JOC The Journal of Organic Chemistry

Article

pubs.acs.org/joc

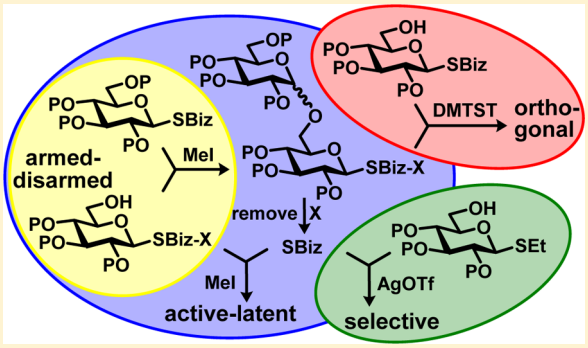
S-Benzimidazolyl (SBiz) Imidates as a Platform for Oligosaccharide Synthesis via Active−Latent, Armed−Disarmed, Selective, and Orthogonal Activations

Scott J. Hasty, Mithila D. Bandara, Nigam P. Rath, and Alexei V. Demchenko*

Department of Chemistry and Biochemistry, University of Missouri—St. Louis, One University Boulevard, St. Louis, Missouri 63121, United States

Supporting Information

ABSTRACT: This article describes the development of *S*-benzimidazolyl (SBiz) imidates as versatile building blocks for oligosaccharide synthesis. The SBiz imidates have been originally developed as a new platform for active-latent glycosylations. This article expands upon the utility of these compounds. The application to practically all common concepts for the expeditious oligosaccharide synthesis including selective, chemoselective, and orthogonal strategies is demonstrated. The strategy development was made possible thanks to our enhanced understanding of the reaction mechanism and the modes by which SBiz imidates interact with various promoters of glycosylation.

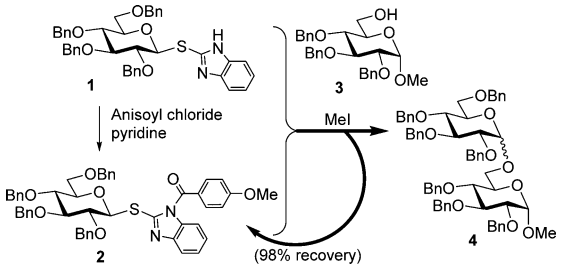


INTRODUCTION

Chemical synthesis of oligosaccharides remains challenging and the development of expeditious strategies for the oligosaccharide and glycoconjugate synthesis stands out as timely and demanding area of research in chemical, biological, and medical sciences.[1,2] As a part of the ongoing research effort, our laboratory has been investigating glycosyl thioimidates, glycosyl donors equipped with the $SCR_1{=}NR_2$ leaving group.[3] Among a variety of leaving groups studied by us and others,[4,5] we determined that *S*-benzimidazolyl (SBiz) imidates are potent glycosyl donors.[6] We also demonstrated that the SBiz leaving group offers an effective new platform for an active-latent strategy pioneered by Roy,[7] Fraser-Reid,[8] Boons,[9] and more recently studied by Kim[10,11] and others.[12−16] Thus, we showed that MeI can activate glycosyl donor **1** equipped with unprotected SBiz (SBiz-H) leaving group, whereas *N*-anisoylated SBiz (SBiz-An) donor **2** remained completely intact and could be recovered nearly quantitatively (98%, Scheme 1).[6]

Subsequent selective activations clearly demonstrated the viability of the SBiz-based active−latent concept. Thus, MeI-promoted glycosylation between building blocks **1** and **5** produced disaccharide **6** bearing the SBiz-An anomeric moiety in 75% yield (Scheme 2). After that, the *N*-anisoyl group was removed by the treatment with one of the following reagents: tetrabutylammonium fluoride (TBAF), NaOMe, or guanidine.[6] The resulting disaccharide **7** bearing the SBiz-H moiety was subsequently activated with MeI to afford trisaccharide **8** in 71% yield. This two-step SBiz activation sequence with the intermediate deprotection step (**1** → **6** → **7** → **8**) mimics the traditional active-latent pathway for oligosaccharide synthesis.[7]

Scheme 1. Competition Experiment between SBiz Donor 1 (Active) and Its *N*-Anisoylated Counterpart 2 (Latent) in the Presence of MeI



We also demonstrated that the intermediate disaccharide **6** can be directly activated for the reaction with acceptor **3** in the presence of a stronger promoter, silver(I) triflate (AgOTf).[6]

The preliminary mechanistic study made us believe that the deactivation effect of the *N*-anisoyl moiety is electronic, and the latter pathway (**1** → **6** → **8**) resembles an armed-disarmed-like activation. While the typical disarming effect in glycosylation refers to the neighboring acyl substituents in the sugar moiety[17] the disarming effect observed with the SBiz imidates is achieved by acylation of the leaving group.

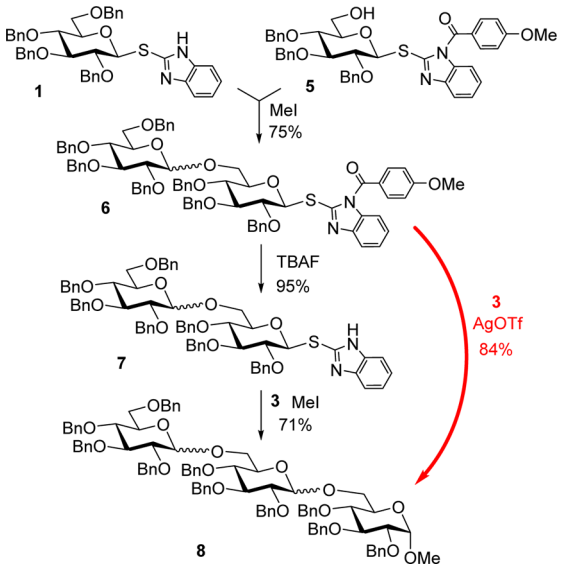
RESULTS AND DISCUSSION

Building upon our previous findings that the application of the SBiz moiety allows for executing a rapid oligosaccharide

