Carbohydrate Research 344 (2009) 240–244

Contents lists available at ScienceDirect

Carbohydrate Research

journal homepage: www.elsevier.com/locate/carres

Note

A novel synthesis of β-D-mannopyranosyl azide by phase transfer catalysis

Polina I. Abronina, Vadim V. Kachala, Leonid O. Kononov *

N. D. Zelinsky Institute of Organic Chemistry of the Russian Academy of Sciences, Leninsky Prospect, 47, 119991 Moscow, Russian Federation

ARTICLE INFO

Article history:
Received 16 September 2008
Received in revised form 24 October 2008
Accepted 26 October 2008
Available online 5 November 2008

Keywords:
Glycosyl azides
1,2-*cis*-Mannopyranosyl azide
Phase transfer catalysis
Stereoselectivity
NMR spectroscopy

ABSTRACT

A simple stereoselective synthesis of per-*O*-benzoyl-β-D-mannopyranosyl azide from per-*O*-benzoyl-α-D-mannopyranosyl bromide using phase transfer catalysis was developed. The stereochemistry at C-1 of the anomeric O-benzoylated α- and β-D-mannopyranosyl azides was unambiguously established using 2D NOESY NMR spectroscopy. Pure deprotected β-D-mannopyranosyl azide was prepared by debenzoylation with sodium methoxide in methanol.

© 2008 Elsevier Ltd. All rights reserved.

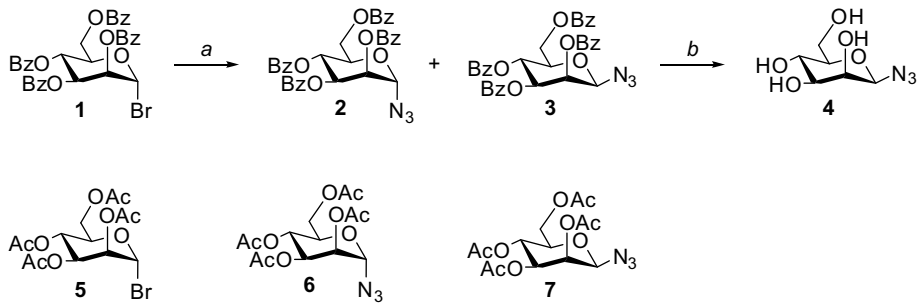
Glycosyl azides receive considerable attention in connection with the versatile reactivity of the azido group and have numerous synthetic applications.[1] For example, they can be used as building blocks in oligosaccharide synthesis,[2] as synthetic precursors of fragments of *N*-glycoprotein glycans[3] and *N*-glycopeptides (prepared from glycosyl azides either directly by a modified Staudinger reaction[4] or via intermediacy of glycosyl amines[1b,c]). Current interest in glycosyl azides stems mainly from the 1,3-dipolar character of the azido group, which had been previously exploited for [2+3]-cycloaddition reactions of glycosyl azides with compounds containing triple bonds. Motivated largely by pharmacological considerations (to obtain compounds with cytostatic properties), a great number of 1-*N*-glycosyl-1,2,3-triazole derivatives have been prepared.[1c] Since the formulation of the 'click chemistry' concept,[5] a number of reports employing this methodology for preparing pseudo-oligosaccharide analogues with 1,2,3-triazole linkers in place of glycosidic bonds was published.[6]

In this regard, β-D-mannopyranosyl azide could be a valuable building block for preparing pseudo-oligosaccharide analogues of the natural *N*-glycoprotein core oligosaccharide chain ($Man_3GlcNAc_2$),[3] which contains a difficulty accessible β-mannosidic linkage[7,8] in addition to α-mannosidic linkages, which are relatively easy to make.[9] Such derivatives may be considered as glycoprotein mimetics useful for glycobiological studies. The assembly of pseudo-oligosaccharide chains by [2+3]-cycloaddition reactions of mannopyranosyl azides with suitable alkynes could be a viable alternative to conventional O-glycosylation provided both α- and β-D-mannopyranosyl azides are readily accessible. While numerous methods for generation of α-D-mannopyranosyl azide are known, only a few syntheses refer to β-D-mannopyranosyl azide (**4**) (Scheme 1).[1] The only practical method for the efficient preparation of β-D-mannopyranosyl azide **4** was proposed by Gyorgydeak and Paulsen in 1977.[10] This synthesis is based on the reaction of per-*O*-benzoyl-α-D-mannopyranosyl bromide (**1**) with NaN_3 in HMPA as a solvent at ambient temperature yielding per-*O*-benzoyl-β-D-mannopyranosyl azide (**3**) in 88% yield. Unprotected β-azide **4** was easily obtained from **3** by Zemplen deacetylation.[10] However, a significant limitation of this method is the proven carcinogenicity of HMPA, which hampers its wide use in laboratory and industrial practice.

