, C5′), 103.5 (o, C1), 76.1 (o, C3), 73.4 (t, OCH_2Ph), 73.23 (t, OCH_2Ph), 73.15 (o, C5), 70.1 (o, C4), 69.3 (t, C1′), 68.2 (t, C6), 53.4 (o, C2), 30.1 (t, C3′), 28.6 (t, C2′); HRMS (FAB) m/z calcd for $C_{26}H_{30}NO_6$ $(M - H)^+$ 452.2073, found 452.2080.[67]

Data for the minor product **15ba-*α***: R_f = 0.26 (40% EtOAc/hexanes); IR (thin film) 3302, 3063, 3031, 1765, 1640 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.40−7.23 (m, 10H, Ar−H), 5.78 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H, H4′), 5.08−4.90 (m, 3H, H5′, NH), 4.87 (d, J = 3.6 Hz, 1H, H1), 4.74 (dd, J = 7.8, 3.5 Hz, 1H, H3), 4.63 (AB, J_{AB} = 11.7 Hz, $\Delta\nu_{AB}$ = 27.9 Hz, 2H, OCH_2Ph), 4.52 (AB, J_{AB} = 12.0 Hz, $\Delta\nu_{AB}$ = 12.4 Hz, 2H, OCH_2Ph), 4.24 (ddd, J = 5.6, 5.6, 3.5 Hz, 1H, H5), 3.98 (dd, J = 3.3, 3.3 Hz, 1H, H4), 3.91 (dd, J = 7.9, 3.6 Hz, 1H, H2), 3.78 (ddd, J = 9.5, 6.5, 6.5 Hz, 1H, H1′a), 3.64 (AB of ABX, J_{AB} = 9.6 Hz, J_{AX} = 5.9 Hz, J_{BX} = 5.8 Hz, $\Delta\nu_{AB}$ = 15.8 Hz, 2H, H6), 3.39 (ddd, J = 9.4, 6.5, 6.5 Hz, 1H, H1′b), 2.09 (apparent q, J = 6.9 Hz, 2H, H3′), 1.66 (apparent pentet, J = 6.9 Hz, 2H, H2′); ^{13}C NMR (75 MHz, $CDCl_3$) δ 159.0 (s, OC(O)NH), 138.0 (o, C4′), 137.9 (s, C_i), 137.3 (s, C_i), 128.6 (o, C_{Ar-H}), 128.4 (o, C_{Ar-H}), 128.2 (o, C_{Ar-H}), 128.0 (o, C_{Ar-H}), 127.7 (o, C_{Ar-H}), 127.6 (o, C_{Ar-H}), 115.0 (t, C5′), 94.7 (o, C1), 74.0 (o, C3), 73.4 (two overlapping resonances, 2t, 2 × OCH_2Ph), 71.7 (o, C4), 68.5 (t, C6), 68.2 (o, C5), 67.8 (t, C1′), 51.6 (o, C2), 30.2 (t, C3′), 28.6 (t, C2′); HRMS (FAB) m/z calcd for $C_{26}H_{32}NO_6$ $(M + H)^+$ 454.2230, found 454.2245.

*4-Pentenyl 2-Amino-2-N,3-O-carbonyl-2-deoxy-4,6-di-O-acetyl-D-gulopyranosides (**15ca**).* The reaction was carried out twice (Run 1, 51.6 mg, 0.189 mmol of **11c**; Run 2, 50.0 mg, 0.183 mmol **11c**), using the general amidoglycosylation procedure. Chromatography (50% EtOAc/hexanes) provided **15ca-*β*** and **15ca-*α*** separately as oils. The yield of the major β anomer was 62% (run 1) and 69% (run 2). Data for the major product **15ca-*β***: R_f = 0.35 (50% EtOAc/hexanes); IR (thin film) 3322, 1774, 1748, 1640 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.92 (br s, 1H, NH), 5.79 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H, H4′), 5.20 (apparent br s, 1H, H4), 5.08−4.93 (m, 2H, H5′a,b), 4.58 (dd, J = 6.5, 2.1 Hz, 1H, H3), 4.43 (d, J = 7.4 Hz, 1H, H1), 4.20 (AB of ABX, J_{AB} = 11.3 Hz, J_{AX} = 7.0 Hz, J_{BX} = 6.0 Hz, $\Delta\nu_{AB}$ = 19.3 Hz, 2H, H6a,b), 4.07 (ddd, J = 6.4, 6.4, 1.7 Hz, 1H, H5), 3.91 (ddd, J = 9.5, 6.6, 6.6 Hz, 1H, H1′a), 3.53 (dd, J = 7.0, 7.0 Hz, 1H, H2), 3.51 (ddd, J = 9.8, 6.8, 6.8 Hz, 1H, H1′b), 2.20−2.05 (m, 2H, H3′a,b), 2.12 (s, 3H, C(O)CH_3), 2.05 (s, 3H, C(O)CH_3), 1.71 (apparent pentet, J = 7.1 Hz, 2H, H2′a,b); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.4 (s, C(O)CH_3), 169.6 (s, C(O)CH_3), 157.7 (s, OC(O)NH), 137.7 (o, C4′), 115.1 (t, C5′), 103.6 (o, C1), 76.0 (o, C3), 70.5 (o, C5), 69.6 (t, C1′), 64.1 (o, C4), 61.4 (t, C6), 53.0 (o, C2), 30.0 (t, C3′), 28.6 (t, C2′), 20.6 (o, two overlapping signals, C(O)CH_3); HRMS (FAB) m/z calcd for $C_{16}H_{24}NO_8$ $(M + H)^+$ 358.1502, found 358.1512.

Data for the minor product **15ca-*α***: R_f = 0.20 (50% EtOAc/hexanes); IR (thin film) 3356, 1765 (shoulder), 1744 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.80 (dddd, J = 17.0, 10.2, 6.7, 6.7 Hz, 1H, H4′), 5.30 (apparent t, J = 2.3 Hz, 1H, H4), 5.11−4.94 (m, 3H, NH, H5′a,b), 4.90 (d, J = 4.3 Hz, 1H, H1), 4.60 (dd, J = 7.2, 2.7 Hz, 1H, H3), 4.38 (ddd, J = 6.2, 6.2, 2.4 Hz, 1H, H5), 4.16 (AB of ABX, J_{AB} = 11.5 Hz, J_{AX} = 6.9 Hz, J_{BX} = 5.6 Hz, $\Delta\nu_{AB}$ = 19.9 Hz, 2H, H6a,b), 3.87 (dd, J = 7.2, 4.3 Hz, 1H, H2), 3.78 (ddd, J = 9.5, 6.5, 6.5 Hz, 1H, H1′),

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3.43 (ddd, J = 9.5, 6.4, 6.4 Hz, 1H, H1′b), 2.20−2.08 (m, 2H, H3′a,b), 2.14 (s, 3H, C(O)CH_3), 2.07 (s, 3H, C(O)CH_3), 1.72 (apparent pentet, J = 6.9 Hz, 2H, H2′a,b); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.4 (s, C(O)CH_3), 169.4 (s, C(O)CH_3), 158.6 (s, OC(O)NH), 137.8 (o, C4′), 115.2 (t, C5′), 94.9 (o, C1), 73.2 (o, C3), 67.9 (t, C1′), 65.0 (o, C4), 64.2 (o, C5), 61.9 (t, C6), 50.5 (o, C2), 30.2 (t, C3′), 28.4 (t, C2′), 20.7 (o, two overlapping signals, C(O)CH_3); HRMS (FAB) m/z calcd for $C_{16}H_{24}NO_8$ $(M + H)^+$ 358.1502, found 358.1525. A comparative NOESY study of the diastereomers was used to assign C-1 configuration of **15ca** anomers. The NOESY spectrum of **15ca-*β*** showed a correlation between H1 (δ 4.43) and H5 (δ 4.07), while a NOESY cross peak was absent between the corresponding **15ca-*α*** resonances (H1 at δ 4.90 and H5 at δ 4.38). The NOESY spectra are included in the Supporting Information.

Amidoglycosylation of Allal 3-Carbamates 12 with 4-Penten-1-ol Acceptor. *4-Pentenyl 2-Amino-2-N,3-O-carbonyl-2-deoxy-4,6-O-isopropylidene-β-D-allopyranoside (**16aa**).* Starting from allal carbamate **12a**[20] (77.9 mg, 0.340 mmol), the general amidoglycosylation procedure, followed by chromatography (40 → 50 → 60% EtOAc/hexanes, 60 mL SiO_2), provided a single anomer **16aa-*β*** (79.2 mg, 74%) as a clear oil. Data for the amidoglycosylation product **16aa-*β***: R_f = 0.32 (65% EtOAc/hexanes); IR (thin film) 3293, 1757, 1641 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.28 (s, 1H, NH), 5.81 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H, H4′), 5.09−4.95 (m, 2H, H5′), 4.83 (dd, J = 7.3, 3.4 Hz, 1H, H3), 4.55 (d, J = 4.7 Hz, 1H, H1), 4.16 (dd, J = 9.8, 3.4 Hz, 1H, H4), 3.98 (dd, J = 9.5, 4.3 Hz, 1H, H6a), 3.90−3.67 (m, 4H, H2, H5, H6b, H1′a), 3.47 (ddd, J = 9.5, 6.5, 6.5 Hz, 1H, H1′b), 2.14 (apparent q, J = 7.1 Hz, 2H, H3′), 1.70 (apparent pentet, J = 7.0 Hz, 2H, H2′), 1.51 (s, 3H, C$(CH_3)_2$); 1.46 (s, 3H, C$(CH_3)_2$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 159.0 (s, OC(O)NH), 137.7 (o, C4′), 115.1 (t, C5′), 101.1 (o, C1), 100.2 (s, C$(CH_3)_2$), 73.9 (o, C3), 69.0 (t, C1′), 68.0 (o, C4), 63.5 (o, C5), 62.7 (t, C6), 55.7 (o, C2), 30.1 (t, C3′), 28.8 (o, C$(CH_3)_2$), 28.7 (t, C2′), 18.8 (o, C$(CH_3)_2$); HRMS (FAB) m/z calcd for $C_{15}H_{24}NO_6$ $(M + H)^+$ 314.1604, found 314.1592.

