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A Generalized Procedure for the One-Pot Preparation of Glycosyl Azides and Thioglycosides Directly from Unprotected Reducing Sugars under Phase-Transfer Reaction Conditions[‡]

Rishi Kumar,[b] Pallavi Tiwari,[a] Prakas R. Maulik,[b] and Anup K. Misra*[a]

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Per-*O*-acetylated glycosyl azides and thioglycosides were prepared in excellent yield directly from unprotected reducing sugars through in situ generation of per-*O*-acetylated glycosyl bromides by a generalized one-pot procedure under phase-transfer conditions. Stereoselective products were formed with complete inversion at the anomeric centers of the glycosyl bromides to provide a general high-yielding procedure for the preparation of 1,2-*trans*-glycosyl azides and thioglycosides.

Introduction

Glycosyl azides and thioglycosides have been widely recognized for some time as important classes of carbohydrate derivatives.[1,2] Glycosyl azides receive considerable attention in connection with the versatile reactivities of the azido group, serving as valuable carbohydrate building blocks especially as precursors for the synthesis of glycosylamines,[3,4] *N*-glycopeptides,[5] *N*-glycoproteins,[6] and glycosyl heterocyclic derivatives such as 1,2,3-triazoles,[7–10] glycosyl bromoimines,[11] etc. Recently, glycosyl azides have also been applied in "click chemistry" for the synthesis of glycosyl heterocycles.[12–14] The azido group in a glycosyl azide can be used as a temporary anomeric center protecting group that can be converted into a glycosyl fluoride,[15,16] a useful glycosyl donor for the synthesis of oligosaccharides and glycoconjugates. Glycosyl azides are used successfully in the solid-phase preparation of glycopeptides.[17,18] Furthermore, they have also been used as chiral templates for α- and β-glycosyl amino acids (GAAs), α-amino glycosyl phosphonic acid derivatives.[19–21]

As in the case of glycosyl azides, thioglycosides have found versatile applications in the field of carbohydrate chemistry as very effective and stable glycosyl donors.[22–24] They are also useful intermediates for the preparation of glycosyl fluorides,[25] sulfoxides, and sulfones, which are used as glycosyl donors for *O*- and *C*-glycosylation.[26–28] The ongoing progress in the syntheses of complex oligosaccharides and glycoconjugates is closely related to the development of newer glycosylation methods exploiting thioglycosides as glycosyl donors.

Previous reports on the preparation of glycosyl azides have included the treatment of glycosyl halides with silver or sodium azides under homogeneous or phase-transfer reaction conditions.[29–31] In another approach, glycosyl azides have been efficiently synthesized by Lewis acid-catalyzed reactions between per-*O*-acetylated sugar derivatives and trimethylsilyl azide.[32] Conventionally, preparation of glycosyl azides from unprotected reducing sugars is achieved in two steps, the first of which involves preparation of the per-*O*-acetylated sugars by treatment with excess acetic anhydride with catalysis by $HClO_4$ and in situ conversion of the per-*O*-acetylated sugars into per-*O*-acetylated glycosyl halides by treatment with HBr/AcOH (30%). The second step then involves the nucleophilic substitution of anomeric halide by metal azide either under homogeneous reaction conditions in high boiling solvents such as DMF, DMSO, etc. or under heterogeneous phase-transfer reaction conditions. Alternatively, initial conversion of free sugars into glycosyl per-*O*-acetates with excess acetic anhydride and pyridine and treatment of the previously prepared glycosyl per-*O*-acetates with trimethylsilyl azide in the presence of a Lewis acid has furnished glycosyl azides.