In this communication, we describe an alternative approach to per-*O*-benzoyl-β-D-mannopyranosyl azide (**3**) using phase transfer catalysis (PTC),[11] which is advantageous from a practical point of view. The application of PTC to the synthesis of β-mannopyranosyl azide, with the 1,2-cis-stereochemistry does not seem to be as straightforward as it was in the case of preparation of *gluco*- and *galacto*-configured glycosyl azides,[11b] which have 1,2-trans-arrangement, due to reasons similar to those that make the synthesis of *O*-β-mannosides (1,2-cis) difficult.[7,8] In fact, the reaction of the in situ generated 2,3,4,6-tetra-*O*-acetyl-α-D-mannopyranosyl bromide (**5**) with NaN_3 under standard PTC conditions (1 M Na_2CO_3–CH_2Cl_2 in the presence of Bu_4NHSO_4, ambient temperature) was reported[12] to give *exclusively* the 1,2-*trans*-mannopyranosyl azide (**6**). Unfortunately, no data confirming the structure of the obtained 1,2-*trans*-mannopyranosyl azide were presented in this publication,[12] preventing justified conclusions concerning the anomeric configuration of the product. Such unverified

* Corresponding author. Tel.: +7 495 1377570; fax: +7 495 1376148.
E-mail address: kononov@ioc.ac.ru (L. O. Kononov).

0008-6215/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.carres.2008.10.027



Scheme 1. Reagents and conditions: (a) NaN_3, Bu_4NHSO_4, 1 M Na_2CO_3–organic solvent (see Table 1 for the details); (b) MeONa, MeOH.

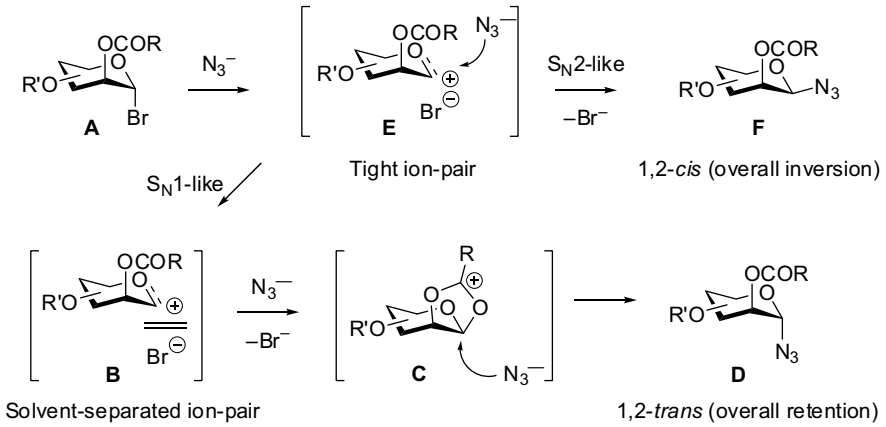
assignments of anomeric configuration had created long-standing ambiguity surrounding the anomeric configuration of mannopyranosyl azides, which has only recently been resolved by combination of X-ray diffraction analysis and 1D NOESY NMR spectroscopy of per-*O*-acetyl-α- and β-D-mannopyranosyl azides (**6** and **7**, respectively).[13] On the other hand, the lack of proof in the cited publication[12] gave us hope that the PTC protocol could be adapted to the preparation of a mannopyranosyl azide with the β-configuration.

The reported[12] *retention* of configuration upon reaction of α-D-mannopyranosyl bromide **5** (1,2-trans) with NaN_3 seems to be the result of neighboring group participation of the acetyl group at C-2. The mechanism of the reaction of a 2-*O*-acyl-glycopyranosyl bromide **A** apparently includes an easy generation of a solvent-separated ion-pair **B** ('glycosyl cation') and subsequent attack of the acyloxonium ion **C**, formed along the S_N1-like pathway, by azide-anion from the opposite side leading to the 1,2-*trans*-glycosyl azide **D** (Scheme 2). The formation of 1,2-*trans*-mannopyranosyl azide **D** with an axial azide substituent is additionally favored by the anomeric effect.[14]

We reasoned that creation of conditions for the realization of S_N2-like pathway could favor the formation a tight ion-pair **E**, nucleophilic attack of which by azide-anion would result in anomeric inversion, thus leading to 1,2-*cis*-mannopyranosyl azide **F** (Scheme 2). The S_N1-like pathway is expected[15] to be disfavored in a nonpolar solvent such as benzene or toluene, which is incapable of solvating cations, rather than in relatively polar dichloromethane used in the earlier study,[12] which has apparently favored the S_N1-like pathway. Dipolar aprotic solvents such as HMPA, which highly favor an S_N2-mechanism,[15] were successfully used for the preparation of β-D-mannopyranosyl azides[10] but are not compatible with PTC protocol due to their miscibility with water.