*4-Pentenyl 2-Amino-2-N,3-O-carbonyl-2-deoxy-4,6-di-O-benzyl-β-D-allopyranoside (**16ba**).* Starting from allal 3-carbamate **12b** (44.7 mg, 0.121 mmol), the general amidoglycosylation procedure, followed by chromatography (40 → 50 → 60 → 70% EtOAc/hexanes, 50 mL SiO_2), provided **16ba-*β*** (36.5 mg, 67%). A trace amount of dihydropyranone **20b** (not isolated) was identified in the crude reaction mixture by comparison to ^{1}H NMR data for **20b** formed in much larger amounts during reactions of 4,6-di-*O*-benzyl glucal 3-carbamate **13b** (see Table 2, entries 9 and 10).[24,69] Data for the amidoglycosylation product **16ba-*β***: R_f = 0.28 (40% EtOAc/hexanes); IR (thin film) 3298, 3062, 3030, 1761, 1639 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.39−7.22 (m, 10H, ArH), 6.14 (br s, 1H, NH), 5.76 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H, H4′), 5.07−4.92 (m, 2H, H5′), 4.89 (dd, J = 7.7, 2.8 Hz, 1H, H3), 4.62 (AB, J_{AB} = 11.2 Hz, $\Delta\nu_{AB}$ = 43.1 Hz, 2H, OCH_2Ph), 4.55 (AB, J_{AB} = 12.1 Hz, $\Delta\nu_{AB}$ = 23.3 Hz, 2H, OCH_2Ph), 4.55 (d, J = 5.5 Hz, 1H, H1), 4.07−3.93 (m, 2H, H4, H5), 3.86 (ddd, J = 9.4, 6.6, 6.6 Hz, 1H, H1′a), 3.75−3.60 (m, 3H, H2, H6), 3.40 (ddd, J = 9.4, 6.7, 6.7 Hz, 1H, H1′b), 2.03 (apparent q, J = 6.9 Hz, 2H, H3′), 1.61 (apparent pentet, J = 7.0 Hz, 2H, H2′); ^{13}C NMR (75 MHz, $CDCl_3$) δ 159.0 (s, OC(O)NH), 137.91 (o, C4′),* 137.87 (s, C_{Ph}),* 137.3 (s, C_i), 128.4 (o, C_{Ph}), 128.3 (o, C_{Ph}), 127.9 (o, C_{Ph}), 127.71 (o, C_{Ph}), 127.66 (o, C_{Ph}), 114.9 (t, C5′), 100.8 (o, C1), 73.8 (o, C3), 73.3 (t, OCH_2Ph), 72.5 (o, C5), 71.9 (t, OCH_2Ph), 70.8 (o, C4), 69.3 (t, C6), 68.8 (t, C1′), 55.3 (o, C2), 30.0 (t, C3′), 28.6 (t, C2′); *these ^{13}C resonances were clearly resolved upon reprocessing the FID with lb = 0; HRMS (FAB) m/z calcd for $C_{26}H_{32}NO_6$ $(M + H)^+$ 454.2230, found 454.2216.

For the amidoglycosylation reaction of allal 3-carbamate **12e** with 4-penten-1-ol (Table 2, entry 5) and for the synthesis and amidoglycosylation reactions of glucal 3-carbamates **13** with 4-penten-1-ol (Table 2, entries 7−16), see ref 24.

Amidoglycosylation of Galactal 3-Carbamates 14 with 4-Penten-1-ol Acceptor. *1,5-Anhydro-2-deoxy-4,6-O-isopropylidene-D-threo-hex-1-en-3-ulose (**19a**).* Beginning from acetonide-protected galactal 3-carbamate **14a** (34 mg, 0.15 mmol), the general amidoglycosylation procedure, followed by chromatography (50 → 60 → 70 → 80% EtOAc/hexanes), provided dihydropyranone **19a** (20.8 mg, 76%). Data for dihydropyranone **19a**: R_f = 0.27 (60% EtOAc/hexanes); IR (thin film) 1664, 1599 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.51 (d, J = 6.2 Hz, 1H), 5.53 (dd, J = 6.2, 1.2 Hz, 1H), 4.25−4.10 (m, 4H), 1.56 (s, 3H), 1.46 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 186.6 (s), 164.1 (o), 105.3 (o), 99.1 (s), 73.0 (o), 68.9 (o), 61.4 (t), 29.1 (o), 18.4 (o); HRMS (FAB) m/z calcd for $C_9H_{13}O_4$ $(M + H)^+$ 185.0814, found 185.0807.

*1,5-Anhydro-2-deoxy-4,6-O-di-tert-butylsilylene-D-threo-hex-1-en-3-ulose (**19d**).* Galactal carbamate **14d** (50 mg, 0.15 mmol) was subjected to the general amidoglycosylation procedure. The crude material was chromatographed (30% EtOAc/hexanes), providing **19d** (21 mg, 49%). Data for dihydropyranone **19d**: R_f = 0.53 (50% EtOAc/hexanes); IR (thin film) 1683, 1600 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.43 (d, J = 6.1 Hz, 1H), 5.50 (dd, J = 6.1, 1.3 Hz, 1H), 4.41 (partially obscured AB of ABX, J_{AB} = 13.0 Hz, J_{AX} = 1.9 Hz, J_{BX} = 1.6 Hz, $\Delta\nu_{AB}$ = 17.1 Hz, 2H), 4.34 (m, 1H), 4.24 (m, 1H), 1.08 (s, 9H), 1.00 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 187.9 (s), 163.2 (o), 105.0 (o), 78.4 (o), 72.7 (o), 65.5 (t), 27.4 (o), 26.7 (o), 23.3 (s), 20.7 (s); HRMS (FAB) m/z calcd for $C_{14}H_{25}O_4Si$ $(M + H)^+$ 285.1522, found 285.1539.

*4-Pentenyl 2-amino-2-N,3-O-carbonyl-2-deoxy-4,6-di-O-benzyl-α-D-talopyranoside (**18ba**) and 1,5-Anhydro-2-deoxy-4,6-di-O-benzyl-D-threo-hex-1-en-3-ulose (**19b**).* Treatment of dibenzyl galactal 3-carbamate **14b** (50.4 mg, 0.137 mmol) under the general amidoglycosylation reaction conditions during 4 h, followed by chromatography (20 → 40% EtOAc/hexanes, 40 mL SiO_2) provided **18ba** (8.6 mg, 14%) as a single anomer and dihydropyranone **19b** (38 mg, 61%). Data for amidoglycosylation product **18ba**: R_f = 0.13 (50% EtOAc/hexanes); IR (thin film) 3317, 3064, 3031, 1762, 1639 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.38−7.25 (m, 10H), 5.77 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H), 5.22 (br s, 1H), 5.05−4.92 (m, 2H), 4.90 (d, J = 2.9 Hz, 1H), 4.89 (d, J = 10.8 Hz, 1H), 4.82 (dd, J = 8.3, 4.5 Hz, 1H), 4.48 (d, J = 11.3 Hz, 1H), 4.44 (AB, J_{AB} = 12.5 Hz, $\Delta\nu_{AB}$ = 15.9 Hz, 2H), 4.01−3.93 (m, 2H), 3.89 (dd, J = 8.3, 2.0 Hz, 1H), 3.73 (ddd, J = 9.5, 6.6, 6.6 Hz, 1H), 3.62−3.52 (m, 2H), 3.39 (ddd, J = 9.4, 6.6, 6.6 Hz, 1H), 2.07 (m, 2H), 1.64 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.7, 137.83,* 137.82,* 137.3, 128.9, 128.41,* 128.38,* 128.0, 127.8, 127.7, 115.0, 97.0, 75.8, 73.7, 73.5, 71.0, 68.8, 68.6, 67.8, 54.5, 30.2, 28.6, *these ^{13}C NMR signals resolved upon processing of the FID with lb = 0; HRMS (FAB) m/z calcd for $C_{26}H_{32}NO_6$ $(M + H)^+$ 454.2230, found 454.2202.

Data for dihydropyranone **19b**:[69a] R_f = 0.43 (40% EtOAc/hexanes); IR (thin film) 3063, 3031, 1680, 1596 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.42−7.20 (m, 11H), 5.44 (dd, J = 6.0, 1.2 Hz, 1H), 4.59 (AB, J_{AB} = 11.9 Hz, $\Delta\nu_{AB}$ = 72.3 Hz, 2H), 4.54 (AB, J_{AB} = 11.7 Hz, $\Delta\nu_{AB}$ = 20.8 Hz, 2H), 4.49 (apparent s, 1H), 3.92 (dd, J = 10.2, 7.1 Hz, 1H), 3.74 (dd, J = 10.2, 5.3 Hz, 1H), 3.69 (apparent s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 189.4 (s), 162.7 (o), 137.4 (s), 137.0 (s), 128.5 (o), 128.4 (o), 128.3 (o), 128.0 (o), 127.9 (o), 127.8 (o), 105.1 (o), 80.6 (o), 74.1 (o), 73.6 (t), 72.0 (t), 67.6 (t); HRMS (FAB) m/z calcd for $C_{20}H_{21}O_4$ $(M + H)^+$ 325.1440, found 325.1426.