The most often employed approaches for the synthesis of thioglycosides involve the treatment of per-*O*-acetylated sugars with alkyl/aryl thiols in the presence of Lewis acids.[33–35] Alternatively, alkyl/aryl thiotrimethylsilanes have also been employed in the presence of a Lewis acid for the preparation of thiglycosides.[36–37] These two methods have similar drawbacks including the anomerization of the thioglycosides under the reaction conditions because of the time

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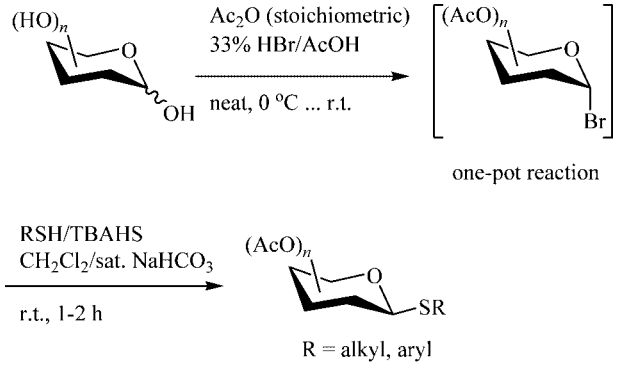
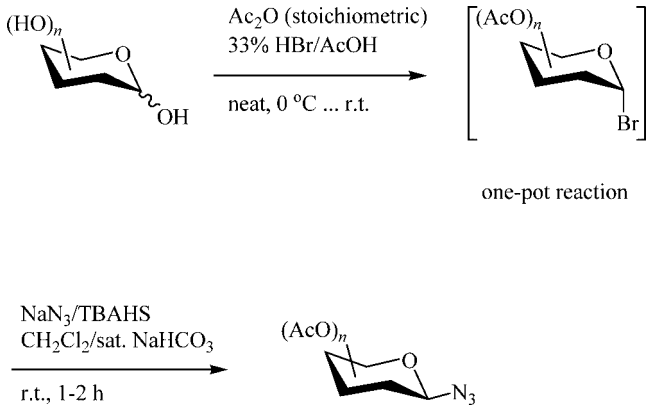
[a] Medicinal and Process Chemistry Division, Central Drug Research Institute,
Chattar Manzil Palace, Lucknow 226001, UP, India
[b] Molecular and Structural Biology Division, Central Drug Research Institute,
Chattar Manzil Palace, Lucknow 226001, UP, India
E-mail: akmisra69@rediffmail.com

and temperature required. Another method for the exclusive preparation of 1,2-*trans*-thioglycosides uses *S*-glycosyl isothiouronium salts generated from glycosyl halides as starting materials.[38,39] Although this method offers a comparatively odorless method, it requires pre-generation of *S*-glycosyl isothiouronium salts from relatively unstable glycosyl halides, and in general this method does not allow preparation of aryl thioglycosides. Synthesis of thioglycosides from free sugars requires at least two steps, the first of which involves the per-*O*-acetylation of free sugars either with excess acetic anhydride and sodium acetate[40] or in the presence of a Lewis acid catalyst or pyridine and pyridine derivatives, which are known to be very toxic and requiring a workup consisting of neutralization of excess reagents and purification prior to the next step. This second step involves the nucleophilic substitution of anomeric acetate groups by thiols in the presence of a Lewis acid. In both cases, the use of excess acetic anhydride and pyridine makes the synthetic procedure tedious. Two reports that have recently appeared in the literature involve the per-*O*-acetylation of a free hexose by use of a stoichiometric quantity of acetic anhydride with catalysis by $Cu(OTf)_2$[41] or iodine[42] and subsequent substitution of the anomeric acetate group to provide a thioglycoside in the presence of $BF_3{\cdot}OEt_2$ or excess iodine and hexamethyldisilane.