Another possibility to favor the S_N2-like pathway is the use of a glycosyl halide with poor nucleofugicity (i.e., leaving-group ability) of a halide anion and hence the lower tendency to form glycosyl cation. This can be achieved if a mannopyranosyl halide, which is known to be poorly reactive, is used. A possible approach could be the use of mannopyranosyl chlorides rather than bromides in the PTC-promoted azidation. However, *O*-acyl hexopyranosyl chlorides are rather poor electrophiles. Even *O*-alkyl hexopyranosyl chlorides, which are used in Lemieux-type 1,2-cis-glycosylations, react very slowly with nucleophiles when unpromoted by heavy metal salts,[8] which is a typical situation in PTC. On the other hand, the use of more powerful electron-withdrawing O-protecting group, which would destabilize 'glycosyl cation' **B**, could affect the reactivity of a mannopyranosyl bromide. Indeed, while 2,3,4,6-tetra-*O*-acetyl-α-D-mannopyranosyl bromide (**5**) is known to be easily activated by Hg(II) salts, the corresponding α-D-mannopyranosyl bromide **1** with *O*-benzoyl protective groups, which possess stronger electron-accepting properties, is fairly *stable* under standard conditions of Hg(II)-promoted glycosylations. Only the use of much more powerful promoters, such as AgOTf, is required to involve per-*O*-benzoyl-glycosyl bromide **1** in a typical O-glycosylation reaction.[9]

We supposed that the use of relatively unreactive α-D-mannopyranosyl bromide **1** with *O*-benzoyl protective groups in a nonpolar solvent such as benzene or toluene, incapable of solvating cations, would reduce charge separation in the intermediate (making pathway via the tight ion-pair **E** more favorable than that via the solvent-separated ion-pair **B**) and hence neighboring-group participation. This would favor S_N2-like mechanism and eventually result in formation of 1,2-*cis*-mannopyranosyl azide **F**. In fact, the heating of 1,2-*trans* per-*O*-benzoyl-α-D-mannopyranosyl bromide (**1**) with NaN_3 (5 equiv) in the presence of Bu_4NHSO_4 (5 equiv) at reflux in a two-phase 1 M Na_2CO_3–benzene mixture for 7 h gave



Scheme 2. A mechanism explaining formation of 1,2-*cis*- and 1,2-*trans*-2-*O*-acyl-glycosyl azides.

Table 1

Entry	Organic solvent[a]	Reaction temperature[b] (°C)	Reaction time (h)	Yield[c] (%)	
				3	**2**
A	Benzene	85	7	70	6
B	Toluene	115	2	66	8
C	EtOAc	22	48	65	7

[a] A two-phase mixture of an organic solvent with aqueous 1 M Na_2CO_3 was used.
[b] Bath temperature.
[c] Isolated yields after silica gel chromatography.

mainly 1,2-*cis*-mannopyranosyl azide **3**, with only small amount of 1,2-*trans*-mannopyranosyl azide **2** being isolated (Scheme 1 and Table 1, ***A***). The formation of α-isomer **2** can be rationalized within the framework of S_N2-like mechanism if one considers a possibility of nucleophilic attack of the tight ion-pair **E** by the liberating bromide anion, which would lead to the formation of β-configured mannopyranosyl bromide (not shown in Scheme 2), the reaction of the latter with azide anion leading to the mannopyranosyl azide **D** with overall retention of configuration.

Similar results were obtained by heating at reflux a two-phase mixture that contained toluene instead of benzene. In this case, the reaction was faster (2 h, Table 1, ***B***). Interestingly, almost the same ratio of the anomers was obtained when more solvating ethyl acetate was used as the organic solvent in two-phase mixture at ambient temperature, albeit the reaction being slower (48 h, Table 1, ***C***). The latter observation clearly indicates that the driving force for preferential formation of 1,2-*cis*-mannopyranosyl azide **3** is the poor nucleofugicity of bromide anion in α-D-mannopyranosyl bromide **1** with *O*-benzoyl protective groups, rather than solvent polarity effects (see above). This suggests that the reported[12] failure to use α-D-mannopyranosyl bromide **5** with *O*-acetyl protective groups for the preparation of 1,2-*cis*-mannopyranosyl azide **7** is apparently related to the improper choice of O-protective groups in glycosyl donor.