Received: October 11, 2016
Published: January 30, 2017

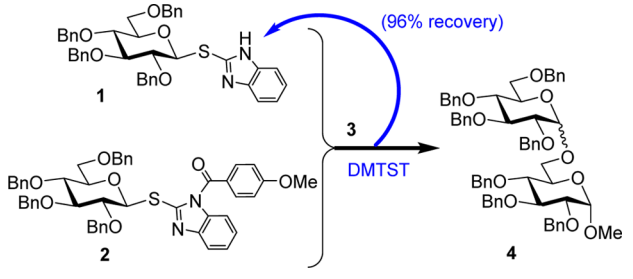
DOI: 10.1021/acs.joc.6b02478
J. Org. Chem. 2017, 82, 1904−1911

Scheme 2. Synthesis of Disaccharide 8 via the Active−Latent (1 → 6 → 7 → 8) and the Armed−Disarmed (1 → 6 → 8) Fashion



assembly via active/latent and leaving group-based armed/disarmed concepts, we continued looking into other possible applications of this new platform. Other conditions applied for the activation of perbenzylated SBiz-H donor **1** and SBiz-An donor **2** for glycosylation with glycosyl acceptor **3**[18,19] included silver tetrafluoroborate ($AgBF_4$) that is a potent activator for thioimidates[20] and common promoters for thioglycoside activation: methyl triflate (MeOTf), *N*-iodosuccinimide (NIS)/triflic acid (TfOH), iodonium dicollidine perchlorate (IDCP), and dimethyl(thiomethyl) sulfonium triflate (DMTST).[21] Both glycosyl donors **1** and **2** could readily be activated with $AgBF_4$, MeOTf, NIS/TfOH, and IDCP producing disaccharide **4** in 15 min to 12 h in 81−96% yield (see the SI for details). To our surprise, only the SBiz-An donor **2** could be activated in the presence of DMTST, whereas SBiz-H donor **1** seemed unreactive. This unexpected result was verified by the direct competition experiment between glycosyl donors **1** and **2** shown in Scheme 3. Opposite the previous

Scheme 3. Unexpected Reactivity of Glycosyl Donors in the Presence of DMTST: Donor 1 Remains Latent and 2 Is Now Active



competition experiment wherein SBiz-An donor **2** remained unreactive in the presence of MeI (Scheme 1), in the presence of DMTST, SBiz-H donor **1** remained practically intact and could be recovered nearly quantitatively (96%).

In our opinion, the set of the competition experiments presented in Schemes 1 and 3 is clearly indicative of the completely orthogonal character of the SBiz-H and SBiz-An leaving groups. Selective activation, wherein one leaving group is activated over another with no protecting group manipulations in between, offers a streamlined access to oligosaccharides.[22] However, aligning multiple leaving groups is not always feasible and syntheses involving sequential activations of three or more different leaving groups are still rare.[23] In this respect, the orthogonal strategy that relies on only two leaving groups that can be orthogonally activated one over another offers a significant advantage. Such activation pathway also requires a pair of orthogonal activators that would activate one, but not the other leaving group. Conceptually, this approach is one of the most effective strategies for expeditious oligosaccharide synthesis.[24−27] Yet this strategy remains somewhat underdeveloped with too few known examples to become universally applicable. Only the following examples are known to date: the original *S*-phenyl vs fluoride introduced by Kanie et al.,[24,25,28] thioimidate-based approaches developed in our lab,[19,29−31] Hotha's *O*-pentenyl vs *O*-propargyl,[32] and *O*-allylphenyl-based approach also introduced by our group.[33] Likewise, we reported a related, albeit less flexible, semiorthogonal approach using *S*-ethyl vs *O*-pentenyl,[34] which was extended to fluoride vs *O*-pentenyl by Fraser-Reid and Lopez.[35]

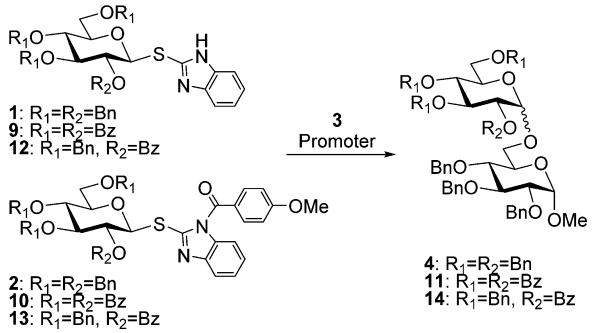
Hence, the subsequent study of this unusual reactivity of SBiz glycosyl donors and their substituted analogues has focused on MeI and DMTST, promoters that showed the greatest difference in the activation profile. The preliminary results with per-benzylated (armed)[17] donors **1** and **2** are summarized in Table 1 (entries 1−4). Thus, while donor **1** was practically unreactive in the presence of DMTST (entry 1), it was readily activated in the presence of MeI. In the latter case, disaccharide **4** was obtained in 89% yield (entry 2). Conversely, donor **2** readily produced disaccharide **4** in the presence of DMTST in 86% yield (entry 3). In the presence of MeI, donor **2** remained unreactive (entry 4).

To determine the relative reactivity of differentially protected SBiz imidates toward glycosidation in the presence of DMTST or MeI we also incorporated 2,3,4,6-*O*-benzoylated (disarmed)[17] SBiz-H donor **9** and its SBiz-An counterpart **10**[6] in our comparative study. When attempting to glycosidate SBiz-H donor **9** with acceptor **3** in the presence of DMTST, no formation of the respective disaccharide **11** was expected based on our observation with the armed benzylated SBiz-H donor **1** that gave no reaction (entry 1). Strikingly, benzoylated SBiz-H donor **9** "disappeared" within 2 h (entry 5). An in depth study showed that no disaccharide **11** was produced; instead, donor **9** was entirely converted into its *N*-thiomethylated derivative **15** (see Table 1 footnote). When per-benzoylated SBiz-H donor **9** was subjected to MeI-promoted activation, no reaction took place (entry 6). Since per-benzylated SBiz-H donor **1** smoothly reacted within 12 h (entry 2), we attribute this result to the electron-withdrawing nature of benzoyl substituents in donor **9** (Fraser-Reid's armed-disarmed concept).[17] The viability of this rationalization was confirmed by the direct chemoselective activation experiment (*vide infra*).