Although glycosyl bromide has been used previously for the preparation of glycosyl azides and thioglycosides, preparation through sequential formation of glycosyl acetates and per-*O*-acetyl glycosyl bromides directly from unprotected reducing sugars in a single pot had not been investigated. In this context, it would be useful to develop an economically convenient generalized one-pot method capable of furnishing glycosyl azides and thioglycosides directly from unprotected reducing sugars without any need for purification of intermediates. In order to avoid the use of excess acetic anhydride and other toxic catalysts such as pyridine, and to shorten the synthetic efforts involved in the preparation of glycosyl azides and thioglycosides, we envisioned that the use of a stoichiometric quantity of acetic anhydride in the presence of HBr/AcOH (30%) could be beneficial for the preparation of a per-*O*-acetylated glycosyl bromide directly from a free sugar and subsequent phase-transfer-catalyzed anomeric azidolysis or thiolysis in one-pot fashion. In an earlier report,[43] HBr/AcOH (30%) and excess acetic anhydride had been used for the preparation of per-*O*-acetylated glycosyl bromides from unprotected reducing sugars. In this report we describe an efficient generalized one-pot phase-transfer reaction approach for the preparation of per-*O*-acetylated thioglycosides and glycosyl azides directly from unprotected reducing sugars (Scheme 1 and Scheme 2).



Scheme 1.

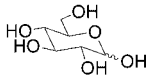
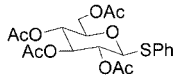
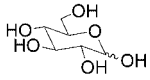
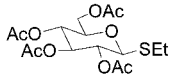
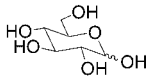
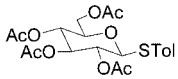
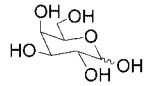
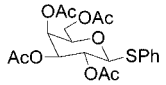
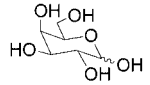
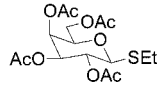
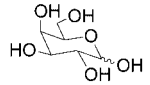
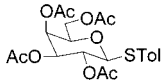
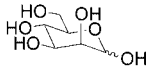
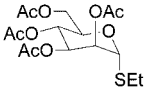
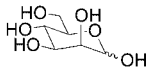
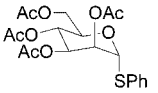
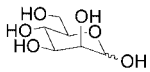
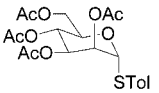
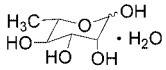
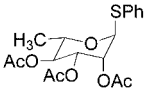
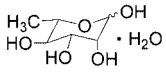
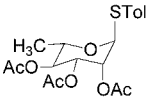
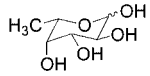
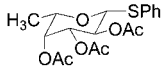
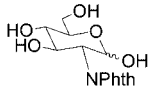
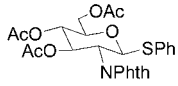
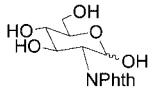
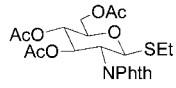
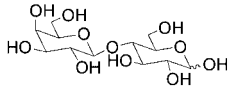
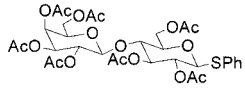
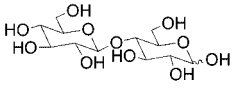
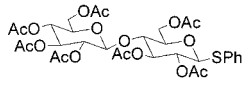
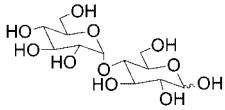
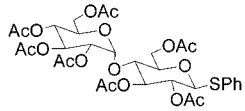


Scheme 2.