We intentionally did not perform any azidation experiments in dichloromethane because there are several reports[13,16] that violent explosions, probably caused by diazidomethane,[16b] occurred when dichloromethane was used as a solvent for azidation or even during workup. We believe that the use of halogenated solvents in such reactions should be avoided and other solvents should be used during workup.[16d,e]

It should be noted that the prepared O-benzoylated anomeric azides **2** and **3** differ in chromatographic mobilities (R_f = 0.67 and 0.52, respectively; toluene–ethyl acetate, 19:1) and can easily be separated.

The previously assigned[10] anomeric configuration of α- and β-mannopyranosyl azides **2** and **3** was not supported by definitive evidence. In this communication, we unambiguously establish the stereochemistry at C-1 of the anomeric O-benzoylated mannopyranosyl azides **2** and **3** using two-dimensional (2D) NOESY NMR spectroscopy.

Typically, the anomeric configuration of a hexopyranose can readily be determined from ^{1}H NMR data if the H-2 proton is axial. In this case, the magnitude of the coupling constant (J) between H-1 and H-2 is relatively large ($J_{1,2} \sim 7$–8 Hz) if H-1 is also axial. But the coupling constant is comparatively small ($J_{1,2} \sim 3.4$ Hz) if H-1 is equatorial. However, when H-2 is oriented equatorially, as in the case of mannopyranose derivatives, the anomeric configuration cannot be assigned reliably from ^{1}H NMR data because axial–equatorial and equatorial–equatorial $J_{1,2}$ couplings are of similar magnitude. The use of ^{13}C chemical shifts and carbon–proton coupling constants ($^1J_{C\text{-}1,H\text{-}1}$) is similarly unreliable for establishing anomeric configuration in mannopyranose derivatives.[17]

To prove anomeric configuration of the β-azide **3**, we used 2D NOESY NMR spectroscopy. For comparison, 2D NOESY experiment was also performed for the α-anomer **2**. As illustrated in Figure 1, correlations of H-1 with H-2, H-3, and H-5 were observed in the 2D NOESY spectrum of β-azide **3**. The presence of correlations of H-1 with H-3 and H-5 in NOESY spectrum of this compound indicated that H-1 is situated at the α-face of the pyranose ring and therefore the compound **3** was the β-anomer. On the contrary, as illustrated in Figure 2, only a *single* correlation of H-1 with H-2 in the 2D NOESY spectrum of α-azide **2** was observed. The absence of correlations of H-1 with H-3 and H-5 in 2D NOESY spectrum of compound **2** indicated that H-1 is at the β-face of the pyranose ring, and that this compound was therefore α-anomer. Our assignments are in full agreement with those reported for per-*O*-acetyl-α- and

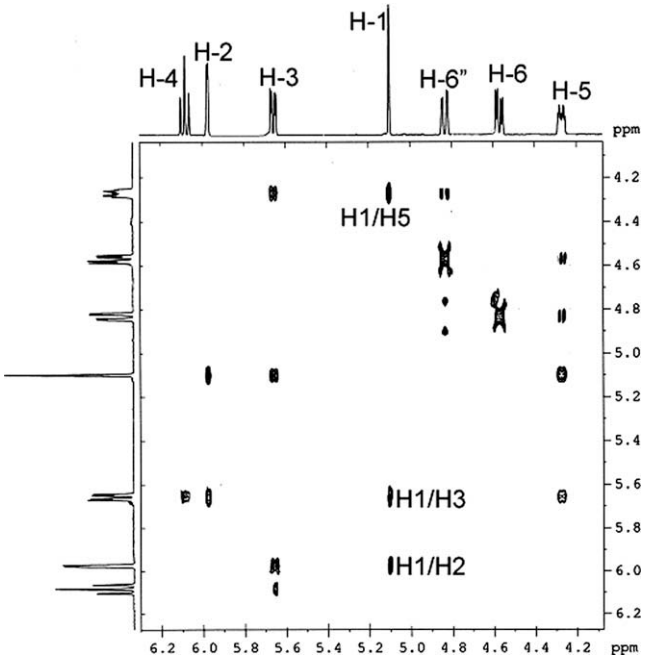


Figure 1. 2D NOESY spectrum for β-azide **3**. The presence of correlations of H-1 with H-3 and H-5 indicates that this is β-anomer.

