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Sequential $Dy(OTf)_3$-Catalyzed Solvent-Free Per-*O*-Acetylation and Regioselective Anomeric De-*O*-Acetylation of Carbohydrates

Yi-Ling Yan,[a] Jiun-Rung Guo,[a] and Chien-Fu Liang*[a]

Dedication ((optional))

Abstract: Dysprosium(III) trifluoromethanesulfonate-catalyzed per-*O*-acetylation and regioselective anomeric de-*O*-acetylation of carbohydrates can be tuned by adjusting the reaction medium. In this study, per-*O*-acetylation of unprotected sugars by using a near stoichiometric amount of acetic anhydride under solvent-free conditions resulted in the exclusive formation of acetylated saccharides as anomeric mixtures, whereas anomeric de-*O*-acetylation in methanol resulted in a moderate to excellent yield. Reactions with various unprotected monosaccharide or disaccharide followed by a semi-one-pot sequential conversion into the corresponding acetylated glycosyl hemiacetal also resulted in high yields. Furthermore, the obtained hemiacetals could be successfully transformed into trichloroimidates following $Dy(OTf)_3$-catalyzed glycosylation.

Introduction

Peracetylated carbohydrates and their derived hemiacetals are valuable building blocks for the preparation of complex oligosaccharides and glycoconjugates.[1,2] Per-*O*-acetylation of carbohydrates is an important organic reaction used for the initial protection of free sugars and is a useful method for the structural elucidation and identification of target molecules. In addition, the acetylated carbohydrates may be valuable compounds for the synthesis of inexpensive CO_2-philes.[3] Generally, such acetylation is performed using acetic anhydride as the reagent and pyridine as the solvent and the base. Occasionally, 4-dimethylaminopyridine is also added to accelerate the reactions.[4] More recently, numerous reagents and catalysts, including PBu_3 in CH_2Cl_2,[5] bases (NaOAc,[6] DABCO,[7] and imidazole[8]), Lewis acids ($FeCl_3$,[9] $ZnCl_2$-ChCl,[10] $Cu(OTf)_2$,[11a-b] $In(OTf)_3$,[12] BF_3-OEt_2,[13] $Sc(OTf)_3$,[11b,14] $Ce(OTf)_3$,[15a-b] $LiClO_4$,[16] $V(O)(OTf)_2$,[17] $Cu(ClO_4)_2{\cdot}6H_2O$,[18] and tetranuclear zinc cluster trifluoroacetic acid adduct[19]), Bronsted acids ($HClO_4$,[20] H_2SO_4,[21] *p*-toluene sulfonic acid[22]), heterogeneous catalysts (montmorillonite K-10,[23] H-β-zeolite,[24] zirconyl sulfophenyl phosphonate,[25] sulfonic acid functionalized nano γ-Al_2O_3,[26] and molecular sieves[27]), I_2,[28] and ionic liquid,[29] have been developed to avoid the use of a large excess of the toxic and foul-smelling pyridine. Moreover, the Hung groups have developed metal-catalyzed per-*O*-acetylation under the solvent-free and use stoichiometric amounts of acetic anhydride conditions.[11a-b,14] Additionally, some previously reported catalysts, such as $Cu(OTf)_2$,[11a-b] $Cu(ClO_4)_2{\cdot}6H_2O$,[18] *p*-toluene sulfonic acid,[22] and I_2,[28] have been employed in one-pot acetylation–thioglycosylation in conjunction with boron trifluoride etherate and thiol derivatives. Although numerous existing catalysts perform acetylation efficiently, new catalysts that are more feasible and environmentally friendly and use stoichiometric amounts of acetic anhydride and solvent-free conditions are still in strong demand. In our previous investigation into clean reactions performed using a Lewis acid catalyst for acetylation, we found that the available lanthanide triflates are very active environmentally friendly catalysts and can be readily recycled.[15] However, effective lanthanide triflate catalysts[15] used in acetylation, such as cerium(III) and erbium(III) triflate, are associated with a few limitations, such as the use of a large excess of acetic anhydride[15b-c] and the use of organic solvents.[15a,c] In this study, we used dysprosium(III) trilfate as a dual catalyst for the preparation of peracetylated carbohydrates by using a stoichiometric amount of acetic anhydride under solvent-free conditions, and we synthesized their derived hemiacetals through sequential $Dy(OTf)_3$-catalyzed regioselective anomeric deacetylation from free sugar. This practical sequential catalysis reaction enabling the preparation of important building blocks from unprotected reducing sugars would be useful. To the best of our knowledge, this is the first study using $Dy(OTf)_3$ for the sequential peracetylation and anomeric deacetylation of carbohydrates, considerably expanding the scope of lanthanide triflate catalysis in carbohydrate chemistry.

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Supporting information for this article is given via a link at the end of the document.

Results and Discussion

The solvent-free conditions were optimized using D-glucose **1a** and acetic anhydride with commercially available $Dy(OTf)_3$, as shown in Table 1. At 10 mol%, $Dy(OTf)_3$ furnished D-glycopyranosyl ester **2a** with a 95% yield (entry 1). To determine the minimum amount of catalyst required, the amount was reduced by 2-fold (entry 2), 10-fold (entry 3), 20-fold (entry 4), and 100-fold (entry 5), and the results revealed that the catalyst retained its activity without significant variation in reaction yield, but a longer reaction time was required for the full conversion of the starting material. Entry 5 was found to be the minimum catalyst concentration for optimum activity, and the reaction was not completed when a lower catalyst concentration (0.05 mol%) was used (entry 6). This optimization study also demonstrated an interesting phenomenon: the α/β ratios were affected by the catalyst concentration.

To extend the scope of this study, the aforementioned optimized conditions for the per-*O*-acetylation reaction were employed for a series of unprotected sugars. The reaction was performed under solvent-free conditions by using stoichiometric amounts of acetic anhydride and 0.1 mol% $Dy(OTf)_3$. The products of the per-*O*-acetylation reaction with various substrates are shown in Table 2. Per-*O*-acetylation of fully unprotected reducing sugars such as D-glucose,