Results obtained with SBiz-An donor **10** were more predictable. DMTST-promoted activation was completed within 24 h and afforded disaccharide **11** in 88% yield and complete β-stereoselectivity due to the participation of the 2-*O*-benzoyl substituent. For comparison, the armed SBiz-An donor **2** reacted faster (12 h, entry 3), which is also indicative of the armed-disarmed-like activation. No glycosidation of SBiz-An

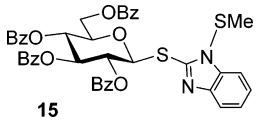
DOI: 10.1021/acs.joc.6b02478
J. Org. Chem. 2017, 82, 1904−1911

Table 1. Glycosidation of Differentially Protected SBiz and *N*-Anisoyl SBiz Glycosyl Donors



entry	donor	promoter[a]	time, h	product (yield, α/β ratio)
1	**1**	DMTST	120	no reaction
2	**1**	MeI	12	**4** (89%, 4.8/1)[6]
3	**2**	DMTST	12	**4** (86%, 3.3/1)
4	**2**	MeI	120	no reaction[6]
5	**9**	DMTST	2	no disaccharide[b]
6	**9**	MeI	120	no reaction
7	**10**	DMTST	24	**11** (88%, β only)
8	**10**	MeI	120	no reaction
9	**12**	DMTST	8	**14** (94%, β only)
10	**12**	MeI	15	**14** (88%, β only)
11	**13**	DMTST	0.75	**14** (92%, β only)
12	**13**	MeI	120	no reaction

[a]Performed in 1,2-dichloroethane in the presence of molecular sieves 3 Å at 35 °C (MeI) or rt (DMTST). [b]The following compound was produced as the only product

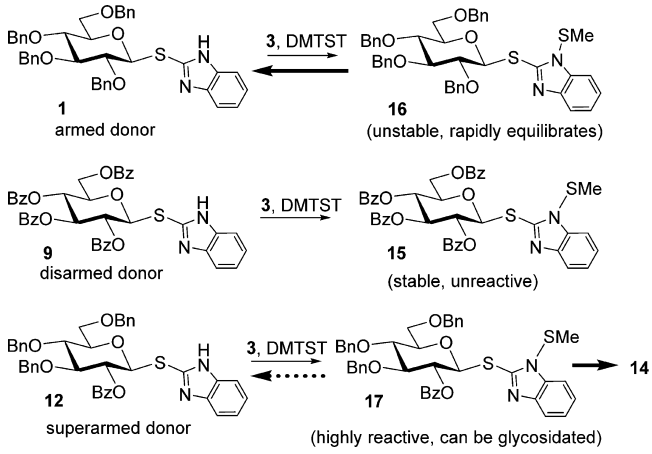


donor **10** took place in the presence of MeI, even after 120 h (entry 8).

We then began investigating glycosyl donors of the superarmed series equipped with 2-*O*-benzoyl-3,4,6-tri-*O*-benzyl protecting group pattern. The superarming in glycosyl donors of this series is based on the combination of electronic and anchimeric effects rationalized by the existence of the O2/O5 cooperative effect in glycosylation.[36−38] Glycosidation of the SBiz-H donor **12** resulted in another interesting outcome: both DMTST and MeI were effective, and the corresponding disaccharide **14** was obtained in high yields in 8 and 15 h, respectively (entries 9 and 10). Again, complete β-stereoselectivity observed in this reaction shall be attributed to the participation of the 2-*O*-benzoyl group. SBiz-An donor **13** was rapidly activated with DMTST and disaccharide **14** was produced in 92% in 45 min (entry 11). Still, no reaction took place with MeI (entry 12).

To investigate these somewhat mixed results obtained with SBiz-H donors **1**, **9**, and **12** in the presence of DMTST, we first set out to determine how the *O*-protecting groups influence the outcome: no reaction (with **1**), the formation of a stable byproduct/intermediate **15** (from **9**), and smooth glycosylation (with **12**). Since the disarmed donor **9** produced intermediate **15** (Table 1 and Scheme 4), we attempted to search for similar intermediates in glycosidation with other series of SBiz-H donors. Upon a more detailed investigation by NMR, we determined that a small amount of unstable compound **16** was

Scheme 4. Activation of Differently Protected SBiz-H Donors 1, 9, and 12 with DMTST



indeed present in the reaction mixture originated from donor **1** (Scheme 4). This intermediate cannot be glycosidated since no disaccharide **4** was produced (entry 1, Table 1), but it instead rapidly equilibrated into the starting material **1**. Therefore, the reaction outcome is overall indicative of DMTST being deactivated by the interaction with donor **1**. In case of the superarmed glycosyl donor **12**, the reaction intermediate **17** is highly reactive. It is possible that it equilibrates back to the starting material **12**, but it can also be glycosidated to form disaccharide **14**. In our opinion, the relatively slow reaction time of 8 h is indicative of the high rate of the competitive reverse reaction. For comparison, the anisoylated superarmed donor **13** was smoothly glycosidated in the presence of DMTST in 45 min (compare entries 9 and 11).

Having uncovered the reaction pathway by which unprotected SBiz leaving group may interact with DMTST, we began studying the activation of substituted SBiz donors. The DMTST-mediated activation of SBiz-An donor **2** smoothly produced disaccharide 4 in 12 h (Table 1, entry 3). To further investigate possible effects of the *N*-substitution, we obtained armed and disarmed *N*-methylated (SBiz-Me) donors **18** and **19**, respectively (Figure 1). When these donors were subjected

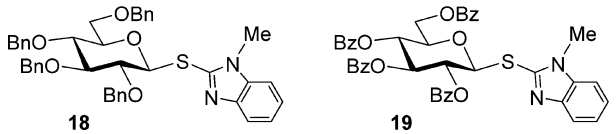


Figure 1. *N*-Methylated SBiz-Me donors **18** and **19**.