*4-Pentenyl 2-Amino-2-N,3-O-carbonyl-2-deoxy-4,6-di-O-acetyl-α-D-talopyranoside (**18ca**) and 1,5-anhydro-2-deoxy-4,6-di-O-acetyl-D-threo-hex-1-en-3-ulose (**19c**).* Starting from galactal 3-carbamate **14c** (50 mg, 0.18 mmol), the general amidoglycosylation procedure, followed by chromatography (60% EtOAc/hexanes), provided **18ca** (16.5 mg, 25%) and dihydropyranone **19c** (19.1 mg, 46%). Data for amidoglycosylation product **18ca**: R_f = 0.55 (90% EtOAc/hexanes); IR (thin film) 3346, 3077, 1770 (shoulder), 1749, 1640 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.80 (dddd, J = 16.9, 10.3, 6.6, 6.6 Hz, 1H, H4′), 5.78 (br s, 1H, NH), 5.45 (dd, J = 5.0, 1.7 Hz, 1H, H4), 5.10−4.95 (m, 2H, H5′), 4.90 (s, 1H, H1), 4.84 (dd, J = 7.7, 5.2 Hz, 1H, H3), 4.24−4.13 (m, 3H, H5, H6), 3.94 (d, J = 7.8 Hz, 1H, H2), 3.75 (ddd, J = 9.5, 6.6, 6.6 Hz, 1H, H1′a), 3.46 (ddd, J = 9.6, 6.5, 6.5 Hz, 1H, H1′b), 2.16 (s, 3H, C(O)CH_3), 2.13 (m, 2H, H3′), 2.07 (s, 3H, C(O)CH_3), 1.70 (apparent pentet, J = 7.0 Hz, 2H, H2′); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.5 (s, C(O)CH_3), 170.1 (s, C(O)CH_3), 158.7 (s, OC(O)NH), 137.6

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(o, C4′), 115.2 (t, C5′), 96.7 (o, C1), 70.9 (o, C3), 67.8 (t, C1′), 65.1 (o, C5), 63.7 (o, C4), 62.6 (t, C6), 53.5 (o, C2), 30.2 (t, C3′), 28.4 (t, C2′), 20.7 (o, $C(O)CH_3$), 20.5 (o, $C(O)CH_3$); HRMS (FAB) m/z calcd for $C_{16}H_{24}NO_8$ $(M + H)^+$ 358.1502, found 358.1523. Additional NMR data for **18ca** obtained in C_6D_6 solvent, including ^1H homonuclear decoupling studies and details of a NOESY study confirming the α-anomeric stereochemistry of **18ca**, can be found in the Supporting Information.

Data for dihydropyranone **19c**:[70] R_f = 0.66 (90% EtOAc/hexanes); IR (thin film) 1746, 1681, 1596 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.34 (d, J = 6.1 Hz, 1H), 5.56 (d, J = 4.5 Hz, 1H), 5.51 (dd, J = 6.0, 0.5 Hz, 1H), 4.78 (ddd, J = 7.3, 4.4, 4.4 Hz, 1H), 4.38 (AB of ABX, J_{AB} = 12.3 Hz, J_{AX} = 7.5 Hz, J_{BX} = 4.0 Hz, $\Delta\nu_{AB}$ = 22.4 Hz, 2H), 2.17 (s, 3H), 2.09 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 185.8, 170.4, 169.2, 161.9, 105.8, 77.9, 68.2, 60.6, 20.6, 20.5; HRMS (FAB) m/z calcd for $C_{10}H_{13}O_6$ $(M + H)^+$ 229.0712, found 229.0714.

*4-Pentenyl 2-amino-2-N,3-O-carbonyl-2-deoxy-4,6-di-O-chloroacetyl-α-D-talopyranoside (**18ga**) and 1,5-anhydro-2-deoxy-4,6-di-O-chloroacetyl-D-threo-hex-1-en-3-ulose (**19g**).* Using the general amidoglycosylation procedure, followed by chromatography (45 → 50% EtOAc/hexanes, 60 mL SiO_2), galactal 3-carbamate **14g** (101 mg, 0.295 mmol) provided amidoglycosylation product **18ga** (49.1 mg, 39%) as a single anomer and dihydropyranone **19g** (18.6 mg, 21%), both as clear, colorless oils. Data for amidoglycosylation product **18ga**: R_f = 0.48 (60% EtOAc/hexanes); IR (thin film) 3360, 1756 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.34 (br s, 1H), 5.80 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H), 5.50 (dd, J = 5.1, 2.7 Hz, 1H), 5.10−4.95 (m, 2H), 4.91 (apparent d, J = 1.3 Hz, 1H), 4.90 (dd, J = 7.8, 5.1 Hz, 1H), 4.43−4.21 (m, 3H), 4.18 (apparent s, 2H), 4.10 (apparent s, 2H), 3.97 (slightly br d, J = 7.8 Hz, 1H), 3.75 (ddd, J = 9.6, 6.6, 6.6 Hz, 1H), 3.48 (ddd, J = 9.6, 6.5, 6.5 Hz, 1H), 2.13 (apparent q, J = 7.1 Hz, 2H), 1.70 (apparent pentet, J = 7.0 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.9 (s), 166.8 (s), 158.9 (s), 137.6 (o), 115.3 (t), 96.6 (o), 70.6 (o), 68.0 (t), 65.7 (o), 64.7 (o), 63.8 (t), 53.4 (o), 40.5 (t), 40.4 (t), 30.1 (t), 28.3 (t); HRMS (FAB) m/z calcd for $C_{16}H_{22}NO_8{}^{35}Cl_2$ $(M + H)^+$ 426.0722, found 426.0719.

Data for dihydropyranone **19g**: R_f = 0.72 (60% EtOAc/hexanes); IR (thin film) 1761, 1686, 1597 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.36 (d, J = 6.1 Hz, 1H), 5.64 (d, J = 4.8 Hz, 1H), 5.55 (d, J = 6.1 Hz, 1H), 4.87 (ddd, J = 7.2, 4.4, 4.4 Hz, 1H), 4.53 (AB of ABX, J_{AB} = 12.3 Hz, J_{AX} = 7.3 Hz, J_{BX} = 3.9 Hz, $\Delta\nu_{AB}$ = 42.6 Hz, 2H), 4.19 (apparent s, 2H), 4.10 (apparent s, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 184.4 (s), 166.8 (s), 165.9 (s), 161.9 (o), 105.8 (o), 77.2 (o), 69.3 (o), 61.9 (t), 40.4 (t), 40.3 (t); HRMS (FAB) m/z calcd for $C_{10}H_{11}O_6{}^{35}Cl_2$ $(M + H)^+$ 296.9933, found 296.9940.

*4-Pentenyl 2-Amino-2-N,3-O-carbonyl-2-deoxy-4-O-chloroacetyl-6-O-p-toluenesulfonyl-α-D-talopyranoside (**18ha**) and 1,5-Anhydro-2-deoxy-4-O-chloroacetyl-6-O-p-toluenesulfonyl-D-threo-hex-1-en-3-ulose (**19h**).* The general procedure for amidoglycosylation was followed with galactal 3-carbamate **14h** (82.7 mg, 0.197 mmol), providing, after chromatography (40 → 50 → 60% EtOAc/hexanes, 60 mL SiO_2), a single anomer of amidoglycosylation product **18ha** (38 mg, 39%; weight and yield are corrected for ∼3 mg of remaining starting carbamate **14h** that coeluted with **18ha**) and dihydropyranone byproduct **19h** (16.3 mg, 22%). Data for amidoglycosylation product **18ha**: R_f = 0.50 (60% EtOAc/hexanes); IR (thin film) 3376, 1762 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.77 (apparent d, J = 8.3 Hz, 2H), 7.34 (apparent d, J = 8.1 Hz, 2H), 6.31 (br s, 1H), 5.79 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H), 5.47 (dd, J = 5.0, 2.5 Hz, 1H), 5.09−4.95 (m, 2H), 4.86 (s, 1H), 4.85 (dd, J = 7.6, 5.1 Hz, 1H), 4.23 (ddd, J = 6.1, 6.1, 2.6 Hz, 1H), 4.08−4.20 (m, 2H), 4.07 (obscured AB, 2H), 3.93 (d, J = 7.7 Hz, 1H), 3.71 (ddd, J = 9.6, 6.6, 6.6 Hz, 1H), 3.42 (ddd, J = 9.6, 6.4, 6.4 Hz, 1H), 2.46 (s, 3H), 2.10 (apparent q, J = 7.1 Hz, 2H), 1.67 (apparent pentet, J = 7.0 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.5 (s), 158.8 (s), 145.4 (s), 137.6 (o), 132.2 (s), 130.0 (o), 128.0 (o), 115.2 (t), 96.5 (o), 70.5 (o), 68.0 (t), 67.4 (t), 65.4 (o), 64.7 (o), 53.3 (o), 40.3 (t), 30.1 (t), 28.3 (t), 21.7 (o); HRMS (FAB) m/z calcd for $C_{21}H_{27}NO_9S^{35}Cl$ $(M + H)^+$ 504.1095, found 504.1082.

Data for dihydropyranone **19h**: R_f = 0.78 (60% EtOAc/hexanes); IR (thin film) 1772, 1686, 1597 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.79 (apparent d, J = 8.3 Hz, 2H), 7.38 (apparent d, J = 8.0 Hz, 2H), 7.29 (d, J = 6.1 Hz, 1H), 5.54 (d, J = 4.6 Hz, 1H), 5.50 (d, J = 6.2 Hz, 1H), 4.81 (ddd, J = 7.1, 4.3, 4.3 Hz, 1H), 4.30 (AB of ABX, J_{AB} = 11.4 Hz, J_{AX} = 7.3 Hz, J_{BX} = 3.9 Hz, $\Delta\nu_{AB}$ = 18.2 Hz, 2H), 4.09 (AB, J_{AB} = 15.3 Hz, $\Delta\nu_{AB}$ = 3.3 Hz, 2H), 2.47 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 184.1 (s), 165.8 (s), 161.9 (o), 145.6 (s), 132.0 (s), 130.0 (o), 128.1 (o), 105.9 (o), 77.2 (o), 69.1 (o), 65.2 (t), 40.2 (t), 21.7 (o); HRMS (FAB) m/z calcd for $C_{15}H_{16}O_7S^{35}Cl$ $(M + H)^+$ 375.0305, found 375.0320.