Results and Discussion

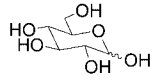
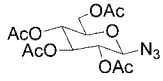
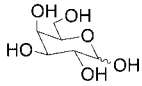
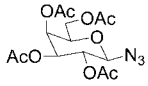
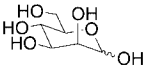
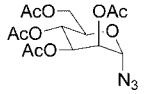
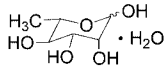
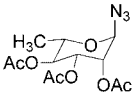
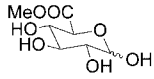
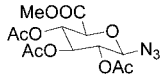
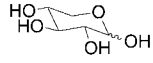
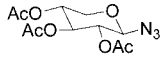
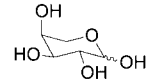
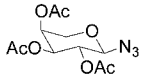
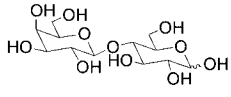
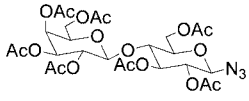
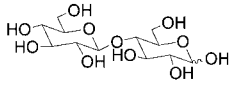
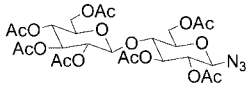
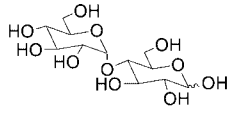
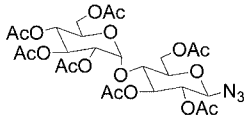
In order to standardize the reaction procedure, HBr/AcOH (30%, 270 μL, 1.0 mmol) was added to a well stirred suspension of D-glucose (180 mg, 1.0 mmol) in acetic anhydride (0.5 mL, 5.3 mmol) at room temperature. An exothermic reaction started immediately and a clear reaction mixture was obtained within few minutes, with clean formation of per-*O*-acetylated D-glucose (TLC). A reduction of the quantity of HBr/AcOH (30%) from 1.0 equiv. to 0.5 equiv. resulted in a very slow reaction for the formation of per-*O*-acetylated D-glucose. After a series of experiments, it was observed that use of 1.02 equiv. of acetic anhydride per hydroxy group in the free sugar and 1.0 equiv. of HBr/AcOH (30%) produced an excellent yield of the per-*O*-acetylated product in a very fast and efficient manner. After formation of the per-*O*-acetylated D-glucose with use of stoichiometric acetic anhydride, the reaction mixture was cooled to 0–5 °C, another portion of HBr/AcOH (30%, 540 μL, 2.0 mmol) was added, and the mixture was allowed to stir at room temperature (approx. 2 h) until TLC revealed the formation of the acetobromo-D-glucose as the sole product. Subsequent azidolysis or thiolysis of the acetobromo-D-glucose formed in situ was carried out by treatment with sodium azide (2.0 equiv.) or thiol (1.5 equiv.) and tetrabutylammonium hydrogen sulfate (TBAHS) under phase-transfer catalysis (PTC) conditions in CH_2Cl_2 at room temperature to furnish the glycosyl azide or thioglycoside in excellent yield. In contrast to the conventional per-*O*-acetylation, in which excess acetic anhydride is used and neutralization followed by workup and purification is essential before the second step, the use of a stoichiometric amount of acetic anhydride for acetylation in the presence of HBr/AcOH (30%) by our

Table 1. One-pot preparation of thioglycosides from free sugars under phase-transfer reaction conditions.[44–52].[a]

	Sugars (1)	Thiols	Products (2)	Time[b] (min)	Yield (%)[c]	Ref.
a		PhSH		30	95	[44]
b		EtSH		30	92	[45]
c		*p*-Me-PhSH		30	95	[46]
d		PhSH		30	91	[47]
e		EtSH		45	90	[45]
f		*p*-Me PhSH		30	88	[46]
g		EtSH		30	90	[48]
h		PhSH		30	95	[49]
i		*p*-Me PhSH		30	92	[50]
j		PhSH		30	86	[51]
k		*p*-Me PhSH		30	90	[52]
l		PhSH		30	90	[53]
m		PhSH		45	90	–
n		EtSH		45	92	–
o		PhSH		45	88	[54]
p		PhSH		45	90	[54]
q		PhSH		45	85	[54]

[a] All reactions were conducted at room temperature. [b] After formation of glycosyl bromide. [c] Isolated yield.