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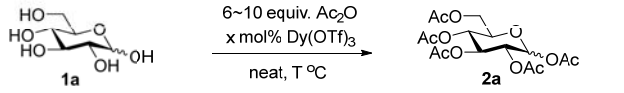
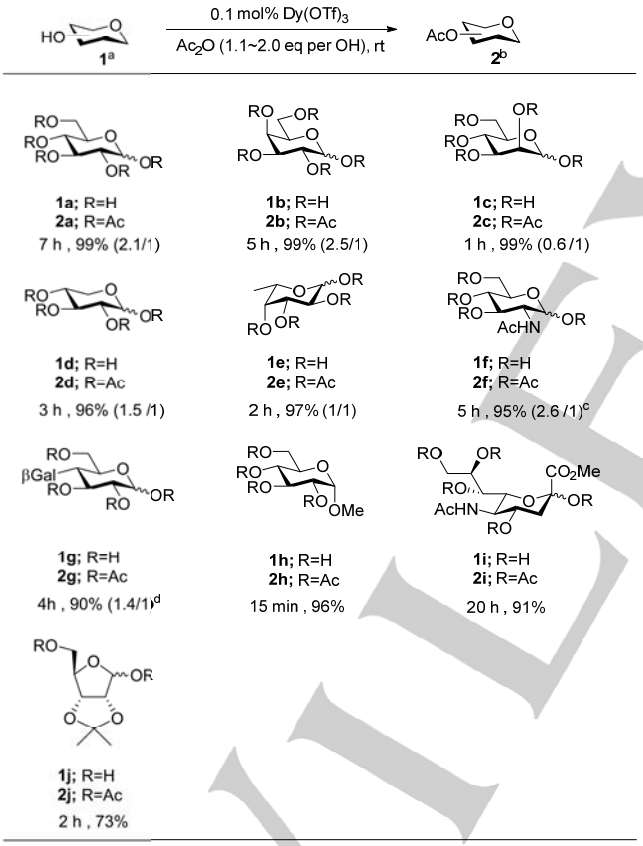
Table 1. Optimization of $Dy(OTf)_3$-catalyzed solvent-free per-*O*-acetylation of D-glucose **1a** with a stoichiometric amount of acetic anhydride.



entry[a]	x	*T* °C	*t* (h)	α/β	yield (%)[b]
1	10	rt	1.5	3.61	95
2	5	rt	2.5	3.40	97
3	1	rt	4.5	2.96	95
4	0.5	rt	6	2.69	96
5	0.1	rt	7.5	2.20	95
6	0.05	rt	7.5	1.54	81[c]

[a] The reactions were carried out with 50 mg of **1a** in neat. [b] Isolated yields. [c] The reaction was not full completion checked by TLC analysis.

Table 2. $Dy(OTf)_3$-catalyzed solvent-free per-*O*-acetylation of carbohydrates.



[a] The reactions were carried out with gram scale of **1** in neat. [b] The isolated yield are given along with the α / β rations in parenthesis. [c] Reaction temperature is 60 °C. [d] Sugar: lactose monohydrate.

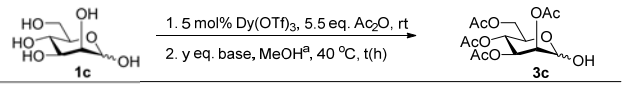
D-galactose, D-mannose, D-xylose, and L-fucose resulted in the formation of the fully acetylated products **2a** (99%), **2b** (99%), **2c** (99%), **2d** (96%), and **2e** (97%), respectively. In the per-*O*-acetylation of D-mannose, the corresponding acetylated product was obtained in a much shorter time (1 h). The procedure was also applied for the synthesis of several important per-*O*-acetylated carbohydrates, such as *N*-acetylglucosamine (**1f**), lactose monohydrate (**1g**), methyl α-glucose (**1h**), sialic acid (**1i**), and 2,3-*O*-isopropylidene ribofuranose (**1j**). The acetylation reaction was successful with disaccharides such as lactose and led to the formation of the product **2g** (90%). Reducing amino sugars such as *N*-acetylglucosamine resulted in a high yield under the heating conditions (60 °C, 95%). A representative complex carbohydrate, *N*-acetylneuraminic acid methylester **1i**, was acetylated to the corresponding product **2i** (91%), in which the hydroxyl group at the C-2 position remained unaffected. The configuration of **2i** was characterized through 400 MHz 1H NMR spectral analysis and was confirmed according to previous reports.[16,19] Moreover, acid-labile group such as isopropylidene ribofuranose was acetylated to the corresponding product **2j** with a good yield (73%). All products were characterized through ^1H and ^{13}C spectrometry, and the data corresponded substantially with the values described in the literature. After the success of the solvent-free acetylation of the unprotected sugars by using stoichiometric amounts of Ac_2O and $Dy(OTf)_3$, we prepared peracetylated hemiacetals by using $Dy(OTf)_3$ to catalyze a sequential regioselective anomeric deacetylation reaction.

Peracetylated hemiacetals of carbohydrates are important intermediates for the preparation of anomeric trichloroacetimidate, a widely used glycosyl donor.[1,30] However, the preparation of such hemiacetals still relies heavily on classical basic or acidic conditions, such as those involving transamidation (benzyl amine, piperidine, and hydrazine acetate),[31] transesterification catalyzed by organic tin reagents,[32] solvolysis by $SnCl_4$,[33] or hydrolysis using silver[34] or mercuric[35] salts from anomeric halogenide. Recently, several species, including $HClO_4$-SiO_2,[36] $FeCl_3 \cdot 6H_2O$,[37] lanthanide triflates,[38] and dimethylaminopropylamine,[39] have been developed to facilitate anomeric deacetylation. These reaction methods are useful; however, these methods are associated with disadvantages such as low shelf stability, toxicity,[31-35] the production of a lipophilic amide byproduct,[31a] the employment of high-temperature conditions,[36,37] and the fact that they are not metal catalytic reactions.[37] Therefore, an effective and environmentally friendly catalyst for regioselective anomeric deacetylation under mild reaction conditions is highly desirable. For the transesterification of anomeric acetate, lanthanide triflates have been applied in anomeric deacetylation.[38] To extend these findings, we performed per-*O*-acetylation and anomeric deacetylation through a sequential $Dy(OTf)_3$-catalyzed one-pot reaction.

To investigate the potential of the $Dy(OTf)_3$-catalyzed one-pot reaction an initial evaluation of the anomeric deacetylation of important carbohydrates was performed (refer to the Supporting Information).[40] The reaction was performed in the presence of 5 mol% $Dy(OTf)_3$ at a temperature ranging from 0 °C to room temperature and under a mild heating condition (40 °C). The anomeric transesterification reaction proceeded simply in commercial methanol under the mild heating condition and cleanly provided a high reaction yield (72%–96%).[40] All products were characterized through ^1H and ^{13}C spectrometry, and the data corresponded substantially with the values described in the literature. After establishing optimal anomeric deacetylation conditions, we performed the sequential $Dy(OTf)_3$-catalyzed one-pot reaction. An initial evaluation of the proposed catalytic reaction was conducted with **1c** in the presence of 5 mol% $Dy(OTf)_3$ and Ac_2O (10 or 6 equiv); this reaction yielded the corresponding per-*O*-acetate, as confirmed by thin-layer chromatography (TLC). MeOH was added to the reaction mixture,

which was stirred at 40 °C (Table 3, entries 1 and 2). Monitoring of the reaction by using TLC revealed a slow conversion into the target

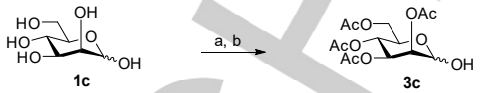
Table 3. Optimization of one-pot conversion of mannose **1c** to per-*O*-acetylated hemiacetal glycoside.



entry[b]	x	base	y	t(h)	yield (%)[c]
1	10	none	none	24	51
2	6	none	none	24	57
3	6	Py	6	24	56
4	6	NEt_3	6	13	52
5	6	$NaHCO_3$	5.5	9	74
6	6	$NaHCO_3$	5	19	68
7	6	$NaHCO_3$	1	50	59
8[d,e]	10	none	none	9	81
9[d,e]	10	Na_3HCO_3	5 mol%	11	90