*4-Pentenyl 2-Amino-4,6-bis-O-tert-butyldimethylsilyl-2-N,3-O-carbonyl-2-deoxy-α-D-talopyranoside (**18ia**) and 1,5-Anhydro-2-deoxy-4,6-bis-O-tert-butyldimethylsilyl-D-threo-hex-1-en-3-ulose (**19i**).* Starting with galactal 3-carbamate **14i** (71.9 mg, 0.172 mmol), the general amidoglycosylation procedure and chromatography (5 → 15 → 25 → 40% EtOAc/hexanes, 60 mL SiO_2) provided **18ia** (27.7 mg, 32%) as a single anomer and dihydropyranone **19i** (14.8 mg, 23%). Data for amidoglycosylation product **18ia**: R_f = 0.27 (20% EtOAc/hexanes); IR (thin film) 3263, 1765 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.81 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H), 5.63 (br s, 1H), 5.08−4.92 (m, 2H), 5.02 (d, J = 5.3 Hz, 1H), 4.66 (dd, J = 9.5, 4.1 Hz, 1H), 4.21 (dd, J = 4.0, 0.9 Hz, 1H), 3.88−3.76 (m, 2H), 3.76−3.65 (m, 3H), 3.45 (ddd, J = 9.7, 6.7, 6.7 Hz, 1H), 2.11 (apparent q, J = 7.2 Hz, 2H), 1.68 (apparent pentet, J = 7.1 Hz, 2H), 0.92 (s, 9H), 0.89 (s, 9H), 0.18 (s, 3H), 0.10 (s, 3H), 0.06 (two overlapping s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.8 (s), 137.9 (o), 115.0 (t), 98.0 (o), 74.4 (o), 72.9 (o), 68.4 (t), 64.9 (o), 61.7 (t), 54.9 (o), 30.2 (t), 28.7 (t), 25.9 (o), 25.8 (o), 18.2 (s), 18.1 (s), −4.3 (o), −5.1 (o), −5.32 (o),* −5.34 (o)*; *these ^{13}C NMR signals were better resolved upon reprocessing of the FID with lb = 0; HRMS (FAB) m/z calcd for $C_{24}H_{48}NO_6Si_2$ $(M + H)^+$ 502.3020, found 502.3015.

Data for dihydropyranone **19i**: R_f = 0.68 (20% EtOAc/hexanes); IR (ATR) 1686, 1599 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.30 (d, J = 6.0 Hz, 1H), 5.35 (dd, J = 6.0, 1.3 Hz, 1H), 4.25 (ddd, J = 6.5, 6.5, 2.4 Hz, 1H), 4.02 (dd, J = 2.5, 1.4 Hz, 1H), 3.94 (apparent d, J = 6.4 Hz, 2H), 0.90 (s, 9H), 0.87 (s, 9H), 0.12 (s, 3H), 0.08 (two overlapping s, 6H), 0.07 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 191.1 (s), 162.1 (o), 104.8 (o), 82.9 (o), 69.4 (o), 60.1 (t), 25.8 (o), 25.6 (o), 18.24 (s),* 18.22 (s),* −4.8 (o), −5.4 (o, 3C); *these ^{13}C NMR resonances were resolved upon reprocessing the FID with lb = 0; HRMS (FAB) m/z calcd for $C_{18}H_{37}O_4Si_2$ $(M + H)^+$ 373.2230, found 373.2238.

*4-Pentenyl 2-Amino-4-O-tert-butyldimethylsilyl-2-N,3-O-carbonyl-2-deoxy-6-O-p-toluenesulfonyl-α-D-talopyranoside (**18ja**) and 1,5-Anhydro-2-deoxy-4-O-tert-butyldimethylsilyl-6-O-p-toluenesulfonyl-D-threo-hex-1-en-3-ulose (**19j**).* Using the general procedure for amidoglycosylation, galactal 3-carbamate **14j** (52.1 mg, 0.114 mmol) gave, after chromatography (20 → 25 → 30 → 35 → 40% EtOAc/hexanes, 40 mL SiO_2) a single anomer of **18ja** (34.0 mg, 55%) and dihydropyranone **19j** (4.6 mg, 10%). Data for amidoglycosylation product **18ja**: R_f = 0.23 (40% EtOAc/hexanes); IR (thin film) 3271, 3153, 3075, 1763, 1640, 1598 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.78 (apparent d, J = 8.3 Hz, 2H), 7.34 (apparent d, J = 8.1 Hz, 2H), 5.90 (br s, 1H), 5.80 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H), 5.08−4.94 (m, 2H), 4.79 (d, J = 3.3 Hz, 1H), 4.65 (dd, J = 9.2, 3.6 Hz, 1H), 4.30 (dd, J = 3.9, 3.9 Hz, 1H), 4.21 (AB of ABX, J_{AB} = 10.5 Hz, J_{AX} = 7.7 Hz, J_{BX} = 4.3 Hz, $\Delta\nu_{AB}$ = 28.2 Hz, 2H), 4.07 (ddd, J = 7.8, 4.0, 4.0 Hz, 1H), 3.82 (ddd, J = 9.2, 3.3, 0.9 Hz, 1H), 3.71 (ddd, J = 9.7, 6.6, 6.6 Hz, 1H), 3.40 (ddd, J = 9.7, 6.4, 6.4 Hz, 1H), 2.45 (s, 3H), 2.09 (apparent q, J = 7.6 Hz, 2H), 1.65 (apparent pentet, J = 7.0 Hz, 2H), 0.86 (s, 9H), 0.14 (s, 3H), 0.04 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.6 (s), 145.0 (s), 137.7 (o), 132.7 (s), 129.9 (o), 128.0 (o), 115.1 (t), 97.4 (o), 74.3 (o), 70.3 (o), 69.4 (t), 68.4 (t), 64.7 (o), 54.5 (o), 30.1 (t), 28.6 (t), 25.6 (o), 21.6 (o), 17.9 (s), −4.6 (o), −5.1 (o); HRMS (FAB) m/z calcd for $C_{25}H_{40}NO_8SSi$ $(M + H)^+$ 542.2244, found 542.2228.

Data for dihydropyranone **19j**: R_f = 0.63 (40% EtOAc/hexanes); IR (thin film) 1682, 1599 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.80

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(apparent d, J = 8.4 Hz, 2H), 7.37 (apparent d, J = 8.1 Hz, 2H), 7.21 (d, J = 6.0 Hz, 1H), 5.36 (dd, J = 6.1, 1.0 Hz, 1H), 4.51 (ddd, J = 7.6, 4.5, 3.2 Hz, 1H), 4.31 (AB of ABX, J_{AB} = 10.8 Hz, J_{AX} = 7.7 Hz, J_{BX} = 4.5 Hz, $\Delta\nu_{AB}$ = 24.6 Hz, 2H), 4.03 (dd, J = 3.3, 1.0 Hz, 1H), 2.46 (s, 3H), 0.81 (s, 9H), 0.08 (s, 3H), 0.06 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 189.6, 161.3, 145.3, 132.3, 130.0, 128.0, 105.1, 79.6, 69.5, 66.1, 25.5, 21.7, 18.1, −4.8, −5.6; HRMS (FAB) m/z calcd for $C_{19}H_{29}O_6SSi$ $(M + H)^+$ 413.1454, found 413.1451.

_N_-Boc Protection and Hydrolysis of 2-Gulosamine and 2-Allosamine Oxazolidinones. *4-Pentenyl 2-Amino-2-N-tert-butoxycarbonyl-2-N,3-O-carbonyl-2-deoxy-4,6-O-isopropylidene-β-D-gulopyranoside (**33**).* To a solution of oxazolidinone **15aa-β** (36.2 mg, 0.116 mmol) in THF (2 mL) were added *N*,*N*-dimethyl-4-aminopyridine (70.5 mg, 0.578 mmol), Et_3N (80 μL, 0.58 mmol), and di-*tert*-butyl dicarbonate (135 μL, 0.588 mmol). The mixture was stirred at 25 °C during 75 min then diluted with CH_2Cl_2 and washed with brine (1 × 15 mL). The aqueous layer was extracted with CH_2Cl_2 (2 × 5 mL), and the combined organic layers were dried ($MgSO_4$), filtered, and concentrated. The residue was chromatographed (30 → 40% EtOAc/hexanes, 50 mL SiO_2), affording *N*-acylated product **33** (46.1 mg, 96%): R_f = 0.46 (45% EtOAc/hexanes); IR (thin film) 1828, 1735, 1640 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.79 (dddd, J = 17.0, 10.3, 6.7, 6.7 Hz, 1H), 5.18−4.91 (m, 2H), 4.47 (dd, J = 6.0, 2.0 Hz, 1H), 4.46 (d, J = 7.5 Hz, 1H), 4.32 (dd, J = 7.2, 6.4 Hz, 1H), 3.20 (dd, J = 1.6, 1.6 Hz, 1H), 4.07 (AB of ABX, J_{AB} = 12.9 Hz, J_{AX} = 2.5 Hz, J_{BX} = 1.6 Hz, $\Delta\nu_{AB}$ = 34.1 Hz, 2H), 3.97 (ddd, J = 9.4, 6.8, 6.8 Hz, 1H), 3.56 (m, 1H), 3.40 (ddd, J = 9.4, 7.0, 7.0 Hz, 1H), 2.11 (apparent q, J = 7.2 Hz, 2H), 1.71 (apparent pentet, J = 7.2 Hz, 2H), 1.53 (s, 9H), 1.48 (s, 3H), 1.44 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 151.1 (s), 148.4 (s), 137.7 (o), 115.0 (t), 101.7 (o), 99.0 (s), 84.0 (s), 75.7 (o), 69.2 (t), 66.1 (o), 63.4 (o), 62.0 (t), 54.8 (o), 30.0 (t), 28.8 (o), 28.6 (t), 27.8 (o), 18.6 (o); HRMS (FAB) m/z calcd for $C_{20}H_{32}NO_8$ $(M + H)^+$ 414.2128, found 414.2134.