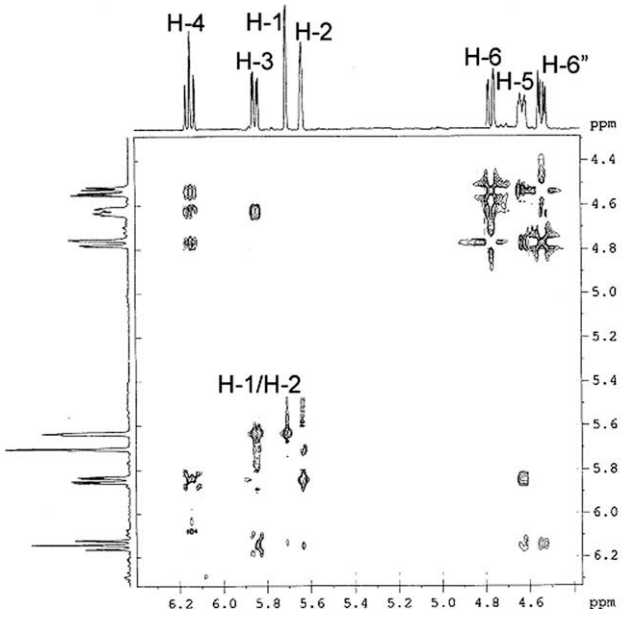


Figure 2. 2D NOESY spectrum for α-azide **2**. The presence of only single correlation of H-1 with H-2 and the absence of correlations of H-1 with H-3 and H-5 indicate that this is α-anomer.

β-D-mannopyranosyl azides (**6** and **7**, 1,2-trans and 1,2-cis, respectively), which have been recently characterized by NMR and X-ray diffraction analysis.[13]

The obtained pure benzoylated β-D-mannopyranosyl azide **7** was treated with sodium methoxide in methanol to give the known[10] β-D-mannopyranosyl azide **4**. The 2D NOESY spectrum (not shown) of azide **4** contained correlations between H-1 with H-2, H-3, and H-5, confirming its structure as the β-anomer (see above).

In conclusion, we have developed a novel expedient synthesis of β-mannopyranosyl azide. Due to its experimental simplicity and low cost of reagents, this procedure may find wide use in laboratory and industrial practice.

1. Experimental

1.1. General methods

The reactions were performed with the use of commercial reagents (Aldrich and Fluka), and anhydrous solvents were purified according to standard procedures. 2,3,4,6-Tetra-*O*-benzoyl-α-D-mannopyranosyl bromide (**1**) was prepared essentially as described for 2,3,4,6-tetra-*O*-benzoyl-α-D-[1-^{13}C]mannopyranosyl bromide.[18] Optical rotations were measured using a PU-07 automatic polarimeter (Russia). ^{1}H and ^{13}C NMR spectra were recorded on a Bruker DRX-500 spectrometer (500.13 and 125.32 MHz, respectively) or on a Bruker AV-600 spectrometer (600.13 and 150.57 MHz, respectively) for solutions in $CDCl_3$ or in D_2O (for **4**). The ^{1}H NMR chemical shifts are referred to the residual signal of $CHCl_3$ (δ_H 7.27) or to the external sodium 3-(trimethylsilyl)-2,2,3,3-tetradeuteropropanoate (TSP) in D_2O (δ_H 0.0), the ^{13}C NMR—to the $CDCl_3$ signal (δ_C 77.0) or to the external MeOH in D_2O (δ_C 31.45). Assignments of the signals in the NMR spectra were performed using 2D-spectroscopy (COSY, gHSQC, and gNOESY) and DEPT-135 experiments. Thin-layer chromatography was carried out on plates with Silica Gel 60 on aluminum foil (Merck). Spots of compounds containing carbohydrates were visualized by dipping a TLC plate into a solution of 85% H_3PO_4 in 96% EtOH (1:10, v/v) with subsequent heating (150 °C). Column chromatography was performed on Silica Gel 60 (40–63 μm, Merck). IR spectra were recorded on a Carl-Zeiss M-82 IR spectrometer in the 600–3800 cm^{-1} range for solutions in $CHCl_3$. Mass spectra (electrospray ionization, ESI) were recorded on a Finnigan LCQ mass spectrometer for 2×10^{-5} M solutions in CH_2Cl_2–MeOH mixtures.