[a] Commercial HPLC grade. [b] Entry1-7 are 50 mg scale. [c] Isolated yields. [d] Gram scale. [e] First step, the reaction was reacted in the presence of 0.1 mol% $Dy(OTf)_3$. After acetylation, acetic acid was removed in vacuo. Second step, the reaction was reacted in the presence of 4.9 mol% $Dy(OTf)_3$.

peracetylated hemiacetal, and only 51% and 57% yields were obtained after purification. We assumed that the acetic acid formed as a byproduct in the initial acetylation impeded the reaction. Hence, after complete acetylation, we utilized different bases to neutralize the acetic acid. Organic bases including pyridine and triethylamine were utilized but did not improve the reaction yield (Table 3, entries 3 and 4). For comparison, a suitable inorganic base was utilized in the same reaction. Using the sodium bicarbonate condition provided a higher reaction yield of 74% and a faster reaction time (Table 3, entry 5). The amount of sodium bicarbonate was also reduced to 5 and 1 equiv, which resulted in a slightly lower yield and a significantly prolonged reaction time (Table 3, entries 6 and 7). However, regardless of the modified conditions, the reaction yield did not improve to our satisfaction when the acetic acid was not removed after acetylation. To prove the necessity of acetic acid removal, we used a semi-one-pot reaction (AcOH removal after acetylation). In the first step, the acetylation reaction was performed under the optimized conditions (Table 2), and the acetic acid was removed after complete acetylation. Subsequently, the reaction was immediately performed in the presence of 4.9 mol% $Dy(OTf)_3$ in commercial methanol (Table 3, entry 8). The results clearly suggest that acetic acid removal is necessary and provided the desired product with an 81% yield, but the side products of multi-hydration were formed in the reaction. However, when the reaction was performed in the presence of 5 mol% $NaHCO_3$ in the second step, the product was obtained in a 90% yield (Table 3, entry 9). It is unexpected that multi-hydration can be suppressed by adding sodium bicarbonate. According to a similar previous report,[41] we assumed that dysprosium(III) is linked through a coordinated bicarbonate anion, resulting in a low initial catalytic activity. To confirm this assumption, **1c** was subjected to a one-pot two-step reaction by using dysprosium(III) carbonate tetrahydrate as a catalyst in the second step, as shown in Scheme 1. The results revealed that the desired product **3c** could also be obtained with an 84% yield by using dysprosium(III) carbonate tetrahydrate as a catalyst; however, the reactions in the second step were considerably prolonged by 2 days. Hence, in the second step, $NaHCO_3$ combined with $Dy(OTf)_3$ is likely to be less reactive than only $Dy(OTf)_3$ and likely results in the formation of fewer side products.



Scheme 1. Reagents and conditions: (a) 0.1 mol% $Dy(OTf)_3$, 10 eq. Ac_2O, rt, 1h; (b) 5 mol% $Dy_2(CO_3)_3{\cdot}4H_2O$, MeOH, 40 °C, 48h, 84%.

Consequently, we employed two methods (Method A and Method B) for our reaction and performed the sequential $Dy(OTf)_3$-catalyzed per-*O*-acetylation–anomeric deacetylation reaction for a series of fully unprotected sugars. The results are summarized in Table 4. The developed protocol could be conducted easily and safely, as mentioned earlier. The observations in Table 4 clearly suggest the necessity of acetic acid removal in both methods, and that 5 mol% $NaHCO_3$ addition improved the yield in several cases (Method B). For example, from the fully unprotected reducing sugars (**1a**–**1d**, entries 1–4), higher yields were obtained using Method B, with consistently high to excellent yields of the acetylated glycosyl hemiacetals **3a** (87%), **3b** (78%), **3c** (90%), **3d** (60%). The reaction with **1e**–**1g** (entries 5–7) could be performed using both methods without obvious differences in the reaction yield. Importantly, acid-sensitive groups such as isopropylidene ribofuranose (entry 8) were more tolerated under the Method B condition. Moreover, we conducted a recycling protocol in the sequential one-pot two-step strategy. After a work-up, the Dy(III) catalyst was recovered from the aqueous phase as a white solid and was reused after drying over P_2O_5. The recycling protocol for **1c** was repeated three times using the Method A condition, and the yield of the peracetylated hemiacetal **3c** was more than 70%, as shown in Figure 1.

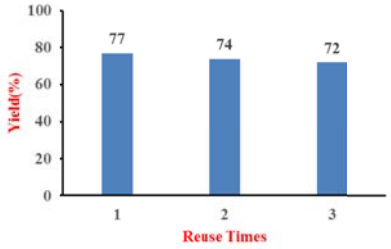
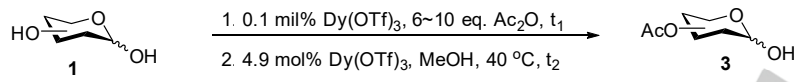


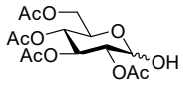
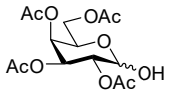
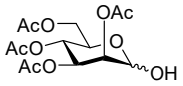
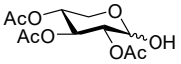
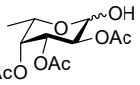
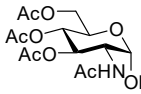
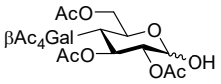
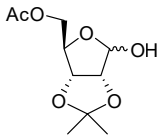
Figure 1.

Finally, to verify the synthetic utility of our developed method in comparison with that of other reported protocols, using the sequential one-pot two-step strategy, both **1a** and **1c** were transformed into glycosyl hemiacetals, which were then converted to trichloroacetimidate derivatives by using trichloroacetonitrile and K_2CO_3, as shown in Scheme 2. The glycosyl imidates **4a** and **4c** were then used in a glycosylation reaction with $Dy(OTf)_3$ as the glycosylation activator, which is similar to the glycosidation reaction

Table 4. Semi-one-pot conversion of free sugars to peracetylated hemiacetal glycosides.