*4-Pentenyl 2-Amino-2-N-tert-butoxycarbonyl-2-deoxy-4,6-O-isopropylidene-β-D-gulopyranoside (**34**).* *N*-Boc-protected oxazolidinone **33** (41.1 mg, 0.0995 mmol) was dissolved in THF/H_2O (1 mL/0.3 mL) and LiOH·H_2O (34.3 mg, 0.816 mmol) was added. The mixture was well stirred during 90 min and poured into satd aq NH_4Cl (20 mL). The mixture was extracted with CH_2Cl_2 (3 × 20 mL) and the combined organic layers were dried ($MgSO_4$), filtered, and concentrated. The crude product was chromatographed (50% EtOAc/hexanes, 45 mL SiO_2), providing C3 alcohol **34** (35.5 mg, 92%): R_f = 0.24 (45% EtOAc/hexanes); IR (thin film) 3448, 3079, 1718, 1697, 1641 cm^{-1}; ^{1}H NMR (300 MHz, acetone-d_6) δ 5.84 (dddd, J = 17.1, 10.3, 6.8, 6.8 Hz, 1H), 5.57 (br d, J = 8.9 Hz, 1H), 5.02 (dddd, J = 17.2, 1.8, 1.8, 1.8 Hz, 1H), 4.92 (dddd, J = 10.2, 2.2, 1.1, 1.1 Hz, 1H), 4.68 (d, J = 4.2 Hz, 1H), 4.64 (d, J = 8.6 Hz, 1H), 4.10 (dd, J = 12.7, 2.1 Hz, 1H), 3.94 (dd, J = 3.1, 1.2 Hz, 1H), 3.90−3.72 (m, 4H), 3.64 (m, 1H), 3.42 (ddd, J = 9.5, 6.7, 6.7 Hz, 1H), 2.14 (m, 2H), 1.63 (m, 2H), 1.43 (s, 3H), 1.40 (s, 9H), 1.32 (s, 3H); ^{13}C NMR (75 MHz, acetone-d_6) δ 156.3 (s), 139.5 (o), 115.0 (t), 100.1 (o), 98.7 (s), 78.8 (s), 71.2 (o), 70.3 (o), 68.6 (t), 66.1 (o), 63.6 (t), 51.9 (o), 31.0 (t), 29.9 (t),* 29.8 (o),* 28.7 (o), 19.2 (o), *the ^{13}C NMR signals at δ 29.9 and 29.8 were obscured by solvent peaks but detected in the DEPT 135 experiment; HRMS (FAB) m/z calcd for $C_{19}H_{34}NO_7$ $(M + H)^+$ 388.2335, found 388.2328.

Confirmation of the $J_{H1,H2}$ value for **34**: From an edited ^{1}H/^{13}C HSQC experiment, the ^{13}C methine resonance at δ 101.1 was correlated to the ^{1}H doublet at δ 4.64 (J = 8.6 Hz). Additionally, deuterium exchange with a drop of added D_2O showed that the nearby ^{1}H doublet at δ 4.68 (J = 4.2 Hz) was the C3-O*H*, removing any ambiguity from the assignment of the H1 signal at δ 4.64. Assignment of the H1 resonance provided the corresponding $J_{H1,H2}$ = 8.6 Hz.

*4-Pentenyl 2-Amino-2-N-tert-butoxycarbonyl-2-N,3-O-carbonyl-2-deoxy-4,6-di-O-benzyl-β-D-allopyranoside (**35**).* Using the same procedure as for **15aa-β** → **33** and purifying the product **35** by chromatography (30% EtOAc/hexanes, 60 mL SiO_2), the allosamine oxazolidinone **16ba-β** (56.0 mg, 0.123 mmol) was converted to the *N*-Boc derivative **35** (57.6 mg, 84%) as a clear, colorless oil: R_f = 0.35 (30% EtOAc/hexanes); IR (ATR) 1821, 1799, 1722 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.38−7.25 (m, 10H, ArH), 5.73 (dddd, J = 17.0, 10.3, 6.6, 6.6 Hz, 1H, H4′), 5.03−4.90 (m, 2H, H5′), 4.84−4.77 (m, 2H, H1, H3), 4.60 (AB, J_{AB} = 11.7 Hz, $\Delta\nu_{AB}$ = 25.5 Hz, 2H, OCH_2Ph), 4.54 (AB, J_{AB} = 12.0 Hz, $\Delta\nu_{AB}$ = 24.4 Hz, 2H, OCH_2Ph), 4.27 (dd, J = 8.6, 1.8 Hz, 1H, H2), 4.24 (dd, J = 9.9, 2.8 Hz, 1H, H4), 4.06 (ddd, J = 10.1, 5.1, 2.3 Hz, 1H, H5), 3.81 (ddd, J = 9.5, 6.6, 6.6 Hz, 1H, H1′a), 3.61 (AB of ABX, J_{AB} = 10.5 Hz, J_{AX} = 5.4 Hz, J_{BX} = 2.0 Hz, $\Delta\nu_{AB}$ = 17.2 Hz, 2H, H6), 3.35 (ddd, J = 9.5, 6.6, 6.6 Hz, 1H, H1′b), 1.97 (apparent q, J = 7.2 Hz, 2H, H3′), 1.60−1.45 (m, 2H, H2′), 1.52 (s, 9H, C$(CH_3)_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 151.1 (s), 149.0 (s), 137.93 (s, $C_{Ar}CH_2O$), 137.88 (o, C4′), 137.3 (s, $C_{Ar}CH_2O$), 128.5 (o, $C_{Ar}H$), 128.4 (o, $C_{Ar}H$), 128.0 (o, $C_{Ar}H$), 127.91 (o, $C_{Ar}H$),* 127.87 (o, $C_{Ar}H$),* 127.7 (o, $C_{Ar}H$) 114.9 (t, C5′), 96.7 (o, C1), 84.3 (s, C$(CH_3)_3$), 73.3 (t, OCH_2Ph), 72.0 (t, OCH_2Ph), 70.5 (o, C5), 70.3 (t, C6), 70.2 (o, C4), 69.6 (o, C3), 68.3 (t, C1′), 57.2 (o, C2), 30.0 (t, C3′), 28.5 (t, C2′), 27.9 (o, C$(CH_3)_3$); *these ^{13}C NMR signals resolved upon processing of the FID with lb = 0; HRMS (ESI) m/z calcd for $C_{31}H_{39}NO_8Na$ $(M + Na)^+$ 576.2573, found 576.2569.

*4-Pentenyl 2-Amino-2-N-tert-butoxycarbonyl-2-deoxy-4,6-di-O-benzyl-β-D-allopyranoside (**36**).* Using the same procedure as for **33** → **34**, the allosamine *N*-Boc oxazolidinone **35** (54 mg, 0.098 mmol) was hydrolyzed to allosamine C3 alcohol **36**. The product alcohol was close in R_f to the starting material, but could be resolved on TLC using three elutions with 25% EtOAc/hexanes in order to monitor the hydrolysis reaction. Chromatography (30% EtOAc/hexanes, 30 mL SiO_2) provided product **36** (35 mg, 68%) as a clear oil: R_f = 0.32 (30% EtOAc/hexanes); IR (ATR) 3446, 3381, 3066, 3031, 1708, 1641 cm^{-1}; ^{1}H NMR (300 MHz, acetone-d_6) δ 7.40−7.20 (m, 10H, ArH), 5.84 (dddd, J = 17.1, 10.3, 6.8, 6.8 Hz, 1H, H4′), 5.66 (br d, J = 9.1 Hz, 1H, NH), 5.03 (dddd, J = 17.2, 1.8, 1.8, 1.8 Hz, 1H, H5′b), 4.93 (dddd, J = 10.2, 2.2, 1.1, 1.1 Hz, 1H, H5′a), 4.62 (AB, J_{AB} = 11.6 Hz, $\Delta\nu_{AB}$ = 55.4 Hz, 2H, OCH_2Ph), 4.62 (d, J = 8.0 Hz, 1H, H1), 4.58 (partially obscured AB, 2H, OCH_2Ph), 4.32 (apparent q, J = 2.8 Hz, 1H, H3), 4.23 (br s, 1H, OH), 3.96 (ddd, J = 9.4, 5.2, 2.0 Hz, 1H, H5), 3.84 (ddd, J = 9.6, 6.1, 6.1 Hz, 1H, H1′a), 3.74 (AB of ABX, J_{AB} = 10.9 Hz, J_{AX} = 5.3 Hz, J_{BX} = 2.0 Hz, $\Delta\nu_{AB}$ = 35.4 Hz, 2H, H6), 3.59 (dd, J = 9.4, 2.4 Hz, 1H, H4), 3.57 (m, 1H, H2), 3.47 (ddd, J = 9.6, 6.6, 6.6 Hz, 1H, H1′b), 2.14 (apparent q, J = 7.2 Hz, 2H, H3′), 1.64 (apparent pentet, J = 7.0 Hz, 2H, H2′), 1.42 (s, 9H, C$(CH_3)_3$); ^{13}C NMR (75 MHz, acetone-d_6) δ 156.0 (s, NHC(O)O), 140.0 (s, $C_{Ar}CH_2O$), 139.6 (s, $C_{Ar}CH_2O$), 139.5 (o, C4′), 129.12 (o, $C_{Ar}H$),* 129.11 (o, $C_{Ar}H$),* 128.8 (o, $C_{Ar}H$), 128.40 (o, $C_{Ar}H$),* 128.39 (o, $C_{Ar}H$),* 128.2 (o, $C_{Ar}H$), 115.1 (t, C5′), 100.9 (o, C1), 78.9 (s, C$(CH_3)_3$), 76.5 (o, C4), 73.8 (t, OCH_2Ph), 73.4 (o, C5), 71.7 (t, OCH_2Ph), 70.8 (t, C6), 69.0 (t, C1′), 68.1 (o, C3), 54.7 (o, C2), 31.0 (t, C3′), 29.9 (t, C2′),† 28.7 (o, C$(CH_3)_3$), *these ^{13}C NMR signals could be resolved upon reprocessing of the FID with lb = 0, †this ^{13}C NMR signal overlapped with a solvent peak, but was detected in DEPT 135 and ^{1}H/^{13}C HSQC experiments; HRMS (ESI) m/z calcd for $C_{30}H_{41}NO_7Na$ $(M + Na)^+$ 550.2781, found 550.2791.

Because there was some overlap of the H1 resonance with one of the benzyl methylene AB systems, we used ^{1}H-coupled HSQC to refine the measurement of $J_{H1,H2}$. Details and spectra for the determination of $J_{H1,H2}$ = 8.3 ± 0.1 Hz are included in the Supporting Information.