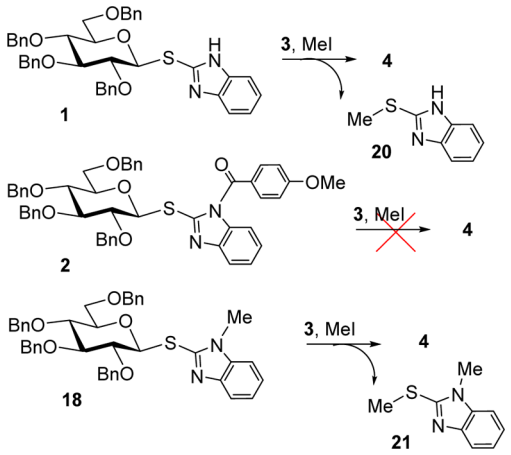
to glycosidation with acceptor **3** in the presence of DMTST, the reactions smoothly produced the corresponding disaccharides **4** and **11** in 9 h (79%) and 72 h (87%), respectively (see the SI for details). This result indicates that the *N*-protection of SBiz leaving group is needed to permit the activation of armed and disarmed SBiz imidates with DMTST. The nature of the substituent is somewhat less important for these activation conditions because both electron-withdrawing *N*-anisoyl and electron-donating *N*-methyl protection produced similar results.

We then began studying the activation pathways for the series of the armed glycosyl donors equipped with the differentially *N*-substituted SBiz-H, SBiz-An, and SBiz-Me leaving groups (**1**, **2**, and **18**, respectively) in the presence of

DOI: 10.1021/acs.joc.6b02478
J. Org. Chem. 2017, 82, 1904−1911

MeI. Previously, we reported that benzyl bromide-mediated glycosidation of SBiz-H donor **1** produced 2-benzylsulfanyl-1*H*-benzimidazole[39,40] indicating the direct activation of the leaving group via the anomeric sulfur atom.[6] Similarly, when SBiz-H donor **1** was glycosidated in the presence of MeI, disaccharide **4** was obtained along with 2-methylsulfanyl-1*H*-benzimidazole **20** (Scheme 5). This result indicates that the MeI-mediated

Scheme 5. Activation of SBiz-H, SBiz-An, and SBiz-Me Donors with MeI



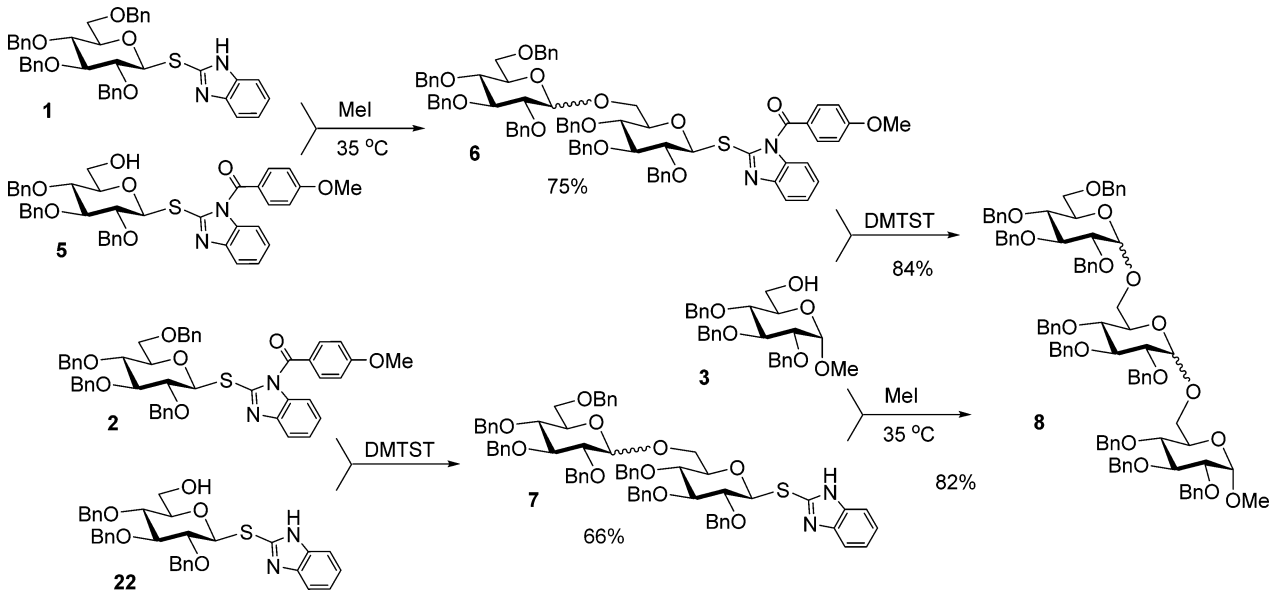
reaction also follows the direct activation pathway rather than the remote activation via the nitrogen atom that could have been another viable activation pathway for the leaving group of this class.[41] When a similar experiment was conducted with SBiz-An donor **2**, neither disaccharide **4** nor products derived from the departed aglycone were detected in the reaction mixture. However, when SBiz-Me donor **18** was subjected to glycosidation with MeI, disaccharide **4** was smoothly produced (15 h, 79%). The departed aglycone was also isolated and determined to be 1-methyl-2-methylsulfanyl-1*H*-benzimidazole **21** by spectral methods and X-ray crystallography.