1 3

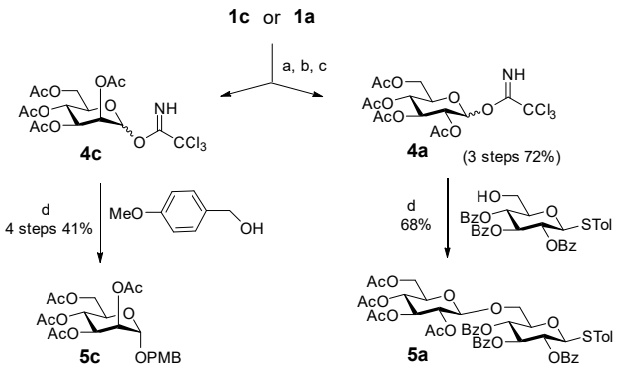
Entry	Sugar	Product	t_1 (h)	Method A[a,b] t_2 (h)	Method A[a,b] Yield (%)	Method A[a,b] α/β	Method B[a,c] t_2 (h)	Method B[a,c] Yield (%)	Method B[a,c] α/β
1	**1a**		7	9	71	1.9/1	40	87	2.8/1
2	**1b**		5	12	48	2.3/1	24	78	2.0/1
3	**1c**		1	9	81	5.4/1	11	90	6.3/1
4	**1d**		3	20	54	1.9/1	12	60	1.9/1
5	**1e**		2	10	71	1.4/1	23	65	2.2/1
6	**1f**		5	12	71	1/0	13	71	1/0
7	**1g**		4	14	78	1.6/1	23	75	1.7/1
8	**1k**		2	23	messy		48	53	0.2/1

[a] Gram scale. [b] Without $NaHCO_3$ addition in second step. [c] 5 mol% $NaHCO_3$ addition in second step.

catalyzed by lanthanide triflates,[42] to obtain the valuable per-*O*-acetylated *p*-methoxyphenyl glycoside **5c** and the disaccharide thioglycoside **5a**, respectively. Both products can be used as donors for the subsequent preparation of important oligosaccharides.

Conclusions

We demonstrated that dysprosium(III) triflate is an effective and dual-purpose catalyst for the solvent-free per-*O*-acetylation and anomeric de-*O*-acetylation of carbohydrates. Furthermore, we developed an efficient and high-yield sequential one-pot two-step protocol for the preparation of peracetylated hemiacetals from free sugars. The reaction conditions were mild, convenient, and nonhazardous. In addition, the use of dysprosium(III) triflate as a catalyst minimized reagent use and purification. We believe that this method of protection and regioselective deprotection for preparing commonly used building blocks would find wide applications in oligosaccharide synthesis.



Scheme 2. Reagents and conditions: (a) 0.1 mol% $Dy(OTf)_3$, 10eq. Ac_2O, rt, 1h (for **1c**) or 7h (for **1a**); (b) 4.9 mol% $Dy(OTf)_3$, 5 mol% $NaHCO_3$, MeOH, 40 °C, 13h (for **1c**) or 40h (for **1a**); (c) CCl_3CN, K_2CO_3, DCM, rt, 4h; (d) 5 mol% $Dy(OTf)_3$, DCM, rt to reflux, 5h.

Experimental Section

General Information. The catalyst, $Dy(OTf)_3$ (Strem Chemicals Inc., USA., Cat. no. 66-4000) was obtained from commercial source and used as received without further precautions. ^1H NMR, ^{13}C NMR and COSY spectra were reported on a Varian 400 MHz NMR spectrometer with $CDCl_3$ as the solvent. Chemical shifts were reported in parts per million (ppm) relative to residual solvent peak (7.26 ppm). The optical rotations were measured on a Roldulph Autopol IV Automatic Polarimeter at 589 nm (Na) at ~24 °C. IR spectra were measured on a Thermo Scientific Nicolet iS5 FT-IR spectrophotometer. TLC was performed on pre-coated glass plates of Silica Gel 60 F254 (0.25 mm, E. Merck); detection was performed by spraying with a solution of 5% H_2SO_4 in MeOH. Flash column chromatography was carried out on Silica Gel 60 (230–400 mesh, E. Merck). The mass spectra were analyzed on a Finnigan LTQ-OrbitrapxL instrument with an ESI† source. Incorporation

General Procedure for Per-*O*-Acetylation of Carbohydrates. A mixture of D-glucose (**1a**) (1g, 5.55 mmol), $Dy(OTf)_3$ (3.4 mg, 0.1 mol%) and acetic anhydride (1.1–2 equivalents per –OH of carbohydrates) was stirred at room temperature under nitrogen atmosphere. After the completion of the reaction, the reaction mixture was diluted with ethyl acetate, which was washed with aqueous $NaHCO_3$ followed by brine. The combined organic layer was dried over $MgSO_4$, filtered and concentrated. The crude product was purified by flash column chromatography to afford the desired product (**2a**).

General Procedure for Anomeric De-*O*-Acetylation of Fully Acetylated Carbohydrates.[40] A solution of 1,2,3,4,6-Penta-*O*-acetyl-D-glucopyranoside (**2a**) (1 g, 2.56 mmol) and $Dy(OTf)_3$ (78.0 mg, 5 mol%) in MeOH (64 mL) was stirred at 0 °C or 40 °C under nitrogen atmosphere. After the completion of the reaction, the reaction mixture was concentrated under reduced pressure to remove MeOH. The residue was dissolved in ethyl acetate, which was washed with brine, dried over $MgSO_4$, filtered and concentrated. The crude product was purified by column chromatography to afford the desired product (**3a**).

General Procedure for Sequential One-Pot Two Steps Per-*O*-Acetylation and Anomeric De-*O*-Acetylation (Method B). A mixture of D-glucose (**1a**) (0.5 g, 2.78 mmol), $Dy(OTf)_3$ (1.80 mg, 0.1 mol%) and acetic anhydride (1.1–2 equivalents per –OH of carbohydrates) was stirred at room temperature under nitrogen atmosphere. Upon complete acetylation, the reaction mixture was concentrated *in vacuo* to remove acetic anhydride. Without purification, do the next step. To a solution of the residue in MeOH (69.4 mL) was added $Dy(OTf)_3$ (82.9 mg, 4.9 mol%) and $NaHCO_3$ (11.7 mg, 5 mol%) and stirred at 40 °C under nitrogen atmosphere. After the completion of the reaction, the reaction mixture was concentrated under reduced pressure to remove MeOH. The residue was dissolved in ethyl acetate, which was washed with brine, dried over $MgSO_4$, filtered and concentrated. The crude product was purified by column chromatography to afford the desired product (**3a**).

General Procedure for Catalyst Recycle Used Strategy of Sequential One-Pot Two Steps Per-*O*-Acetylation and Anomeric De-*O*-Acetylation. A mixture of D-mannose (**1c**) (0.5 g, 2.78 mmol), $Dy(OTf)_3$ (1.8 mg, 0.1 mol%) and acetic anhydride (1.1–2 equivalents per –OH of carbohydrates) was stirred at room temperature under nitrogen atmosphere. Upon complete acetylation, the reaction mixture was concentrated *in vacuo* to remove acetic anhydride and acetic acid. Without purification, do the next step. To a solution of the residue in MeOH (69.4 mL) was added $Dy(OTf)_3$ (82.9 mg, 4.9 mol%) and $NaHCO_3$ (11.7 mg, 5 mol%) and stirred at 40 °C under nitrogen atmosphere. After the completion of the reaction, the reaction mixture was concentrated under reduced pressure to remove MeOH. The residue was dissolved in ethyl acetate, which was washed with brine. The combined organic layer was dried over $MgSO_4$, filtered, concentrated and purified by column chromatography to afford the desired product (**3a**). After work-up, the aqueous phase was evaporated under reduced pressure and the $Dy(OTf)_3$ was recovered and reused after drying over P_2O_5 in vacuum for overnight.