Amidoglycosylation of D-Glycal 3-Carbamates 11 (Gulal), 12 (Allal), 13 (Glucal), and 14 (Galactal) with Other Alcohol Acceptors. *Allyl 2-Amino-2-N,3-O-carbonyl-2-deoxy-4,6-di-O-acetyl-β-D-gulopyranoside (**15cb-β**) and the Minor Anomer (**15cb-α**).* The bis-acetyl-protected gulal 3-carbamate **11c** (98.9 mg, 0.362 mmol) was combined with allyl alcohol (5.1 equiv) under the general amidoglycosylation conditions, and chromatography (55 → 60 → 65 → 75% EtOAc/hexanes, 50 mL SiO_2) provided **15cb-β** (96.8 mg, 81%) and **15cb-α** (8.6 mg, 7%) separately, both as clear, colorless oils. Data for the major anomer **15cb-β**: R_f = 0.39 (60% EtOAc/hexanes);

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IR (ATR) 3316, 1769, 1740 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.92 (dddd, J = 17.1, 10.3, 6.7, 5.3 Hz, 1H, H2′), 5.87 (br s, 1H, NH), 5.38−5.23 (m, 2H, H3′), 5.23 (apparent slightly br t, J = 1.8 Hz, 1H, H4), 4.62 (dd, J = 6.6, 2.2 Hz, 1H, H3), 4.52 (d, J = 7.4 Hz, 1H, H1), 4.40 (dddd, J = 12.5, 5.3, 1.3, 1.3 Hz, 1H, H1′a), 4.23 (AB of ABX, J_{AB} = 11.4 Hz, J_{AX} = 7.1 Hz, J_{BX} = 5.8 Hz, $\Delta\nu_{AB}$ = 16.1 Hz, 2H, H6), 4.16−4.05 (m, 2H, H1′b, H5), 3.60 (dd, J = 7.0, 7.0 Hz, 1H, H2), 2.14 (s, 3H, $H_3CC(O)O$), 2.08 (s, 3H, $H_3CC(O)O$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.4 (s, $H_3CC(O)O$), 169.5 (s, $H_3CC(O)O$), 157.6 (s, OC(O)NH), 132.9 (o, C2′), 118.9 (t, C3′), 102.3 (o, C1), 75.9 (o, C3), 70.6 (o, C5), 70.3 (t, C1′), 64.2 (o, C4), 61.4 (t, C6), 53.0 (o, C2), 20.64 (o, $H_3CC(O)O$), 20.60 (o, $H_3CC(O)O$); HRMS (FAB) m/z calcd for $C_{14}H_{20}NO_8$ $(M + H)^+$ 330.1189, found 330.1183.

Data for the minor anomer **15cb-α**: R_f = 0.22 (60% EtOAc/hexanes); IR (ATR) 3332, 1768 (shoulder), 1742 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.89 (dddd, J = 17.1, 10.8, 6.1, 4.9 Hz, 1H, H2′), 5.39−5.18 (m, 4H, H3′, H4, NH), 4.97 (d, J = 4.3 Hz, 1H, H1), 4.62 (dd, J = 7.2, 2.8 Hz, 1H, H3), 4.41 (ddd, J = 6.7, 5.8, 2.4 Hz, 1H, H5), 4.28 (dddd, J = 13.0, 4.9, 1.5, 1.5 Hz, 1H, H1′a), 4.17 (AB of ABX, J_{AB} = 11.5 Hz, J_{AX} = 7.1 Hz, J_{BX} = 5.5 Hz, $\Delta\nu_{AB}$ = 21.6 Hz, 2H, H6), 4.02 (dddd, J = 13.0, 6.1, 1.3, 1.3 Hz, 1H, H1′b), 3.91 (dd, J = 7.2, 4.3 Hz, 1H, H2), 2.14 (s, 3H, $H_3CC(O)O$), 2.08 (s, 3H, $H_3CC(O)O$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.4 (s, $H_3CC(O)O$), 169.4 (s, $H_3CC(O)O$), 158.7 (s, OC(O)NH), 132.8 (o, C2′), 118.1 (t, C3′), 93.9 (o, C1), 73.2 (o, C3), 68.6 (t, C1′), 65.0 (o, C4), 64.4 (o, C5), 61.8 (t, C6), 50.5 (o, C2), 20.73 (o, $H_3CC(O)O$), 20.68 (o, $H_3CC(O)O$); HRMS (FAB) m/z calcd for $C_{14}H_{20}NO_8$ $(M + H)^+$ 330.1189, found 330.1197.

*Geranyl 2-Amino-2-N,3-O-carbonyl-2-deoxy-4,6-di-O-acetyl-β-D-gulopyranoside (**15cc-β**) and the Minor anomer (**15cc-α**).* Under the general amidoglycosylation conditions, gulal 3-carbamate **11c** (100.5 mg, 0.368 mmol) reacted with geraniol (5.0 equiv). Chromatography (30 → 40 → 50 → 60% EtOAc/hexanes, 50 mL SiO_2) separated the β anomer from α-enriched material, providing **15cc-β** (135 mg, 86%) and **15cc-α** (6.0 mg, 4%), both as clear, colorless oils (NMR characterization indicated that the α anomer was isolated as a ∼ 3:1 mixture with the β diastereomer under these chromatography conditions). Data for the major anomer **15cc-β**: R_f = 0.25 (40% EtOAc/hexanes); IR (ATR) 3321, 1769 (shoulder), 1743 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.62 (slightly br s, 1H, NH), 5.32 (broadened approx t, J = 7.2 Hz, 1H, H2′), 5.23 (br apparent t, J = 1.8 Hz, 1H, H4), 5.08 (m, 1H, H6′), 4.60 (dd, J = 6.5, 2.2 Hz, 1H, H3), 4.48 (d, J = 7.5 Hz, 1H, H1), 4.34 (apparent br dd, J = 11.8, 6.3 Hz, 1H, H1′a), 4.30−4.16 (m, 3H, H6, H1′b), 4.07 (ddd, J = 6.8, 6.0, 1.7 Hz, 1H, H5), 3.57 (dd, J = 7.0, 7.0 Hz, 1H, H2), 2.15−2.03 (m, 4H, H4′, H5′), 2.13 (s, 3H, $H_3CC(O)O$), 2.07 (s, 3H, $H_3CC(O)O$), 1.69 (2 overlapping br s, 6H, H9′ and H8′ or H10′), 1.61 (br s, 3H, H8′ or H10′); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.4 (s, $H_3CC(O)O$), 169.5 (s, $H_3CC(O)O$), 157.4 (s, OC(O)NH), 142.9 (s, C3′ or C7′), 131.9 (s, C3′ or C7′), 123.6 (o, C6′), 118.6 (o, C2′), 101.7 (o, C1), 75.9 (o, C3), 70.6 (o, C5), 65.4 (t, C1′), 64.2 (o, C4), 61.5 (t, C6), 53.0 (o, C2), 39.5 (t, C4′ or C5′), 26.3 (t, C4′or C5′), 25.6 (o, C8′ or C9′ or C10′), 20.6 (o, 2C, $H_3CC(O)O$), 17.7 (o, C8′ or C10′), 16.4 (o, C8′ or C9′ or C10′); HRMS (FAB) m/z calcd for $C_{21}H_{30}NO_8$ $(M - H)^+$ 424.1971, found 424.1986.[67]

Data for the minor anomer **15cc-α**: R_f = 0.13 (40% EtOAc/hexanes); IR (ATR) 3354, 1743 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.30 (dd, J = 2.4, 2.4 Hz, 1H, H4), 5.28 (m, 1H, H2′), 5.07 (m, 1H, H6′), 5.03 (br s, 1H, NH), 4.95 (d, J = 4.3 Hz, 1H, H1), 4.61 (dd, J = 7.3, 2.8 Hz, 1H, H3), 4.42 (ddd, J = 6.7, 5.9, 2.4 Hz, 1H, H5), 4.28−4.03 (m, 4H, H6, H1′), 3.88 (dd, J = 7.3, 4.3 Hz, 1H, H2), 2.17−2.01 (m, 4H, H4′, H5′), 2.14 (s, 3H, $H_3CC(O)O$), 2.08 (s, 3H, $H_3CC(O)O$), 1.69 (2 overlapping br s, 6H, H9′ and H8′ or H10′), 1.61 (br s, 3H, H8′ or H10′); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.5 (s, $H_3CC(O)O$), 169.4 (s, $H_3CC(O)O$), 158.6 (s, OC(O)NH), 142.4 (s, C3′ or C7′), 131.9 (s, C3′ or C7′), 123.7 (o, C6′), 118.9 (o, C2′), 93.0 (o, C1), 73.1 (o, C3), 65.1 (o, C4), 64.3 (o, C5), 64.0 (t, C6 or C1′), 62.0 (t, C6 or C1′), 50.5 (o, C2), 39.6 (t, C4′ or C5′), 26.3 (t, C4′or C5′), 25.7 (o, C8′ or C9′ or C10′), 20.73 (o, $H_3CC(O)O$), 20.69 (o, $H_3CC(O)O$), 17.7 (o, C8′ or C10′), 16.4 (o, C8′ or C9′ or C10′); HRMS (FAB) m/z calcd for $C_{21}H_{31}NO_8Na$ $(M + Na)^+$ 448.1947, found 448.1945.

*2-(Trimethylsilyl)ethyl 2-Amino-4,6-O-benzylidene-2-N,3-O-carbonyl-2-deoxy-β-D-allopyranoside (**16ed**).* Applying the general amidogylcosylation procedure with allal 3-carbamate **12e** (99.2 mg, 0.358 mmol) and 2-(trimethylsilyl)ethanol (250 μL, 1.74 mmol) as the acceptor, followed by chromatography of the crude material (40% EtOAc/hexanes, 50 mL SiO_2), provided **16ed** (94.4 mg, 67%) as a clear, colorless oil: R_f = 0.49 (60% EtOAc/hexanes); IR (ATR) 3293, 1757 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.55−7.45 (m, 2H, ArH), 7.41−7.31 (m, 3H, ArH), 6.27 (slightly br s, 1H, NH), 5.58 (s, 1H, PhC*H*), 4.96 (dd, J = 7.4, 3.3 Hz, 1H, H3), 4.61 (d, J = 4.7 Hz, 1H, H1), 4.40 (dd, J = 10.4, 4.9 Hz, 1H, H6eq), 4.13 (dd, J = 9.9, 3.4 Hz, 1H, H4), 3.99 (ddd, J = 10.1, 10.1, 4.9 Hz, 1H, H5), 3.93 (ddd, J = 10.6, 9.8, 6.5 Hz, 1H, H1′a), 3.79 (ddd, J = 7.3, 4.7, 0.5 Hz, 1H, H2), 3.72 (dd, J = 10.2, 10.2 Hz, 1H, H6ax), 3.55 (ddd, J = 10.6, 9.8, 6.3 Hz, 1H, H1′b) 0.96 (m, 2H, H2′), 0.04 (s, 9H, $Si(CH_3)_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 159.0 (s, OC(O)NH), 136.7 (s, $C_{Ar}CH$), 129.3 (o, $C_{Ar}H$), 128.3 (o, $C_{Ar}H$), 126.3 (o, $C_{Ar}H$), 102.7 (o, PhCH), 100.5 (o, C1), 75.0 (o, C4), 73.4 (o, C3), 69.5 (t, C6), 67.2 (t, C1′) 62.6 (o, C5), 55.8 (o, C2), 18.2 (t, C2′), −1.4 (o, $Si(CH_3)_3$); HRMS (FAB) m/z calcd for $C_{19}H_{26}NO_6Si$ $(M - H)^+$ 392.1529, found 392.1531.[67]