Overall, these mechanistic studies have ultimately proven the activation pathways of the differentially *N*- and *O*-substituted SBiz imidates. We also discovered that the *N*-methylated SBiz leaving group can be smoothly activated independently on the type of the activation conditions used. The extended study of the *N*-methylated SBiz donors as well as their *N*-allyl and *N*-benzyl counterparts will be reported elsewhere.

This mechanistic study that allowed us to understand the driving forces for the unusual orthogonal reactivity profile of the SBiz-H and SBiz-An leaving groups has then evolved into studying various synthetic pathways for the expeditions oligosaccharide assembly. First, the two-way orthogonal synthesis of trisaccharide **8** was explored (Scheme 6). On the one hand, SBiz-H donor **1** was activated over SBiz-An acceptor **5** in the presence of MeI. The resulting disaccharide **6** isolated in 75% yield was then glycosidated with acceptor **3** in the presence of DMTST to afford trisaccharide **8** in 84% yield. On the other hand, the activation of the SBiz-An leaving group of glycosyl donor **2** over the SBiz-H leaving group of acceptor **22** was effected in the presence of DMTST. The resulting disaccharide **7** isolated in 66% yield was then glycosidated with acceptor **3** in the presence of MeI to afford trisaccharide **8** in 82% yield.

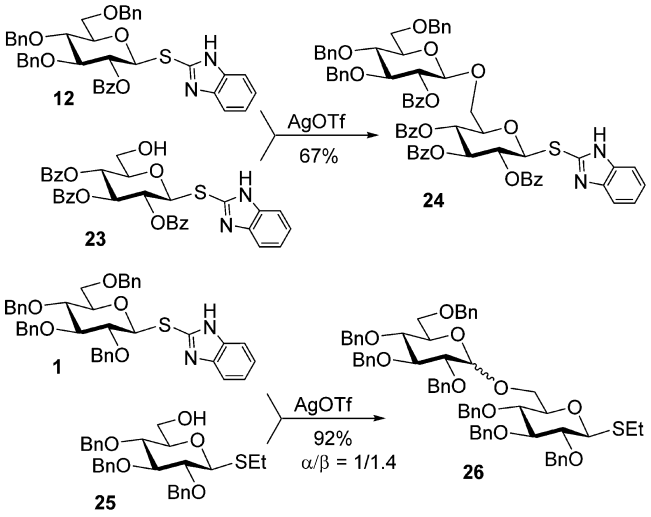
Subsequently, we decided to expand upon our previous finding of differential reactivity of armed, disarmed and superarmed SBiz-H donors **1**, **9**, and **12.** Direct chemoselective activation of the superarmed glycosyl donor **12** over benzoylated (disarmed) glycosyl acceptor **23**[42] was conducted in the presence of AgOTf or MeI (not shown). As a result, disaccharide **24** was produced in 10 min in 67% yield ultimately confirming the electronic (arming-disarming) effects of *O*-protecting groups on the reactivity of differentially protected SBiz-H imidates (Scheme 7). It should be mentioned that AgOTf-mediated activation of thioimidates in general and SBiz in particular also offers a convenient and reliable entry into oligosaccharide synthesis via selective activation over alkyl/aryl thioglycosides.[22] To illustrate the viability of this statement, we conducted a AgOTf-mediated activation of SBiz donor **1** over *S*-ethyl acceptor **25**.[43] This selective activation led to the

Scheme 6. Orthogonal Activation of SBiz-H and SBiz-An Imidates for the Synthesis of Trisaccharide 8



DOI: 10.1021/acs.joc.6b02478
J. Org. Chem. 2017, 82, 1904−1911

Scheme 7. Chemoselective and Selective Activations Using SBiz-H Donors 1 and 12



formation of disaccharide **26** in 92% yield. Apparently, both disaccharides **24** and **26** can be used in subsequent chain elongations without the need for the interim protecting or leaving group manipulations.

CONCLUSIONS

We have uncovered various activations pathways that *S*-benzimidazolyl leaving group platform offers. Efficient activations for the multistep oligosaccharide synthesis via a variety of conceptual approaches were possible due to the mechanistic study that enhanced our understanding of how *O*- and *N*-substituents influence the reactivity of benzimidazole-based thioimidate leaving groups. We have demonstrated further reactivity exploitations of *S*-benzimidazolyl imidates involving DMTST-mediated activation complementing our previous study employing MeI. Through our investigation it was determined that the nitrogen protection, utilizing whether an alkyl or an acyl group, is a requirement to achieve glycosylations using DMTST with all but the superarmed SBiz imidates. Also reported is an orthogonal strategy in which essentially the same class of building blocks can be used, but the promoter selection as well as the *N*-protection is critical. Our further investigation of this promising platform in application to the synthesis of linear and branched oligosaccharide sequences using conventional solution or automated solid-phase synthesis is underway in our laboratory.

EXPERIMENTAL SECTION

General Remarks. The reactions were performed using commercial reagents and the ACS grade solvents used for reactions were purified and dried in accordance with standard procedures. Column chromatography was performed on silica gel 60 (70−230 mesh), reactions were monitored by TLC on Kieselgel 60 F_{254}. The compounds were detected by examination under UV light and by charring with 10% sulfuric acid in methanol. Solvents were removed under reduced pressure at <40 °C. CH_2Cl_2 and $ClCH_2CH_2Cl$ were distilled from CaH_2 directly prior to application. Anhydrous DMF was used as is. Methanol was dried by refluxing with magnesium methoxide, distilled, and stored under argon. Pyridine and acetonitrile were dried by refluxing with CaH_2 and then distilled and stored over molecular sieves (3 Å). Molecular sieves (3 or 4 Å), used for reactions, were crushed and activated *in vacuo* at 390 °C during 8 h in the first instance and then for 2−3 h at 390 °C directly prior to application. DOWEX MONOSPHERE 650C (H^+) was washed three times with MeOH and stored under MeOH. Optical rotations were measured using a polarimeter. ^{1}H NMR spectra were recorded at 300 or 600 MHz, ^{13}C NMR spectra were recorded at 75 or 150 MHz. The ^{1}H NMR chemical shifts are referenced to the signal of the residual $CHCl_3$ (δ_H = 7.27 ppm) for solutions in $CDCl_3$. The ^{13}C NMR chemical shifts are referenced to the central signal of $CDCl_3$ (δ_C = 77.23 ppm) for solutions in $CDCl_3$. HRMS determinations were made with the use of a mass spectrometer with FAB ionization and ion-trap detection.