The Procedure for $Dy_2(CO_3)_3{\cdot}4H_2O$ Catalysed the Sequential One-Pot Two Steps Per-*O*-Acetylation and Anomeric De-*O*-Acetylation. A mixture of D-mannose (**1c**) (0.5 g, 2.78 mmol), $Dy(OTf)_3$ (1.8 mg, 0.1 mol%) and acetic anhydride (1.1–2 equivalents per –OH of carbohydrates) was stirred at room temperature under nitrogen atmosphere. Upon complete acetylation, the reaction mixture was concentrated *in vacuo* to remove acetic anhydride. Without purification, do the next step. To a solution of the residue in MeOH (69.4 mL) was added $Dy_2(CO_3)_3{\cdot}4H_2O$ (78.5 mg, 4.9 mol%) and $NaHCO_3$ (11.7 mg, 5 mol%) and stirred at 40 °C under nitrogen atmosphere. After the completion of the reaction, the reaction mixture was concentrated under reduced pressure to remove MeOH. The residue was dissolved in ethyl acetate, which was washed with brine, dried over $MgSO_4$, filtered and concentrated. The crude product was purified by column chromatography to afford the desired product **3c** (two steps, 84% yield).

1,2,3,4,6-Penta-O-acetyl-D-glucopyranoside (2a).[11] (2.15 g, 99%) $[\alpha]_D^{24}$ +57.64 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2981, 1739, 1433, 1369, 1206, 1136; ^1H NMR (400 MHz, $CDCl_3$) δ 6.32 (d, *J* = 3.7 Hz, 1H), 5.70 (d, *J* = 8.3 Hz, 0.48H), 5.49–5.43 (m, 1H), 5.24 (t, *J* = 9.4 Hz, 1H), 5.17–5.06 (m, 3H), 4.27 (ddd, *J* = 12.7, 8.6, 4.4 Hz, 1H), 4.15–4.05 (m, 2H), 3.83 (ddd, *J* = 10.0, 4.5, 2.2 Hz, 1H), 2.20–1.98 (m, 22H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.5, 170.0, 169.5, 169.2, 168.6, 91.6, 88.9, 72.5, 72.6, 70.1, 69.6, 69.0 67.7, 67.6, 61.3, 20.7, 20.5, 20.5, 20.4, 20.3.

1,2,3,4,6-Penta-O-acetyl-D-galactopyranoside (2b).[18] (2.15 g, 99%) $[\alpha]_D^{24}$ +62.78 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2960, 1738, 1433, 1369, 1205, 1137; ^1H NMR (400 MHz, $CDCl_3$) δ 6.37 (d, *J* = 1.4 Hz, 1H), 5.69 (d, *J* = 8.3 Hz, 0.4H), 5.42 (d, *J* = 2.8 Hz, 1H), 5.38–5.28 (m, 3H), 5.10–5.05 (m, 1H), 4.38–4.29 (m, 1H), 4.24–4.02 (m, 3H), 2.19–1.96 (m, 26H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.2, 170.0, 170.0, 169.8, 168.8, 99.0, 92.0, 89.6, 71.6, 70.7, 69.1, 68.6, 67.7, 67.3, 67.2, 66.7, 66.3, 61.1, 20.8, 20.7, 20.5, 20.5, 20.4.

1,2,3,4,6-Penta-O-acetyl-D-mannopyranoside (2c).[11] (2.15 g, 99%) $[\alpha]_D^{24}$ +27.93 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2959, 1739, 1433, 1368, 1206, 1147; ^1H NMR (400 MHz, $CDCl_3$) δ 6.08 (d, *J* = 1.8 Hz, 1H), 5.86 (d, *J* = 0.9 Hz, 0.56H), 5.48 (d, *J* = 2.5 Hz, 1H), 5.38–5.24 (m, 4H), 5.13 (dd, *J* = 10.0, 3.3 Hz, 1H), 4.29 (ddd, *J* = 12.3, 10.2, 5.1 Hz, 2H), 4.17–4.00 (m, 3H), 3.80 (ddd, *J* = 9.8, 5.3, 2.3 Hz, 1H), 2.23–1.98 (m, 25H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.5, 169.9, 169.6, 169.4, 167.9, 90.5, 90.3, 73.1, 70.5, 70.5, 68.6, 68.2, 68.1, 65.4, 65.3, 62.5, 62.0, 20.7, 20.6, 20.6, 20.5, 20.5.

1,2,3,4-Tetra-O-acetyl-D-xylopyranoside (2d).[43] (1.7 g, 96%) $[\alpha]_D^{24}$ +39.98 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2963, 1742, 1433, 1368, 1207, 1129; ^1H NMR (400 MHz, $CDCl_3$) δ 6.24 (d, *J* = 3.5 Hz, 1H), 5.70 (d, *J* = 6.9 Hz, 0.68H), 5.45 (t, *J* = 9.8 Hz, 1H), 5.38–5.15 (m, 2H), 5.06–4.99 (m, 2H), 4.63 (dd, *J* = 12.2, 6.3 Hz, 0.52H), 4.27–4.08 (m, 2H), 3.92 (dd, *J* = 11.2, 5.9 Hz, 1H), 3.70 (t, *J* = 10.9 Hz, 1H), 3.51 (dd, *J* = 12.0, 8.5 Hz, 1H), 2.19–1.98 (m, 23H); ^{13}C NMR (100 MHz, $CDCl_3$) δ170.0, 169.7, 169.6, 169.6, 169.6, 169.2, 168.9, 168.8, 98.8, 92.7, 91.9, 89.1, 79.8, 79.3, 74.2, 69.2, 68.5, 62.7, 62.2, 61.5, 60.5, 20.9, 20.8, 20.7, 20.7, 20.6, 20.5, 20.4, 20.3.

1,2,3,4-Tetra-O-acetyl-L-fucopyranose (2e).[11] (1.78 g, 97%) $[\alpha]_D^{24}$ -55.81 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2989, 1740, 1434, 1369, 1208, 1126; ^1H NMR

(400 MHz, $CDCl_3$) δ 6.33 (d, J = 2.8 Hz, 1H), 5.67 (d, J = 8.3 Hz, 1H), 5.34–5.28 (m, 4H), 5.18–5.03 (m, 2H), 4.31–4.18 (m, 2H), 3.98–3.92 (m, 1H), 3.70 (t, J = 10.9 Hz, 1H), 3.51 (dd, J = 12.0, 8.5 Hz, 1H), 2.20–1.96 (m, 24H), 1.22 (d, J = 6.4 Hz, 3H), 1.15 (d, J = 6.5 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.9, 170.6, 170.3, 90.9, 71.4, 68.6, 67.9, 64.7, 21.1, 21.0, 20.9, 16.2.