1.2. 2,3,4,6-Tetra-*O*-benzoyl-α-D-mannopyranosyl azide (2) and 2,3,4,6-tetra-*O*-benzoyl-β-D-mannopyranosyl azide (3)

Method **A.** To a solution of 2,3,4,6-tetra-*O*-benzoyl-α-D-mannopyranosyl bromide (**1**) (100 mg, 0.152 mmol) in benzene (2 mL), tetrabutylammonium hydrogen sulfate (TBAHS) (51.6 mg, 0.152 mmol), NaN_3 (50 mg, 0.76 mmol), and 1 M Na_2CO_3 (2 mL) were added. The two-phase mixture was vigorously stirred at 85 °C (bath) for 7 h, after which time TLC indicated complete transformation of the halide. Benzene (20 mL) was then added, the organic phase was separated and successively washed with satd $NaHCO_3$, H_2O (×2), and brine. The combined organic extracts were dried (Na_2SO_4), filtered, and evaporated under reduced pressure. The resultant syrup was purified by chromatography on a silica gel column (toluene→toluene–EtOAc, 19:1) to give 2,3,4,6-tetra-*O*-benzoyl-α-D-mannopyranosyl azide (**2**) (5 mg, 6%; R_f = 0.67, toluene–EtOAc, 19:1) and 2,3,4,6-tetra-*O*-benzoyl-β-D-mannopyranosyl azide (**3**) (66 mg, 70%; R_f = 0.52, toluene–EtOAc, 19:1).

Method **B.** To a solution of 2,3,4,6-tetra-*O*-benzoyl-α-D-mannopyranosyl bromide (**1**) (100 mg, 0.152 mmol) in toluene (2 mL) TBAHS (51.6 mg, 0.152 mmol), NaN_3 (50 mg, 0.76 mmol), and 1 M Na_2CO_3 (2 mL) were added. The two-phase mixture was vigorously stirred at 115 °C (bath) for 2 h, after which time TLC indicated complete transformation of the halide. Toluene (20 mL) was then added, the organic phase was separated and successively washed with satd $NaHCO_3$, H_2O (×2), and brine. The combined organic extracts were processed as described above to give α-D-mannopyranosyl azide **2** (7 mg, 8%) and β-D-mannopyranosyl azide **3** (62.3 mg, 66%), identical to those obtained in *Method* **A**.

Method **C.** To a solution of 2,3,4,6-tetra-*O*-benzoyl-α-D-mannopyranosyl bromide **1** (100 mg, 0.152 mmol) in EtOAc (2 mL) TBAHS (51.6 mg, 0.152 mmol), NaN_3 (50 mg, 0.76 mmol), and 1 M $NaHCO_3$ (2 mL) were added. The two-phase mixture was vigorously stirred at room temperature (~20 °C) for 48 h, after which time TLC indicated complete transformation of the halide. EtOAc (20 mL) was then added, the organic phase was separated and successively washed with satd $NaHCO_3$, H_2O (×2), and brine. The combined organic extracts were processed as described above to give α-D-mannopyranosyl azide **2** (6 mg, 7%) and β-D-mannopyranosyl azide **3** (61.4 mg, 65%), identical to those obtained in *Method* **A**.

1.2.1. Data for 2,3,4,6-tetra-*O*-benzoyl-α-D-mannopyranosyl azide (2)

$[\alpha]_D^{25}$ +14.1 (*c* 1.2, $CHCl_3$) (lit.[10] $[\alpha]_D^{25}$ +13 (*c* 1.0, $CHCl_3$)); IR (cm^{-1}): 2124 (N_3) (lit.[10] 2120, 2180), 1736 (CO) (lit.[10] 1720–1740); ^{1}H NMR (500.13 MHz, $CDCl_3$): δ_H 4.54 (1H, dd, $J_{6,6'}$ = 12.3, $J_{5,6}$ = 4.5, H-6), 4.63 (1H, ddd, $J_{4,5}$ = 10.1, $J_{5,6}$ = 2.5, $J_{5,6}$ = 4.5, H-5), 4.77 (1H, dd, $J_{5,6}$ = 2.5, $J_{6,6'}$ = 12.3, H-6′), 5.63 (3H, dd, $J_{1,2}$ = 2.1, $J_{2,3}$ = 3.3, H-2), 5.70 (1H, d, $J_{1,2}$ = 1.9, H-1), 5.84 (1H, dd, $J_{2,3}$ = 3.3, $J_{3,4}$ = 10.1, H-3), 6.14 (1H, t, *J* = 10.1, H-4), 7.26–8.14 (20H, m, Ph); ^{13}C NMR (125.32 MHz, $CDCl_3$): δ_C 62.6 (C-6), 66.4 (C-4), 69.3 (C-2), 70.2 (C-3), 71.0 (C-5), 87.7 (C-1), 128.4, 128.5, 128.7, 129.8, 129.9 (CH, Ph), 133.2, 133.3, 133.6, 133.7 (C_{quat}, Ph), 165.4 (3C), 166.1 (C=O); ESIMS: found *m/z* 644.1 [M+Na]$^+$. Calcd for $C_{34}H_{27}N_3NaO_9$: 644.16.