Synthesis of Glycosyl Donors. *Benzimidazol-2-yl 2,3,4,6-Tetra-O-benzyl-1-thio-β-D-glucopyranoside (**1**).* The title compound was obtained from ethyl 2,3,4,6-tetra-*O*-benzyl-1-thio-β-D-glucopyranoside[44] and 2-benzimidazolethione, potassium salt (KSBiz) as previously reported.[6] Analytical data for **1** were the same as those reported previously.[6]

*(N-Anisoyl)benzimidazol-2-yl 2,3,4,6-Tetra-O-benzyl-1-thio-β-D-glucopyranoside (**2**).* The title compound was obtained from **1** and anisoyl chloride as previously reported.[6] Analytical data for **2** were the same as those reported previously.[6]

*Benzimidazol-2-yl 2,3,4,6-Tetra-O-benzoyl-1-thio-β-D-glucopyranoside (**9**).* The title compound was obtained from 2,3,4,6-tetra-*O*-benzoyl-α-D-glucopyranosyl bromide[45] and KSBiz as previously reported.[6] Analytical data for **9** were the same as those reported previously.[6]

*(N-Anisoyl)benzimidazol-2-yl 2,3,4,6-Tetra-O-benzoyl-1-thio-β-D-glucopyranoside (**10**).* The title compound was obtained from **9** and anisoyl chloride as previously reported.[6] Analytical data for **10** were the same as those reported previously.[6]

*Benzimidazol-2-yl 2-O-Benzoyl-3,4,6-tri-O-benzyl-1-thio-β-D-glucopyranoside (**12**).* The title compound was obtained from 3,4,6-tri-*O*-benzyl-1,2-*O*-methoxybenzylidene-α-D-glucopyranose[46] and 2-mercaptobenzimidazole as previously reported.[6] Analytical data for **12** were the same as those reported previously.[6]

*(N-Anisoyl)benzimidazol-2-yl 2-O-Benzoyl-3,4,6-tri-O-benzyl-1-thio-β-D-glucopyranoside (**13**).* Anisoyl chloride (0.58 mL, 4.29 mmol) was added dropwise to a stirring solution of **12** (1.0 g, 1.4 mmol) in pyridine (10 mL). The resulting reaction mixture was stirred under argon for 15 min at rt. After that, the volatiles were removed *in vacuo* and the residue was coevaporated with toluene (3 × 10 mL). The residue was diluted with CH_2Cl_2 (200 mL), and washed with water (20 mL), 1N aq. HCl (20 mL), water (20 mL), sat. aq. $NaHCO_3$ (2 × 20 mL), and water (3 × 10 mL). The organic phase was separated, dried over Na_2SO_4, and concentrated *in vacuo*. The residue was purified by column chromatography on silica gel (ethyl acetate−toluene gradient elution) to afford the title compound (1.05 g, 91%) as an off-white foam. Analytical data for **13**: R_f = 0.52 (ethyl acetate/toluene, 1/9, v/v); $[\alpha]_D^{27}$ + 119.5 (c = 1.0, $CHCl_3$); ^{1}H-n.m.r.: δ, 3.89−4.08 (m, 7H, H-4, 5, 6a, 6b, OCH_3), 4.11 (dd, 1H, $J_{3,4}$ = 8.7 Hz, H-3) 4.68 (dd, 2H, ^2J = 12.0 Hz, CH_2Ph), 4.85 (dd, 2H, ^2J = 10.9 Hz, CH_2Ph), 4.85 (dd, 2H, ^2J = 11.1 Hz, CH_2Ph), 5.63 (dd, 1H, $J_{2,3}$ = 9.8 Hz, H-2), 6.27 (d, 1H, $J_{1,2}$ = 10.4 Hz, H-1), 6.93−7.67 (m, 28H, aromatic) ppm; ^{13}C-n.m.r.: δ, 55.7, 68.7, 72.8, 73.5, 75.1, 75.4, 77.8, 80.1, 83.6, 84.3, 113.3, 114.2, 118.9, 123.3, 124.1, 124.4, 127.7, 127.8, 127.9, 128.0 (×6), 128.2 (×2), 128.4 (×3), 128.5 (×2), 129.6 (×2), 130.0 (×3), 132.6 (×2), 132.9, 133.3, 134.6, 137.8, 138.1, 143.6, 151.6, 164.4, 165.2, 167.1 ppm; HR-FAB MS $[M+Na]^+$ calcd for $C_{49}H_{44}N_2O_8SNa^+$ 843.2716, found 843.2699.

*(N-Methyl)benzimidazol-2-yl 2,3,4,6-Tetra-O-benzyl-1-thio-β-D-glucopyranoside (**18**).* Methyl iodide (0.14 mL, 2.2 mmol) was added to a stirring solution of benzimidazol-2-yl 2,3,4,6-tetra-*O*-benzoyl-1-thio-β-D-glucopyranoside (0.25 g, 0.37 mmol) and KOH (0.10 g, 1.9 mmol) in tetrahydrofuran (5 mL) and the resulting mixture was stirred under argon for 30 min at rt. Upon completion (TLC), the reaction mixture was diluted with CH_2Cl_2 (~100 mL) and washed with water (20 mL), sat. aq. $NaHCO_3$ (20 mL), and water (3 × 20 mL). The organic phase was separated, dried over $NaSO_4$, and concentrated *in vacuo*. The residue was purified by column chromatography on silica gel (ethyl acetate−hexane gradient elution) to afford the title compound (0.229 g, 90% yield) as a colorless syrup.