1,3,4,6-Tetra-O-acetyl-2-N-acetyl-D-glucosamine (2f).[22] (2.04 g, 95%) $[\alpha]_D^{24}$ +61.81 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 3291, 2960, 1740, 1662, 1538, 1434, 1367, 1209, 1127; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.16 (d, J = 3.7 Hz, 1H), 5.68 (d, J = 8.8 Hz, 0.38H), 5.64 (d, J = 9.0 Hz, 1H), 5.27–5.16 (m, 2H), 5.15–5.08 (m, 1H), 4.52–4.44 (m, 1H), 4.29–4.20 (m, 2H), 4.14–3.95 (m, 3H), 3.79 (s, 1H), 2.23–1.90 (m, 23H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.5, 170.6, 170.2, 169.0, 168.6, 92.3, 90.5, 72.5, 72.5, 70.5, 69.5, 67.7, 67.4, 61.5, 61.4, 52.6, 50.8, 22.8, 20.8, 20.6, 20.5, 20.4.

D-Lactose octa-O-acetate (2g).[43] (3.39 g, 90%) $[\alpha]_D^{24}$ +29.72 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2953, 1740, 1431, 1367, 1209; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.24 (d, J = 3.7 Hz, 1H), 5.66 (d, J = 8.3 Hz, 0.71H), 5.50–5.40 (m, 1H), 5.34 (dd, J = 3.7, 2.6 Hz, 2H), 5.23 (t, J = 9.1 Hz, 1H), 5.15–4.91 (m, 5H), 4.52–4.40 (m, 3H), 4.20–3.95 (m, 6H), 3.91–3.71 (m, 4H), 2.19–1.94 (m, 32H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.5, 170.6, 170.2, 169.0, 168.6, 92.3, 90.5, 72.5, 72.5, 70.5, 69.5, 67.7, 67.4, 61.5, 61.4, 52.6, 50.8, 22.9, 22.8, 20.7, 20.5, 20.4.

1-O-Methyl-2,3,4,6-tetra-O-acetyl-α-D-glucopyranoside (2h).[18] (1.93 g, 96%) $[\alpha]_D^{24}$ +122.93 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2939, 1739, 1460, 1372, 1216, 1132; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.43 (t, J = 9.8 Hz, 1H), 5.03 (t, J = 9.8 Hz, 1H), 4.94–4.82 (m, 2H), 4.23 (dd, J = 12.3, 4.6 Hz, 1H), 4.07 (dd, J = 12.3, 4.3 Hz, 1H), 3.95 (ddd, J = 10.2, 4.5, 2.3 Hz, 1H), 3.38 (s, 3H), 2.10–1.94 (m, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.5, 170.0, 169.9, 169.5, 96.6, 70.6, 69.9, 68.3, 67.0, 61.8, 55.3, 20.6, 20.5, 20.5.

Methyl 5-Acetamido-4,7,8,9-tetra-O-acetyl-3,5-dideoxy-α-D-glycero-D-galacto-2-nonulopyranosonate (2i).[44] (2.48 g, 91%) $[\alpha]_D^{24}$ -1.89 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 3253, 3071, 2924, 1734, 1720, 1649, 1570, 1434, 1366, 1276, 1230, 1211, 1159, 1130; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.85 (d, J = 9.5 Hz, 1H), 5.35 (dd, J = 5.2, 1.8 Hz, 1H), 5.26–5.16 (m, 2H), 4.78 (s, 1H), 4.53 (dd, J = 12.3, 2.3 Hz, 1H), 4.23–4.10 (m, 2H), 4.01 (dd, J =12.3, 7.7 Hz, 1H), 3.85 (s, 3H), 2.13 (s, 3H), 2.09 (s, 3H), 2.02 (s, 3H), 2.01 (s, 3H), 1.89 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.5, 171.1, 170.8, 170.5, 170.2, 169.0, 94.8, 72.0, 71.2, 69.2, 68.3, 62.5, 53.2, 48.9, 36.0, 22.9, 21.0, 20.8, 20.7, 20.7.

1,5-Di-O-acetyl-2,3-O-isopropylidene-D-ribofuranose (2j).[45] (1.11 g, 73%) $[\alpha]_D^{24}$ -39.61 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2990, 1739, 1436, 1373, 1209, 1160, 1114; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.21 (s, 1H), 4.71 (s, 1H), 4.46 (t, J = 6.8 Hz, 1H), 4.11 (dd, J = 6.7, 3.4 Hz, 2H), 2.08 (s, 3H), 2.05 (s, 3H), 1.49 (s, 3H), 1.33 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.7, 169.5, 113.4, 102.3, 85.5, 85.3, 81.7, 64.3, 26.6, 25.2, 21.4, 21.0.

2,3,4,6-Tetra-O-acetyl-D-glucopyranose (3a).[46] (842.9 mg, 87%) $[\alpha]_D^{24}$ +68.26 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 3468, 2922, 2853, 1740, 1456, 1367, 1212, 1154; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.53 (t, J = 9.6 Hz, 1H), 5.46 (d, J = 3.4 Hz, 1H), 5.25 (t, J = 9.6 Hz, 1H), 5.08 (t, J = 9.0 Hz, 1H), 4.90 (dd, J = 10.2, 3.6 Hz, 1H), 4.29–4.20 (m, 2H), 4.17–4.09 (m, 2H), 2.10–1.99 (m, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.9, 170.8, 170.6, 170.2, 169.6, 169.5, 95.4, 90.0, 73.1, 72.3, 71.9, 71.1, 69.9, 69.6, 68.5, 68.4, 67.0, 62.0, 29.6, 20.7, 20.6, 20.6, 20.5, 20.5.

2,3,4,6-Tetra-O-acetyl-D-glactopyranose (3b).[47] (755.2 mg, 78%) $[\alpha]_D^{24}$ +58.63 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 3467, 2925, 1738, 1433, 1369, 1212, 1154, 1126; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.53 (t, J = 3.4 Hz, 1H), 5.48 (d, J = 2.4 Hz, 1H), 5.41 (dd, J = 10.8, 3.3 Hz, 1H), 5.17 (dd, J = 10.8, 3.5 Hz, 1H), 5.07–5.00 (m, 1H), 4.47 (t, J = 6.5 Hz, 1H), 4.17–4.04 (m, 3H), 2.17–1.99 (m, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.8, 170.6, 170.4, 170.3, 170.1, 170.1, 95.7, 90.4, 70.8, 70.7, 70.4, 68.3, 68.1, 67.2, 67.1, 65.9, 61.7, 61.4, 20.7, 20.6, 20.5, 20.5, 20.5, 20.4.

2,3,4,6-Tetra-O-acetyl-D-mannopyranose (3c).[47] (870.7 mg, 90%) $[\alpha]_D^{24}$ +26.71 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 3457, 2923, 2853, 1739, 1460, 1371, 213, 1126; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.39 (dd, J = 9.9, 3.2 Hz, 1H), 5.25 (ddd, J = 9.6, 9.1, 7.0 Hz, 3H), 4.26–4.18 (m, 2H), 4.17–4.07 (m, 2H), 2.15–1.95 (m, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.9, 170.3, 170.1, 169.8, 92.0, 70.0, 68.7, 68.3, 66.0, 62.5, 20.9, 20.7, 20.7, 20.7.