*2-Pentynyl 2-Amino-4,6-O-benzylidene-2-N,3-O-carbonyl-2-deoxy-β-D-allopyranoside (**16ee**).* The general amidoglycosylation procedure was followed, using allal 3-carbamate **12e** (98.3 mg, 0.355 mmol) with 2-pentyn-1-ol (5.0 equiv) as the glycosyl acceptor. Chromatography (50% EtOAc/hexanes, 50 mL SiO_2), yielded an inseparable 13:1 β:α mixture of the internal alkyne-containing product **16ee** (94.7 mg, 74%) as a yellow-tinged white solid. The yield of the major β product, corrected for the presence of the α diasteromer, was 69%. NMR signals listed are for **16ee-β**, unless otherwise noted: R_f = 0.36 (60% EtOAc/hexanes); IR (ATR) 3274, 3169, 2227, 1761, 1747 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.55−7.45 (m, 2H, ArH), 7.42−7.31 (m, 3H, ArH), 6.29 (slighly br s, 1H, NH), 5.58 (s, 1H, PhC*H*), 4.98 (dd, J = 7.7, 3.3 Hz, 1H, H3), 4.83 (d, J = 4.1 Hz, 1H, H1), 4.40 (dd, J = 10.6, 4.7 Hz, 1H, H6eq), 4.37 (apparent dt, J = 15.1, 2.2 Hz, 1H, H1′a), 4.28 (apparent dt, J = 15.3, 2.1 Hz, 1H, H1′b), 4.19 (dd, J = 10.0, 3.4 Hz, 1H, H4), 4.05 (ddd, J = 10.0, 10.0, 5.0 Hz, 1H, H5), 3.91 (ddd, J = 7.8, 4.1, 0.6 Hz, 1H, H2), 3.73 (dd, J = 10.2, 10.2 Hz, 1H, H6ax), 2.26 (apparent qt, J = 7.5, 2.1 Hz, 2H, H4′), 1.16 (t, J = 7.5 Hz, 3H, H5′). Additional nonoverlapping ^1H NMR signals detected for the **16ee-α** anomer: δ 6.58 (br s, 1H, NH), 5.97 (d, J = 2.3 Hz, 1H, H1), 5.61 (s, 1H, PhC*H*), 5.05 (dd, J = 8.9, 3.1 Hz, 1H, H3), 3.69 (dd, J = 10.2, 10.2 Hz, H6ax), 2.40 (q, J = 7.5 Hz, 2H, H4′), 1.24 (t, J = 7.5 Hz, 3H, H5′); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.8 (s, OC(O)NH), 136.7 (s, $C_{Ar}CH$), 129.3 (o, $C_{Ar}H$), 128.3 (o, $C_{Ar}H$), 126.3 (o, $C_{Ar}H$), 102.6 (o, PhCH), 98.1 (o, C1), 89.9 (s, C2′ or C3′), 74.7 (o, C4), 73.6 (s, C2′ or C3′), 72.8 (o, C3), 69.5 (t, C6), 62.5 (o, C5), 56.3 (t, C1′), 55.2 (o, C2), 13.6 (o, C5′), 12.4 (t, H4′); HRMS (FAB) m/z calcd for $C_{19}H_{22}NO_6$ $(M + H)^+$ 360.1447, found 360.1455.

*Propargyl 4-O-Acetyl-2-amino-2-N,3-O-carbonyl-2-deoxy-6-O-p-toluenesulfonyl-α-D-mannopyranoside (**17ff**).* With propargyl alcohol (5.1 equiv) as the glycosyl acceptor, glucal 3-carbamate **13f** (102 mg, 0.267 mmol) was treated under the standard amidoglycosylation conditions. Chromatography (55 → 65% EtOAc/hexanes, 90 mL SiO_2) provided **17ff** (52.4 mg, 45%) as a clear oil, as well as recovered starting material **13f** (48.5 mg, 47%). Data for **17ff**: R_f = 0.30 (65% EtOAc/hexanes); IR (ATR) 3375, 3285, 1760, 1598 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.78 (apparent d, J = 8.3 Hz, 2H, ArH_o), 7.36 (apparent d, J = 8.0 Hz, 2H, ArH_m), 6.03 (slightly br s, 1H, NH), 5.06 (s, 1H, H1), 4.98 (dd, J = 9.9, 7.3 Hz, 1H, H4), 4.68 (dd, J = 7.4, 7.4 Hz, 1H, H3), 4.21 (AB of ABX, J_{AB} = 15.8 Hz, J_{AX} = 2.4 Hz, J_{BX} = 2.3 Hz, $\Delta\nu_{AB}$ = 6.8 Hz, 2H, H1′), 4.14−4.02 (m, 3H, H2, H6), 3.97 (ddd, J = 9.8, 6.1, 3.7 Hz, 1H, H5), 2.50 (apparent t, J = 2.4 Hz, 1H, H3′), 2.46 (s, 3H, Ar-**CH_3**), 2.08 (s, 3H, $H_3CC(O)O$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 169.5 (s, $H_3CC(O)O$), 158.1 (s, OC(O)NH), 145.2 (s, Ar), 132.4 (s, Ar), 129.9

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(o, Ar-*meta*), 128.0 (o, Ar-*ortho*), 94.6 (o, C1), 77.8 (s, C2′), 75.8 (C3′)*, 75.5 (o, C3), 68.4 (o, C4), 68.2 (t, C6), 66.2 (o, C5), 55.6 (o, C2), 54.7 (t, C1′), 21.7 (o, Ar-CH_3), 20.7 (o, $H_3CC(O)O$), *this ^{13}C resonance gave a much diminished positive peak in the DEPT 135 spectrum and a negatively phased cross-peak in a phase-sensitive HSQC experiment, presumably due to the large C_{sp}−H coupling constant; HRMS (FAB) *m*/*z* calcd for $C_{19}H_{22}NO_9S$ $(M + H)^+$ 440.1015, found 440.1010.

*4-Pentynyl 4-O-Acetyl-2-amino-2-N,3O-carbonyl-2-deoxy-6-O-p-toluenesulfonyl-α-D-mannopyranoside (**17fg**).* The glycal 3-carbamate **13f** (105 mg, 0.272 mmol) and 4-pentyn-1-ol (5.1 equiv) as the glycosyl acceptor were used in the general amidoglycosylation procedure. Column chromatography (50 → 55 → 60 → 65 → 70% EtOAc/hexanes, 90 mL SiO_2), followed by preparative TLC (50% EtOAc/hexanes, 3 elutions), provided 4-pentynyl glycoside **17fg** as single α anomer (20.1 mg, 16%) as a brittle foam. Starting carbamate **13f** (55.4 mg, 53%) was also recovered during the chromatography. Data for **17fg**: R_f = 0.36 (65% EtOAc/hexanes); IR (ATR) 3374, 3291, 1761, 1598 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.78 (apparent d, *J* = 8.3 Hz, 2H), 7.36 (apparent d, *J* = 8.1 Hz, 2H), 6.09 (s, 1H), 4.97 (dd, *J* = 9.5, 7.1, 1H), 4.84 (s, 1H), 4.67 (dd, *J* = 7.4, 7.4 Hz, 1H), 4.08 (AB of ABX, J_{AB} = 10.7 Hz, J_{AX} = 4.0 Hz, J_{BX} = 3.5 Hz, $\Delta\nu_{AB}$ = 18.1 Hz, 2H), 4.07 (m, 1H), 3.99 (ddd, *J* = 9.4, 6.2, 3.5 Hz, 1H), 3.80 (ddd, *J* = 10.0, 6.0, 6.0 Hz, 1H), 3.47 (ddd, *J* = 9.8, 5.9, 5.9 Hz, 1H), 2.46 (s, 3H), 2.28 (apparent td, *J* = 6.9, 2.6 Hz, 2H), 2.08 (s, 3H), 2.00 (apparent t, *J* = 2.6 Hz, 1H), 1.78 (apparent pentet, *J* = 6.6 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 169.5 (s), 158.3 (s), 145.2 (s), 132.4 (s), 129.9 (o), 128.0 (o), 96.2 (o), 83.1 (s), 75.7 (o), 69.3 (o), 68.34 (o)*, 68.31 (t)*, 66.2 (t), 65.7 (o), 55.7 (o), 27.8 (t), 21.7 (o), 20.7 (o), 15.1 (t), *these ^{13}C resonances distinguished by reprocessing the FID with lb = 0 and by their opposite phases in the DEPT 135 spectrum; HRMS (ESI) *m*/*z* calcd for $C_{21}H_{25}NO_9SNa$ $(M + Na)^+$ 490.1148, found 490.1144.