Table 2. One-pot preparation of glycosyl azides from free sugars under phase-transfer reaction conditions with use of sodium azide.[a]

	Sugars (3)	Products (4)	Time (h)[b]	Yield (%)[c]	Ref.
a			1.5	90	[31]
b			1.5	85	[31]
c			1.5	90	[55]
d			1.5	85	–
e			2.5	82	[56]
f			2.0	90	[57]
g			2.0	90	–
h			3.0	85	[31]
i			3.0	80	[58]
j			3.0	82	[31]

[a] All reactions were conducted at room temperature. [b] After formation of glycosyl bromide. [c] Isolated yield.

method, followed by in situ generation of glycosyl bromide, offers an excellent opportunity to carry out sequential per-*O*-acetylation–anomeric azidolysis or thiolysis in one-pot fashion. By a similar reaction sequence, a series of aryl/alkyl thioglycosides and glycosyl azides were successfully synthesized in a very convenient manner, starting from a variety of unprotected mono- and disaccharides (Table 1 and Table 2). Per-*O*-acetylated thioglycosides and glycosyl azides prepared from commonly available sugars gave acceptable ^{1}H NMR and ^{13}C NMR spectra that matched data reported in the cited references. All reactions occurred with high stereoselectivity and completely anomerically inverted products (i.e., 1,2-*trans* glycosyl azides and thioglycosides) were obtained, thanks to the formation of a 1,2-oxocarbonium ion as a result of neighboring group participation of the acetyl group at C-2, followed by the attack of azide or thiols from the opposite side of the oxocarbonium ion intermediate. It is noteworthy that no formation of glycofuranosyl azides or thioglycosides was observed under these reaction conditions. Although all acetylation reactions were performed at room temperature at milligram scales, cooling arrangements are required for multigram scales to avoid the loss of reagents and decomposition of products due to overheating resulting from the exothermic reaction.

Conclusions

In summary, this one-pot phase-transfer methodology offers a generalized, convenient, mild, completely stereoselective, and high-yielding route to per-*O*-acetylated glycosyl azides and thioglycosides directly from the free sugars without purification of intermediates. This procedure is compatible with acid- and base-sensitive protecting groups used for protection of carbohydrates. Use of readily available reagents, without any need either for heavy metallic salts or for high-boiling solvents and expensive Lewis acids makes this operationally simple one-pot reaction procedure for the preparation of glycosyl azides and thioglycosides directly from free sugars an attractive alternative to the existing methods.

Experimental Section

Typical Experimental Procedure for the Preparation of Per-*O*-acetylated Thioglycosides

Phenyl 2,3,4,6-Tetra-*O*-acetyl-1-thio-β-D-galactopyranoside (2d): A suspension of D-galactose (1.8 g, 10.0 mmol) in acetic anhydride (4.82 mL, 51.0 mmol) was placed in an ice bath with continuous stirring. HBr/AcOH (30%, 2.7 mL, 10.0 mmol) was added in one portion to the cold suspension. An exothermic reaction started immediately and the reaction mixture was allowed to stir at room temperature until a clear solution was obtained (approx. 15 min). The reaction mixture was cooled to 0 °C, additional HBr/AcOH (30%, 5.4 mL, 20 mmol) was added slowly, and stirring was continued for 2 h at room temperature. After completion of the reaction (monitored by TLC; hexane/EtOAc 1:1), solvents were removed under reduced pressure and coevaporated with toluene. Thiophenol (1.5 mL, 14.6 mmol), tetrabutylammonium hydrogen sulfate (TBAHS) (510 mg, 1.5 mmol) and aq. Na_2CO_3 (1 M, 70 mL) were added successively to a solution of the crude mass in CH_2Cl_2 (50 mL) and the two-phase reaction mixture was allowed to stir vigorously for another 30 min. The reaction mixture was diluted with CH_2Cl_2 (50 mL). The organic layer was separated and washed with water, dried (Na_2SO_4), and concentrated under reduced pressure. Purification of the crude reaction product over SiO_2 with hexane/EtOAc (4:1) furnished pure **2d**, which was further crystallized from Et_2O/hexane (4.0 g, 91%). A series of thioglycosides was prepared by a similar reaction procedure (Table 1).