2,3,4-Tri-O-acetyl-D-xylopyranose (3d).[46] (461.3 mg, 60%) $[\alpha]_D^{24}$ +21.89 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2955, 2923, 2854, 1462, 1377, 1260, 1097; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.50 (t, J = 9.6, 1H), 5.38 (t, J = 3.3 Hz, 1H), 5.22 (t, J =9.2 Hz, 1H), 4.99–4.91 (m, 1H), 4.83 (dd, J = 9.9, 3.5 Hz, 1H), 4.67 (t, J = 7.7 Hz, 1H), 4.12 (dd, J = 11.7, 5.6 Hz, 1H), 3.88–3.77 (m, 2H), 3.43–3.42 (m, 1H), 2.08(s, 3H), 2.04(s, 3H), 2.03(s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.9, 170.2, 170.1, 170.1, 169.9, 95.9, 95.8, 90.3, 90.1, 71.2, 69.2, 69.1, 69.0, 62.7, 58.4, 58.2, 20.9, 20.8, 20.7, 20.7, 20.5.

2,3,4-Tri-O-acetyl-L-fucopyranose (3e).[48] (525.3 mg, 65%) $[\alpha]_D^{24}$ +21.89 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2955, 2923, 2854, 1462, 1377, 1260, 1097; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.45 (t, J = 2.9, 1H), 5.39 (dd, J = 10.4, 2.8 Hz, 1H), 5.29 (d, J =3.8 Hz, 1H), 5.13 (dd, J = 10.8, 3.5, 1H), 4.68–4.61 (m, 1H), 4.40 (q, J = 6.4 Hz, 1H), 4.24 (t, J = 5.0 Hz, 1H), 3.84 (d, J = 7.8 Hz, 1H), 3.58 (d, J = 3.1 Hz, 1H), 3.45 (s, 1H), 2.18–1.96 (m, 17H), 1.21 (d, J = 6.4 Hz, 1H), 1.13 (d, J = 6.5 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.4, 170.1, 169.9, 169.8, 169.3, 169.0, 92.0, 89.0, 89.7, 70.5, 70.3, 70.2, 70.0, 67.8, 67.7, 67.2, , 67.1, 20.9, 20.8, 20.7, 20.6, 20.5, 20.4, 15.8, 15.7

2-Acetamido-2-deoxy-3,4,6-tri-O-acetyl-D-glucopyranose (3f).[46] (684.2 mg, 71%) $[\alpha]_D^{24}$ +41.48 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 3366, 2960., 2360 1744, 1661, 1542, 1371, 1244; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.00 (d, J = 9.3 Hz, 1H), 5.31–5.27 (m, 1H), 5.26–5.23 (m, 1H), 5.12 (t, J = 9.4 Hz, 1H), 4.23–4.09 (m, 4H), 2.10–1.94 (m, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.4, 171.1, 170.9, 169.5, 91.3, 70.9, 68.2, 67.2, 62.0, 52.2, 23.0, 20.7, 20.7, 20.6.

4'-O-(2,3,4,6-Tetra-O-acetyl-β-D-galactopyranosyl)-2',3',6'-tri-O-acetyl-D-glucopyranose (3g).[47] (1.3 g, 75%) $[\alpha]_D^{24}$ +33.99 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 3433, 2923, 2853, 1740, 1432, 1367, 1214, 1171; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.50 (t, J = 9.6 Hz, 1H), 5.33 (d, J = 3.5 Hz, 2H), 5.21 (t, J = 9.3 Hz, 1H), 5.14–5.04 (m, 1H), 4.98–4.90 (m, 1H), 4.84–4.75 (m, 1H), 4.73 (d, J = 6.3 Hz, 1H), 4.52–4.43 (m, 3H), 4.20–4.01 (m, 6H), 3.87 (t, J = 6.9 Hz, 2H), 3.76 (dd, J = 20.0, 10.4 Hz, 2H), 3.69–3.60 (m, 1H), 2.15–1.93 (m, 26H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.1, 170.7, 170.6, 170.5, 170.1, 170.1, 100.4, 95.6, 90.5, 71.2, 71.1, 70.8, 70.2, 69.4 68.4, 67.7, 64.3, 20.8, 20.6, 20.6, 20.6, 20.5, 16.0, 15.9.

5-O-Acetyl-2,3-O-isopropylidene-D-ribofuranose (3j).[49] (341.3 mg, 53%) $[\alpha]_D^{24}$ -17.39 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 3446, 2989, 2943, 1744, 1375 1241, 1161; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.46 (s, 1H), 4.70 (d, J = 5.9 Hz, 1H), 4.65–4.62 (m, 2H), 4.40–4.35 (m, 1H), 4.34–4.28 (m, 2H), 4.16–4.08 (m, 3H), 2.10 (s, 3H), 1.48 (s, 3H), 1.33 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.0, 112.4, 102.8, 85.6, 84.3, 81.8, 68.1, 65.2, 26.3, 24.7, 20.7.

4'-O-(2,3,4,6-Tetra-O-acetyl-α-D-gulcopyranosyl)-2',3',6'-tri-O-acetyl-D-glucopyranose (3l).[18] (1.53 g, 96%) $[\alpha]_D^{24}$ +82.66 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 3503, 2923, 2853, 1739, 1429, 1366, 1224, 1148, 1127; ^{1}H NMR

(400 MHz, $CDCl_3$) δ 5.56 (t, J = 9.6 Hz, 1H), 5.41 (d, J = 3.9 Hz, 1H), 5.39–5.36 (m, 1H), 5.35–5.31 (m, 2H), 5.30–5.23 (m, 1H), 5.09–4.99 (m, 2H), 4.83 (ddd, J = 10.5, 3.9, 2.0 Hz, 2H), 4.77–4.71 (m, 2H), 4.51–4.42 (m, 2H), 4.28–4.15 (m, 4H), 4.07–3.90 (m, 5H), 3.76–3.69 (m, 1H), 3.45 (s, 1H), 2.13–1.96 (m, 27H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.7, 170.6, 170.6, 170.6, 170.6, 170.5, 170.5, 170.3, 170.1, 170.1, 169.9, 169.9, 169.4, 169.4, 95.4, 95.4, 94.7, 89.8, 74.8, 73.6, 72.5, 72.2, 71.5, 69.9, 69.3, 69.2, 68.4, 68.3, 67.9, 67.5, 62.8, 62.7, 61.4, 61.3, 29.6, 20.9, 20.8, 20.8, 20.8, 20.6, 20.5, 20.5.