1.2.2. Data for 2,3,4,6-tetra-*O*-benzoyl-β-D-mannopyranosyl azide (3)

$[\alpha]_D^{25}$ −98.2 (*c* 1.0, $CHCl_3$) (lit.[10] $[\alpha]_D^{26}$ −97 (*c* 3.17, $CHCl_3$)); IR (cm^{-1}): 2128 (N_3) (lit.[10] 2120), 1736 (CO) (lit.[10] 1725–1740); ^{1}H NMR (500.13 MHz, $CDCl_3$): δ_H 4.25 (1H, ddd, H-5), 4.55 (1H, dd, $J_{5,6'}$ = 4.4, $J_{6,6'}$ = 12.2, H-6), 4.82 (1H, dd, $J_{5,6'}$ = 2.6, $J_{6,6'}$ = 12.2, H-6′), 5.08 (1H, s, H-1), 5.63 (1H, dd, $J_{2,3}$ = 2.9, $J_{3,4}$ = 10.1, H-3), 5.96 (1H, d, $J_{2,3}$ = 2.9, H-2), 6.07 (1H, t, $J_{4,5}$ = 10.0, H-4), 7.25–8.18 (20H, m, Ph); ^{13}C NMR (125.32 MHz, $CDCl_3$): δ_C 62.5 (C-6), 66.1 (C-4), 70.0 (C-2), 71.9 (C-3), 74.7 (C-5), 85.5 (C-1), 128.3, 128.5, 128.6, 129.8, 130.0 (CH, Ph), 133.2, 133.4, 133.56, 133.58 (C_{quat}, Ph), 165.2 (2C), 165.5, 166.0 (C=O); ESIMS: found *m/z* 644.1 [M+Na]. Calcd for $C_{34}H_{27}N_3NaO_9$: 644.16.

1.3. β-D-Mannopyranosyl azide (4)

To a solution of 2,3,4,6-tetra-*O*-benzoyl-β-D-mannopyranosyl azide (**3**) (60 mg, 0.097 mmol) in MeOH (0.5 mL), 1 M solution of MeONa in MeOH (0.5 mL) was added. The mixture was stirred at ~21 °C for 18 h, after which time TLC indicated complete transformation. The reaction mixture was neutralized with Dowex 50 × 8 (H^+) ion-exchange resin. The resin was filtered and washed with MeOH (20 mL), the combined filtrates were evaporated under reduced pressure. The resultant syrup was dissolved in water (20 mL) and washed with light petroleum ether (5 × 25 mL), and the aqueous phase was concentrated in vacuo to give β-D-mannopyranosyl azide (**4**) (18.3 mg, 92%; R_f = 0.62, $CHCl_3$–MeOH, 4:1). $[\alpha]_D^{20}$ −36.8 (*c* 1.0, H_2O) (lit.[10] $[\alpha]_D^{23}$ −37 (*c* 0.98, H_2O)); ^{1}H NMR (600.13 MHz, D_2O): δ_H 3.43–3.47 (1H, m, H-5), 3.575 (1H, t, $J_{3,4}$ = 9.7, $J_{4,5}$ = 9.6, H-4), 3.626 (1H, dd, $J_{2,3}$ = 3.2, $J_{3,4}$ = 9.7, H-3),

3.738 (1H, dd, $J_{5,6}$ = 6.4, $J_{6,6'}$ = 12.4, H-6), 3.920 (1H, dd, $J_{5,6'}$ = 2.1, H-6′), 3.990 (1H, d, H-2), 4.831 (1H, s, $J_{1,2}$ < 1.5,H-1); ^{13}C NMR (150.57 MHz, D_2O): δ_C 62.40 (C-6), 67.91 (C-4), 72.54 (C-2), 74.28 (C-3), 79.80 (C-5), 88.72 (C-1).

Acknowledgments

Authors are grateful to Professor L. V. Backinowsky for stimulating discussions and to Professor A. S. Shaskov and Dr. A. A. Grachev for recording NMR spectra on a Bruker DRX-500 spectrometer. This work was supported by the Russian Foundation for Basic Research (Project No. 09-03-00521).