*Benzyl 4-O-Acetyl-2-amino-2-N,3-O-carbonyl-2-deoxy-6-O-p-toluenesulfonyl-α-D-mannopyranoside (**17fh**).* Reaction of glycal carbamate **13f** (61.1 mg, 0.159 mmol) and benzyl alcohol (5.2 equiv) using the general amidoglycosylation conditions, but with 3.1 equiv PhIO instead of the usual 1.8 equiv, gave a single α anomer of benzyl glycoside **17fh** (53.5 mg, 69%) as a glass, following chromatography (90% Et_2O/pentane, 80 mL SiO_2): R_f = 0.22 (90% Et_2O/pentane); IR (ATR) 3367, 1761, 1598 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.79 (apparent d, *J* = 8.3 Hz, 2H, ArH_o), 7.42−7.27 (m, 7H, ArH_m, $CH_2C_6H_5$), 6.13 (slightly br s, 1H, NH), 4.97 (dd, *J* = 9.5, 7.2 Hz, 1H, H4), 4.92 (s, 1H, H1), 4.68 (dd, *J* = 7.4, 7.4 Hz, 1H, H3), 4.56 (AB, J_{AB} = 11.4 Hz, $\Delta\nu_{AB}$ = 63.7 Hz, 2H, $CH_2C_6H_5$), 4.12−3.97 (m, 4H, H2, H5, H6), 2.45 (s, 3H, Ar-**CH**$_3$), 2.06 (s, 3H, $H_3CC(O)O$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 169.6 (s, $H_3CC(O)O$), 158.3 (s, OC(O)NH), 145.2 (s, Ar), 136.0 (s, Ar), 132.6 (s, Ar), 129.9 (o, Ar), 128.6 (o, Ar), 128.5 (o, Ar), 128.3 (o, Ar-*para*′), 128.0 (o, Ar-*ortho*), 95.2 (o, C1), 75.7 (o, C3), 69.6 (t, $CH_2C_6H_5$), 68.5 (o, C4), 68.3 (t, C6), 66.0 (o, C5), 55.8 (o, C2), 21.6 (o, Ar-CH_3), 20.6 (o, $H_3CC(O)O$); HRMS (ESI) *m*/*z* calcd for $C_{23}H_{25}NO_9SNa$ $(M + Na)^+$ 514.1148, found 514.1148.

For the amidoglycosylation reactions leading to **17ci** and **17fj** (Table 3, entries 8−10), see ref 24.

*2-[2-(2-Chloroethoxy)ethoxy]ethyl 4-O-Acetyl-2-amino-2-N,3-O-carbonyl-2-deoxy-6-O-p-toluenesulfonyl-α-D-mannopyranoside (**17fk**).* Using the general amidoglycosylation procedure, reaction of glucal 3-carbamate **13f** (66.4 mg, 0.172 mmol) and 2-[2-(2-chloroethoxy)ethoxy]ethanol (5.0 equiv) followed by chromatography (50 → 80 → 90 → 100% EtOAc/hexanes, 80 mL SiO_2) and further purification by preparative TLC (100% EtOAc, several elutions) gave a single anomer of product **17fk** (33.6 mg, 35%) as a clear, colorless oil: R_f = 0.26 (90% EtOAc/hexanes); IR (ATR) 3301, 1761, 1598 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.77 (apparent d, *J* = 8.3 Hz, 2H, ArH_o), 7.36 (apparent d, *J* = 8.0 Hz, 2H, ArH_m), 6.18 (br s, 1H, NH), 4.97 (dd, *J* = 9.1, 7.3 Hz, 1H, H4), 4.93 (s, 1H, H1), 4.68 (dd, *J* = 7.5, 7.5 Hz, 1H, H3), 4.13−3.99 (m, 4H, H2, H5, H6), 3.83−3.73 (m, 3H, 2H of H1′-H5′, H6′a), 3.71−3.58 (m, 9H, 8H of H1′-H5′, H6′b), 2.45 (s, 3H, Ar−CH_3), 2.06 (s, 3H, $H_3CC(O)O$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 169.5 (s, $H_3CC(O)O$), 158.2 (s, OC(O)NH), 145.1 (s, Ar), 132.5 (s, Ar), 129.9 (o, Ar-*meta*), 128.0 (Ar-*ortho*), 96.5 (o, C1), 75.7 (o, C3), 71.3 (t, OCH_2′), 70.6 (t, OCH_2′), 70.4 (t, OCH_2′), 70.0 (t, OCH_2′), 68.5 (o, C4), 68.3 (t, C6), 67.1 (t, OCH_2′), 65.8 (o, C5), 55.8 (o, C2), 42.8 (t, CH2′Cl), 21.6 (o, Ar-CH_3), 20.6 (o, $H_3CC(O)O$); HRMS (ESI) *m*/*z* calcd for $C_{22}H_{30}NO_{11}SClNa$ $(M + Na)^+$ 574.1126, found 574.1116.

*2-(Trimethylsilyl)ethyl 2-Amino-4-O-tert-butyldimethylsilyl-2-N,3-O-carbonyl-2-deoxy-6-O-p-toluenesulfonyl-α-D-talopyranoside (**18jd**).* The general amidoglycosylation procedure, with galactal 3-carbamate **14j** (74.9 mg, 0.164 mmol) and 2-(trimethylsilyl)ethanol (4.9 equiv) as the acceptor, followed by chromatography (40 → 50% EtOAc/hexanes, 75 mL SiO_2), provided **18jd** (53.5 mg, 57%) as a clear, colorless glass: R_f = 0.47 (50% EtOAc/hexanes); IR (thin film) 3264, 1763, 1598 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.78 (apparent d, *J* = 8.3 Hz, 2H, ArH_o), 7.33 (apparent d, *J* = 8.0 Hz, 2H, ArH_m), 5.65 (br s, 1H, NH), 4.83 (d, *J* = 3.6 Hz, 1H, H1), 4.63 (dd, *J* = 9.2, 3.6 Hz, 1H, H3), 4.29 (dd, *J* = 3.8, 3.8 Hz, 1H, H4), 4.20 (AB of ABX, J_{AB} = 10.4 Hz, J_{AX} = 7.5 Hz, J_{BX} = 4.6 Hz, $\Delta\nu_{AB}$ = 24.2 Hz, 2H, H6), 4.06 (ddd, *J* = 7.3, 4.2, 4.2 Hz, 1H, H5), 3.82 (ddd, *J* = 10.1, 10.1, 6.4 Hz, 1H, H1′a), 3.79 (dd, *J* = 9.9, 3.3 Hz, 1H, H2), 3.50 (ddd, *J* = 10.0, 10.0, 6.5 Hz, 1H, H1′b), 2.44 (s, 3H, ArCH_3), 0.90 (m, 2H, H2′), 0.86 (s, 9H, $SiC(CH_3)_3$), 0.14 (s, 3H, Si^{t}BuCH_3), 0.04 (s, 3H, Si^{t}BuCH_3), 0.02 (s, 9H, $Si(CH_3)_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.5 (s, OC(O)NH), 144.9 (s, Ar), 132.8 (s, Ar), 129.9 (o, Ar-*meta*), 128.0 (o, Ar-*ortho*), 96.9 (o, C1), 74.3 (o, C3), 70.3 (o, C5), 69.2 (t, C6), 66.6 (t, C1′), 64.8 (o, C4), 54.6 (o, C2), 25.7 (o, $SiC(CH_3)_3$), 21.6 (o, $ArCH_3$), 18.02 (t, C2′), 17.97 (s, $SiC(CH_3)_3$), −1.4 (o, $Si(CH_3)_3$) −4.5 (o, Si^{t}BuCH_3), −5.1 (o, Si^{t}BuCH_3); HRMS (ESI) *m*/*z* calcd for $C_{25}H_{43}NO_8Si_2SNa$ $(M + Na)^+$ 596.2145, found 596.2159.

*Benzyl 2-Amino-4-O-tert-butyldimethylsilyl-2-N,3-O-carbonyl-2-deoxy-6-O-p-toluenesulfonyl-α-D-talopyranoside (**18jh**).* The starting galactal carbamate **14j** (76.5 mg, 0.167 mmol) was treated under the standard amidoglycosylation conditions with benzyl alcohol (4.9 equiv) as the acceptor, but using 3.3 equiv iodosobenzene. The additional iodosobenzene (beyond the typical 1.8 equiv) was necessary to minimize unreacted starting carbamate. Chromatography (50% EtOAc/hexanes, 75 mL SiO_2) provided benzyl glycoside **18jh** (47.6 mg, 51%) as a clear, colorless oil: R_f = 0.28 (50% EtOAc/hexanes); IR (thin film) 3264, 1763, 1598 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.80 (apparent d, *J* = 8.4 Hz, 2H, *p*-TolH_o), 7.40−7.23 (m, 7H, *p*-TolH_m, $CH_2C_6H_5$), 5.53 (br s, 1H, NH), 4.89 (d, *J* = 3.8 Hz, 1H, H1), 4.63 (dd, *J* = 9.2, 3.6 Hz, 1H, H3), 4.59 (AB, J_{AB} = 11.7 Hz, $\Delta\nu_{AB}$ = 69.8 Hz, 2H, $CH_2C_6H_5$), 4.26 (dd, *J* = 3.7, 3.7 Hz, 1H, H4), 4.20 (AB of ABX, J_{AB} = 10.2 Hz, J_{AX} = 7.4 Hz, J_{BX} = 3.8 Hz, $\Delta\nu_{AB}$ = 12.0 Hz, 2H, H6), 4.08 (ddd, *J* = 7.1, 4.0, 4.0 Hz, 1H, H5), 3.86 (ddd, *J* = 9.2, 3.8, 0.9 Hz, 1H, H2), 2.43 (s, 3H, ArCH_3), 0.80 (s, 9H, $SiC(CH_3)_3$), 0.10 (s, 3H, $SiCH_3$), 0.01 (s, 3H, $SiCH_3$); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.3 (s, OC(O)NH), 145.0 (s, *p*-Tol or Ph), 136.5 (s, *p*-Tol or Ph), 132.8 (s, *p*-Tol or Ph), 129.9 (o, *p*-Tol-*meta*), 128.7 (o, Ph), 128.30 (o, Ph)*, 128.29 (o, Ph)*, 128.0 (o, *p*-Tol-*ortho*), 96.2 (o, C1), 74.1 (o, C3), 70.6 (o, C5), 70.3 (t, CH_2Ph), 69.4 (t, C6), 64.9 (o, C4), 54.5 (o, C2), 25.6 (o, $SiC(CH_3)_3$), 21.6 (o, $ArCH_3$), 17.9 (s, $SiC(CH_3)_3$), −4.5 (o, $SiCH_3$), −5.1 (o, $SiCH_3$), *the ^{13}C resonances at δ 128.30 and 128.29 were distinguished by reprocessing the FID with lb = 0; HRMS (ESI) *m*/*z* calcd for $C_{27}H_{37}NO_8SiSNa$ $(M + Na)^+$ 586.1907, found 586.1901.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.8b00893.

Additional NMR characterization data and copies of ^1H, ^{13}C NMR, and 2-D NMR spectra (PDF)

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Notes

The authors declare no competing financial interest.

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