Typical Experimental Procedure for the Preparation of Per-*O*-acetylated Glycosyl Azides

2,3,4,6-Tetra-O-acetyl-*β*-D-galactopyranosyl Azide (4b): A suspension of D-galactose (1.8 g, 10.0 mmol) in acetic anhydride (4.82 mL, 51.0 mmol) was placed in an ice bath with continuous stirring. HBr/AcOH (30%, 2.7 mL, 10.0 mmol) was added in one portion to the cold suspension of the reaction mixture. An exothermic reaction started immediately and the reaction mixture was allowed to stir at room temperature until a clear solution was obtained (approx. 15 min). The reaction mixture was cooled to 0 °C, additional HBr/AcOH (30%, 5.4 mL, 20 mmol) was added slowly, and stirring was continued for 2 h at room temperature. After completion of the reaction (monitored by TLC; hexane/EtOAc 1:1), solvents were removed under reduced pressure and coevaporated with toluene. Sodium azide (1.3 g, 20 mmol), tetrabutylammonium hydrogen sulfate (TBAHS) (510 mg, 1.5 mmol) and aq. Na_2CO_3 (1 M, 70 mL) were added successively to a solution of the crude mass in CH_2Cl_2 (50 mL) and the two-phase reaction mixture was allowed to stir vigorously for another 1.5 h. The reaction mixture was diluted with CH_2Cl_2 (50 mL). The organic layer was separated and washed with water, dried (Na_2SO_4), and concentrated under reduced pressure. Purification of the crude reaction product over SiO_2 with hexane/EtOAc (3:1) furnished pure **4b**, which was further crystallized from Et_2O/hexane (3.17 g, 85%). A series of glycosyl azides was prepared by a similar reaction procedure (Table 2).

Spectral Data for Compounds not Reported Earlier

Phenyl 3,4,6-Tri-*O*-acetyl-2-deoxy-2-phthalimido-1-thio-*β*-D-glucopyranoside (2m): Yield 90%, oil. $[\alpha]_D^{25}$ = +70.5 (c = 1.5, $CHCl_3$). ^1H NMR ($CDCl_3$, 300 MHz): δ = 7.88–7.74 (m, 4 H, Ar-H), 7.43–7.26 (m, 5 H, Ar-H), 5.86–5.76 (t, J = 10.1 Hz, 1 H, 3-H), 5.80–5.71 (t, J = 10.0 Hz, 1 H, 4-H), 5.19–5.10 (t, J = 10.0 Hz, 1 H, 2-H), 4.41–4.36 (d, J = 10.4 Hz, 1 H, 1-H), 4.35–4.23 (m, 2 H, 6-H^{a,b}), 3.95–3.87 (m, 1 H, 5-H), 2.10, 2.02, 1.84 (3×s, 9 H, 3×COCH_3) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ = 170.9, 170.4, 169.8, 168.1, 167.3, 134.8–124.0 (C arom.), 83.4, 76.3, 72.0, 69.1, 62.6, 53.9, 21.1, 20.9, 20.7 ppm. IR (neat): $\tilde{\nu}$ = 2952, 1747, 1417, 1591, 1384, 1228, 1074, 1037, 719 cm^{-1}. ESI-MS: 550 [M + Na]$^+$. $C_{26}H_{25}NO_9S$ (527.1): C 59.19, H 4.78; found C 58.95, H 5.0.