References

1. For the reviews on synthesis and transformations of glycosyl azides, see: (a) Micheel, F.; Klemer, A. *Adv. Carbohydr. Chem.* **1961**, *16*, 85–103; (b) Györgydeák, Z.; Szilágyi, L.; Paulsen, H. *J. Carbohydr. Chem.* **1993**, *12*, 139–163; (c) Györgydeák, Z.; Thiem, J. *Adv. Carbohydr. Chem. Biochem.* **2006**, *60*, 103–182.
2. Bröder, W.; Kunz, H. *Bioorg. Med. Chem.* **1997**, *5*, 1–19.
3. Paulsen, H. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 823–839.
4. (a) Malkinson, J. P.; Falconer, R. A.; Toth, I. *J. Org. Chem.* **2000**, *65*, 5249–5252 and references cited therein; (b) He, Y.; Hinklin, R. J.; Chang, J.; Kiessling, L. L. *Org. Lett.* **2004**, *6*, 4479–4482; (c) Bianchi, A.; Bernardi, A. *J. Org. Chem.* **2006**, *71*, 4565–4577.
5. Kolb, H. C.; Finn, M. G.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2001**, *40*, 2004–2021.
6. (a) Wilkinson, B. L.; Bornaghi, L. F.; Poulsen, S.-A.; Houston, T. A. *Tetrahedron* **2006**, *62*, 8115–8125 and references cited therein; (b) Cheshev, P.; Marra, A.; Dondoni, A. *Org. Biomol. Chem.* **2006**, *4*, 3225–3227; (c) Dedola, S.; Nepogodiev, S. A.; Field, R. A. *Org. Biomol. Chem.* **2007**, *5*, 1006–1017; (d) Dondoni, A. *Chem. Asian J.* **2007**, *2*, 700–708; (e) Meldal, M.; Tornøe, C. W. *Chem. Rev.* **2008**, *108*, 2952–3015.
7. For a recent review on β-selective mannosylation, see: Hashihayata, T. *J. Synth. Org. Chem. Jpn.* **2007**, *65*, 715–716.
8. For the reviews on 1,2-cis-glycosylation, see: (a) Demchenko, A. V. *Curr. Org. Chem* **2003**, *7*, 35–79; (b) Demchenko, A. V. *Synlett* **2003**, 1225–1240.
9. For recent reviews on various aspects of glycosylation, see: *Handbook of Chemical Glycosylation Advances in Stereoselectivity and Therapeutic Relevance*; Demchenko, A. V., Ed.; Wiley-VCH: Weinheim, 2008; p 501.
10. Gyorgydeak, Z.; Paulsen, H. *Liebigs Ann. Chem.* **1977**, 1987–1991.
11. (a) Makosza, M. *Pure Appl. Chem.* **2000**, *72*, 1399–1403 and references cited therein; (b) Tropper, F. D.; Andersson, F. O.; Braun, S.; Roy, R. *Synthesis* **1992**, 618–620.
12. Kumar, R.; Tiwari, P.; Maulik, P. R.; Misra, A. K. *Eur. J. Org. Chem.* **2006**, 74–79.
13. Cosgrove, K. L.; Bernhardt, P. V.; Ross, B. P.; McGeary, R. P. *Aust. J. Chem.* **2006**, *59*, 473–476.
14. (a) Kirby, A. J. *The Anomeric Effect and Related Stereoelectronic Effects at Oxygen*; Springer: Berlin, 1983; p 149; (b) Deslongchamps, P. *Stereoelectronic Effects in Organic Chemistry*; Pergamon Press: Oxford, 1983; p 375; (c) Juaristi, E.; Cuevas, G. *The Anomeric Effect*; CRC Press: Boca Raton, FL, 1995; p 229.
15. Smith, M. B.; March, J. *March's Advanced Organic Chemistry: Reactions, Mechanisms, and Structure*, 5th ed.; John Wiley & Sons: New York, 2001; pp 450–454.
16. (a) Bräse, S.; Gil, C.; Knepper, K.; Zimmermann, V. *Angew. Chem., Int. Ed.* **2005**, *44*, 5188–5240; (b) Hassner, A.; Stern, M.; Gottlieb, H. E. *J. Org. Chem.* **1990**, *55*, 2304–2306; (c) Dharanipragada, R.; VanHulle, K.; Bannister, A.; Bear, S.; Kennedy, L.; Hruby, V. J. *Tetrahedron* **1992**, *48*, 4733–4748; (d) Hruby, V. J.; Boteju, L.; Li, G. *Chem. Eng. News* **1993**, *71*, 2; (e) http://pubs.acs.org/cen/safety/index.html.
17. Szilagyi, L.; Gyorgydeak, Z. *Carbohydr. Res.* **1985**, *143*, 21–41.
18. Ivlev, E. A.; Backinowsky, L. V.; Abronina, P. I.; Kononov, L. O.; Kochetkov, N. K. *Polish J. Chem.* **2005**, *79*, 275–286.