DOI: 10.1021/acs.joc.6b02478
J. Org. Chem. 2017, 82, 1904−1911

Analytical data for **18**: R_f 0.55 (ethyl acetate/hexane 3/7, v/v); $[\alpha]_D^{18}$ + 3.7 (*c* 1.0, $CHCl_3$); ^{1}H-n.m.r.: δ 3.51−3.79 (m, 6H, H-2, 3, 4, 5, 6a, 6b), 3.74 (s, 3H, NCH_3), 4.44 (dd, 2H, ^2J = 11.9 Hz, CH_2Ph), 4.66 (dd, 2H, ^2J = 10.9 Hz, CH_2Ph), 4.87 (dd, 2H, ^2J = 10.9 Hz, CH_2Ph), 5.02 (dd, 2H, ^2J = 10.7 Hz, CH_2Ph), 5.68 (d, 1H, $J_{1,2}$ = 9.0 Hz, H-1), 7.14−7.78 (m, 24H, aromatic) ppm; ^{13}C-n.m.r.: δ 31.0, 68.9, 73.5, 75.1, 75.5, 75.9, 79.2, 81.0, 86.2, 86.7, 109.5, 119.6, 122.4, 122.9, 127.8, 127.9 (x2), 128.0 (x3), 128.2 (x2), 128.4, 128.5 (x5), 128.6 (x6), 129.1, 136.8, 138.1, 138.2, 138.3, 138.5, 143.4, 147.2 ppm; HRMS−MS (*m*/*z*): $[M+Na]^+$ calcd for $C_{42}H_{42}N_2O_5SNa^+$, 709.2712; found, 709.2719

*(N-Methyl)benzimidazol-2-yl 2,3,4,6-Tetra-O-benzoyl-1-thio-β-D-glucopyranoside (**19**).* The titled compound was obtained from **9** as described for the synthesis of **18** in 90% yield as a white amorphous solid. Analytical data for **18**: R_f = 0.55 (ethyl acetate/hexane, 3/7, v/v); $[\alpha]_D^{21}$ + 68.0 (*c* 1.0, $CHCl_3$); ^{1}H-n.m.r.: δ, 3.66 (s, 3H, OCH_3), 4.34 (m, 1H, $J_{5,6a}$ = 5.9, $J_{5,6b}$ = 2.1 Hz, H-5), 4.45 (dd, 1H, $J_{6a,6b}$ = 11.9 Hz, H-6a), 4.60 (dd, 1H, H-6b), 5.77 (dd, 1H, $J_{4,5}$ = 9.6 Hz, H-4), 5.80 (dd, 1H, $J_{2,3}$ = 10.2 Hz, H-2), 6.11 (dd, 1H, $J_{3,4}$ = 9.5 Hz, H-3), 6.21 (dd, 1H, $J_{1,2}$ = 10.3 Hz, H-1), 7.13−7.97 (m, 24H, aromatic) ppm; ^{13}C-n.m.r.: δ, 30.6, 63.2, 69.4, 71.1, 74.1, 85.1, 109.4, 119.0, 122.6, 122.9, 128.5 (x7), 128.6 (x2), 128.7 (x2), 128.9, 129.5, 129.8 (x2), 129.9 (x2), 130.0 (x2), 130.1 (x2), 130.3, 133.2, 133.5, 133.7, 136.7, 143.2, 147.4, 165.3, 165.6, 165.8, 166.2 ppm; HR-FAB MS $[M+H]^+$ calcd for $C_{42}H_{35}N_2O_9S^+$ 743.2063, found 743.2062.

Synthesis of Glycosyl Acceptors. *Methyl 2,3,4-Tri-O-benzyl-α-D-glucopyranoside (**3**).* Analytical data for the title compound was the same as previously described.[18,19]

*(N-Anisoyl)benzimidazol-2-yl 2,3,4-Tri-O-benzyl-1-thio-β-D-glucopyranoside (**5**).* The title compound was obtained from **23** and anisoyl chloride via temporary TMS-protection of the primary hydroxyl as previously reported.[6] Analytical data for **5** were the same as those reported previously.[6]

*Benzimidazol-2-yl 2,3,4-Tri-O-benzyl-1-thio-β-D-glucopyranoside (**22**).* The title compound was obtained from 2,3,4-tri-*O*-benzoyl-6-*O*-*tert*-butyldimethylsilyl-β-D-glucopyranosyl bromide[47] and 2-benzimidazolethione, potassium salt (KSBiz) followed by desilylation as previously reported.[6] Analytical data for **23** were the same as those reported previously.[6]

*Benzimidazol-2-yl 2,3,4-Tri-O-benzoyl-1-thio-β-D-glucopyranoside (**23**).* The title compound was obtained from ethyl 2,3,4-tri-*O*-benzoyl-6-*O*-*tert*-butyldimethylsilyl-1-thio-β-D-glucopyranoside[48] and 2-benzimidazolethione, potassium salt (KSBiz) followed by desilylation as previously reported.[42] Analytical data for **24** were the same as those reported previously.[42]

*Ethyl 2,3,4-Tri-O-benzyl-1-thio-β-D-glucopyranoside (**25**).* Analytical data for the title compound was the same as previously described.[43]

Synthesis of Glycosides. *Typical DMTST-Promoted Glycosylation Procedure.* A mixture of glycosyl donor (0.036 mmol), glycosyl acceptor (0.030 mmol), and freshly activated molecular sieves (4 Å, 100 mg) in 1,2-dichloroethane (1.0 mL) was stirred under argon for 1 h at rt. DMTST (0.072 mmol) was added and the reaction mixture was monitored by TLC. Upon completion (see Tables 1, S1, and S2), Et_3N (0.3 mL) was added and the resulting mixture was stirred for 30 min. The mixture was then diluted with CH_2Cl_2 (∼15 mL), the solid was filtered off and washed successively with CH_2Cl_2. The combined filtrate (∼40 mL) was washed with sat. aq. $NaHCO_3$ (10 mL) and water (3 × 10 mL). The organic phase was separated, dried with Na_2SO_4, and concentrated *in vacuo*. The residue was purified by column chromatography on silica gel (ethyl acetate−toluene gradient elution). Anomeric ratios (if applicable) were determined by comparison of the integral intensities of relevant signals in ^{1}H NMR spectra.