Ethyl 3,4,6-Tri-*O*-acetyl-2-deoxy-2-phthalimido-1-thio-*β*-D-glucopyranoside (2n): Yield 92%, oil. $[\alpha]_D^{25}$ = +90.5 (c = 1.5, $CHCl_3$). ^1H NMR ($CDCl_3$, 300 MHz): δ = 7.81–7.65 (m, 4 H, Ar-H), 5.80–5.71 (t, J = 9.6 Hz, 1 H, 3-H), 5.42 (d, J = 10.6 Hz, 1 H, 1-H), 5.15–5.05 (t, J = 9.6 Hz, 1 H, 4-H), 4.37–4.26 (t, J = 10.4 Hz, 1 H, 2-H), 4.20–4.02 (dq, 2 H, 6-H^{a,b}), 3.87–3.80 (m, 1 H, 5-H), 2.70–2.50 (q, 2 H, SCH_2CH$_3$), 2.02, 1.95, 1.78 (3×s, 9 H, 3×COCH_3), 1.17–1.10 (t, J = 7.5 Hz, 3 H, SCH$_2$CH_3) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ = 170.9, 170.4, 169.8, 168.0, 167.5, 134.7, 131.9, 131.6, 124.0 (3 C), 81.5, 76.3, 71.9, 69.3, 62.3, 54.1, 24.6, 21.0, 20.9, 20.7, 15.2 ppm. IR (neat): $\tilde{\nu}$ = 2965, 1753, 1413, 1597, 1380, 1236, 1070, 1042, 736 cm^{-1}. ESI-MS: 502 [M + Na]$^+$. $C_{22}H_{25}NO_9S$ (479.1): C 55.11, H 5.26; found: C 55.35, H 5.48.

2,3,4-Tri-*O*-acetyl-6-deoxy-α-L-mannopyranosyl Azide (4d): Yield 85%, oil. $[\alpha]_D^{25}$ = –163 (c = 1.2, $CHCl_3$). ^1H NMR (200 MHz, $CDCl_3$): δ = 5.32–5.31 (d, J = 1.4 Hz, 1 H, 1-H), 5.24–5.20 (m, 1 H, 2-H), 5.15–5.03 (m, 2 H, 3-H and 4-H), 4.10–3.96 (m, 1 H, 5-H), 2.16, 2.06, 1.99 (3×s, 9 H, 3×COCH_3), 1.29–1.26 (d, J = 6.2 Hz, 3 H, CH_3) ppm. ^{13}C NMR (50 Hz, $CDCl_3$): δ = 170.21 (3 C), 87.85, 70.81, 69.80, 68.97, 68.66, 21.11, 21.06, 20.93, 17.77 ppm. IR (neat): $\tilde{\nu}$ = 2116, 1749, 1374, 1243, 1124, 1046, 936, 758 cm^{-1}. ESI-MS: 338 [M + Na]$^+$. $C_{12}H_{17}N_3O_7$ (315.1): C 45.71, H 5.43; found C 45.48, H 5.60.

2,3,4-Tri-*O*-acetyl-β-L-arabinopyranosyl Azide (4g): Yield 90%, pale yellow solid; m.p. 105 °C. $[\alpha]_D^{25}$ = –5.4 (c = 1.2, $CHCl_3$). ^1H NMR ($CDCl_3$, 300 MHz): δ = 5.30–5.23 (m, 1 H, 2-H), 5.18–4.97 (m, 2 H, 3-H and 4-H), 4.57–4.53 (d, J = 7.3 Hz, 1 H, 1-H), 4.12–4.04 (dd, J = 2.8 and 13.1 Hz, 1 H, 5-H^a), 3.78–3.71 (dd, J = 1.5 and 13.1 Hz, 1 H, 5-H^b), 2.16, 2.10, 2.01 (3×s, 9 H, 3×COCH_3) ppm. ^{13}C NMR ($CDCl_3$, 75 MHz): δ = 170.6, 170.4, 169.7, 88.8, 70.0, 68.3, 67.4, 65.5, 20.7, 20.5, 20.3 ppm. IR (neat): $\tilde{\nu}$ = 2124, 1757, 1370, 1249, 1132, 1046, 940, 757 cm^{-1}. ESI-MS: 324 [M + Na]$^+$. $C_{11}H_{15}N_3O_7$ (301.1): C 43.86, H 5.02; found C 43.67, H 5.28.

Acknowledgments

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