1-O-p-methoxybenzyl-2,3,6-tri-O-acetyl-α-D-mannopyranoside (5c). A mixture of D-mannose (**1c**) (0.5 g, 2.78 mmol), $Dy(OTf)_3$ (1.8 mg, 0.1 mol%) and acetic anhydride (1.1–2 equivalents per –OH of carbohydrates) was stirred at room temperature under nitrogen atmosphere. Upon complete acetylation, the reaction mixture was concentrated *in vacuo* to remove acetic anhydride. To a solution of the residue in MeOH (69.4 mL) was added $Dy(OTf)_3$ (82.9 mg, 4.9 mol%) and $NaHCO_3$ (11.7 mg, 5 mol%) and stirred at 40 °C under nitrogen atmosphere. After the completion of the reaction, the reaction mixture was concentrated under reduced pressure to remove MeOH. The residue was dissolved in ethyl acetate, which was washed with brine, dried over $MgSO_4$, filtered and concentrated. The resulting residue was dissolved in dry DCM (9.8 mL), followed by addition of CCl_3CN (1.1mL, 11.1 mmol) and K_2CO_3 (2 g, 14.2 mmol) and stirred at room temperature. After the completion of the reaction, the reaction mixture was filtered with a short pad of Celite, rinsed with DCM and concentrated *in vacuo*. Without purification, do the next step. $Dy(OTf)_3$ (84.7 mg, 5 mol%) and *p*-methoxy benzyl alcohol (1.2 mL, 11.1 mmol) were added to a solution of residue in DCM (13.9 mL) and stirred at reflux. After the completion of the reaction, the reaction mixture was extracted with DCM, dried over $MgSO_4$ and concentrated. The residue was purified by column chromatography to afford the product **4** (515.7 mg, four steps 41% yield). $[\alpha]_D^{24}$ +57.18 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2923, 2853, 1737, 1612, 1516, 1372, 1223, 1176, 1128; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26–7.25 (m, 1H), 7.25–7.23 (m, 1H), 6.90–6.88 (m, 1H), 6.87–6.85 (m, 1H), 5.35 (dd, J = 10.0, 3.4 Hz, 1H), 5.30–5.26 (m, 1H), 5.24 (dd, J = 3.4, 1.8 Hz, 1H), 4.84 (d, J = 1.6 Hz, 1H), 4.62 (d, J = 11.6 Hz, 1H), 4.48 (d, J = 11.6 Hz, 1H), 4.27 (dd, J = 12.5, 5.1 Hz, 1H), 3.80 (s, 3H), 2.12 (s, 3H), 2.10 (s, 3H), 2.02 (s, 3H), 1.96 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.6, 170.0, 169.8, 169.7, 159.6, 129.9, 128.6, 128.1, 113.9, 96.3, 69.6, 69.3, 69.1, 68.5, 66.1, 62.4, 55.2, 29.6, 20.9, 20.7, 20.7, 20.6; HRMS (ESI) $[M + Na]^+$ Anal. Calcd for $C_{22}H_{28}O_{11}Na$: 491.1512. Found: 491.1524.

p-Tosyl 6-O-(2,3,4,6-tetra-O-acetyl-β-D-glucopyranosyl)-2,3,6-tri-O-benzyl-thio-β-D-glucopyranose (5a). A mixture of D-glucose (**1a**) (0.5 g, 2.78 mmol), $Dy(OTf)_3$ (1.8 mg, 0.1 mol%) and acetic anhydride (1.1–2 equivalents per –OH of carbohydrates) was stirred at room temperature under nitrogen atmosphere. Upon complete acetylation, the reaction mixture was concentrated *in vacuo* to remove acetic anhydride. To a solution of the residue in MeOH (69.4 mL) was added $Dy(OTf)_3$ (82.9 mg, 4.9 mol%) and $NaHCO_3$ (11.7 mg, 5 mol%) and stirred at 40 °C under nitrogen atmosphere. After the completion of the reaction, the reaction mixture was concentrated under reduced pressure to remove MeOH. The residue was dissolved in ethyl acetate, which was washed with brine, dried over $MgSO_4$, filtered and concentrated. The resulting residue was dissolved in DCM (9.8 mL), followed by addition of CCl_3CN (1.1 mL, 11.1 mmol) and K_2CO_3 (2 g, 14.2 mmol) and stirred at room temperature. After the completion of the reaction, the reaction mixture was filtered with a short pad of Celite, rinsed with DCM and concentrated *in vacuo*. The residue was purified by column chromatography to afford 2,3,4,6-tetra-*O*-acetyl-*β*-D-glucopyranosyl trichloroacetimidate **4a** (986.2 mg, three steps 72% yield). To a solution of **4a** (300 mg, 0.6 mmol) in DCM (15 mL) was added *p*-Tosyl-2,3,4-tri-*O*-benzoyl-1-thio-*β*-D-glucopyranoside (0.12 g, 0.2 mmol) and $Dy(OTf)_3$ (6.1 mg, 5 mol%) and stirred at reflux. After the completion of the reaction, the reaction mixture was extracted with DCM, dried over $MgSO_4$ and concentrated. The residue was purified by column chromatography to afford the product **5a** (379 mg, 68% yield). $[\alpha]_D^{24}$ +4.70 (*c* 1.0, $CHCl_3$); IR (cm^{-1}): 2924, 1730, 1601, 1493, 1451,1366, 1278, 1215, 1177; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.96 (d, J = 7.2 Hz, 2H), 7.90 (d, J = 7.3 Hz, 2H), 7.77 (d, J = 7.2 Hz, 2H), 7.53 (td, J = 7.4, 3.9 Hz, 2H), 7.39 (p, J = 7.4 Hz, 7H), 7.26 (dd, J = 9.5, 6.9 Hz, 2H), 7.18 (d, J = 8.0 Hz, 2H), 5.85 (t, J = 9.5 Hz, 1H), 5.42 (t, J = 9.7 Hz, 1H), 5.33 (t, J = 9.8 Hz, 1H), 5.20 (t, J = 9.5 Hz, 1H), 5.09–4.98 (m, 2H), 4.95 (d, J = 10.0 Hz, 1H), 4.62 (d, J = 8.0 Hz, 1H), 4.20 (ddd, J = 12.3, 4.9 Hz, 1H), 4.08–3.97 (m, 3H), 3.81 (dd, J = 11.3, 7.7 Hz, 1H), 3.65 (ddd, J = 9.9, 4.7, 2.1 Hz, 1H), 2.38 (s, 3H), 2.03 (s, 3H), 2.03 (s, 3H), 2.02 (s, 3H), 2.00 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.6, 170.2, 169.5, 169.4, 165.6, 165.3, 165.0, 138.6, 133.6, 133.3, 133.2, 129.9, 129.8, 129.8, 129.6, 129.1, 128.7, 128.5, 128.4, 128.3, 1282, 128.0, 100.8, 86.3, 77.9, 74.0, 72.8, 71.7, 71.1, 70.4, 69.4, 68.7, 68.2, 61.7, 21.2, 20.7, 20.6, 20.6; HRMS (ESI) $[M + Na]^+$ Anal. Calcd for $C_{48}H_{48}O_{17}NaS$: 951.2488. Found: 951.2504.

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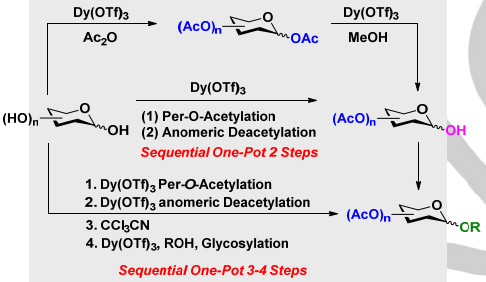

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