Typical Methyl Iodide-Promoted Glycosylation Procedure. A mixture of glycosyl donor (0.036 mmol), glycosyl acceptor (0.030 mmol), and freshly activated molecular sieves (4 Å, 100 mg) in 1,2-dichloroethane (1.0 mL) was stirred under argon for 1 h at rt. Methyl iodide (0.216 mmol) was added and the reaction mixture was monitored by TLC. Upon completion (see Tables 1 and S2) the mixture was then diluted with CH_2Cl_2 (∼15 mL), the solid was filtered off and washed successively with CH_2Cl_2. The combined filtrate (∼40 mL) was washed with 20% aq $Na_2S_2O_3$ (5 mL) and water (3 × 5 mL). The organic phase was separated, dried with Na_2SO_4, and concentrated *in vacuo*. The residue was purified by column chromatography on silica gel (ethyl acetate−toluene gradient elution). Anomeric ratios (if applicable) were determined by comparison of the integral intensities of relevant signals in ^{1}H NMR spectra.

Typical AgOTf-Promoted Glycosylation Procedure. A mixture of glycosyl donor (0.036 mmol), glycosyl acceptor (0.030 mmol), and freshly activated molecular sieves (3 Å, 100 mg) in 1,2-dichloroethane (1.0 mL) was stirred under argon for 1 h. AgOTf (0.072 mmol) was added and the reaction mixture was monitored by TLC. Upon completion, the reaction mixture was then diluted with CH_2Cl_2 (∼15 mL), the solid was filtered off and washed successively with CH_2Cl_2. The combined filtrate (∼40 mL) was washed with sat. aq. $NaHCO_3$ (10 mL) and water (3 × 10 mL). The organic phase was separated, dried with Na_2SO_4, and concentrated *in vacuo*. The residue was purified by column chromatography on silica gel (ethyl acetate−toluene gradient elution). Anomeric ratios (if applicable) were determined by comparison of the integral intensities of relevant signals in ^{1}H NMR spectra.

*Methyl 6-O-(2,3,4,6-Tetra-O-benzyl-α/β-D-glucopyranosyl)-2,3,4-tri-O-benzyl-α-D-glucopyranoside (**4**).* The title compound was prepared from donor **1** or **2** and acceptor **3** as described in Tables 1, S1, and S2. Analytical data for **4** was the same as previously described.[49,50]

*(N-Anisoyl)benzimidazol-2-yl 6-O-(2,3,4,6-Tri-O-benzyl-α/β-D-glucopyranosyl)-2,3,4-tri-O-benzyl-β-D-glucopyranoside (**6**).* The title compound was prepared from donor **1** and acceptor **5** in 75% yield in accordance with the general glycosylation procedure in the presence of MeI. The analytical data for **6** were in a good agreement with those reported previously.[6]

*2-Benzimidazolyl 6-O-(2,3,4,6-Tetra-O-benzyl-α/β-D-glucopyranosyl)-2,3,4-tri-O-benzyl-β-D-glucopyranoside (**7**).* The title compound was prepared from donor **2** and acceptor **22** in 66% yield in accordance with the general glycosylation procedure in the presence of DMTST. The analytical data for **7** were in a good agreement with those reported previously.[6]

*Methyl O-(2,3,4,6-Tetra-O-benzyl-α/β-D-glucopyranosyl)-(1→6)-O-(2,3,4-tri-O-benzyl-α/β-D-glucopyranosyl)-(1→6)-2,3,4-tri-O-benzyl-β-D-glucopyranoside (**8**).* The title compound was prepared from donor **6** and acceptor **3** in 84% yield in accordance with the general glycosylation procedure in the presence of DMTST. The title compound was also prepared from donor **7** and acceptor **3** in 82% yield in accordance with the general glycosylation procedure in the presence of MeI. The analytical data for **7** were in a good agreement with those reported previously.[31]

*Methyl 6-O-(2,3,4,6-Tetra-O-benzoyl-β-D-glucopyranosyl)-2,3,4-tri-O-benzyl-α-D-glucopyranoside (**11**).* The title compound was prepared from donor **9** or **10** and acceptor **3** as described in Tables 1, S1, and S2 in accordance with the general glycosylation procedure in the presence of DMTST. Analytical data for **11** was the same as previously described.[49]

*Methyl 6-O-(2-O-Benzoyl-3,4,6-tri-O-benzyl-β-D-glucopyranosyl)-2,3,4-tri-O-benzyl-α-D-glucopyranoside (**14**).* The title compound was prepared from donor **12** or **13** and acceptor **3** as described in Table 1. Analytical data for **14** was the same as previously described.[50]

*Benzimidazol-2-yl 6-O-(2-O-benzoyl-3,4,6-tri-O-benzyl-α/β-D-glucopyranosyl)-2,3,4-tri-O-benzoyl-1-thio-β-D-glucopyranoside (**24**).* The title compound was prepared from donor **12** and acceptor **23** in 67% yield in accordance with the general glycosylation procedure in the presence of AgOTf. Analytical data for **24**: R_f = 0.70 (ethyl acetate/toluene, 3/7, v/v); $[\alpha]_D^{22}$ + 56.8 (*c* = 1.0, $CHCl_3$); ^{1}H-NMR (600 MHz, $CDCl_3$): δ, 3.31 (dd, 1H, $J_{6a',6b'}$ = 10.5 Hz, H-6a′), 3.50−3.58 (m, 3H, $J_{5',6a'}$ = 4.3 Hz, H-4′, 5′, 6b′), 3.87 (dd, 1H, $J_{3',4'}$ = 8.7 Hz, H-3′), 3.92 (dd, 1H, $J_{6a,6b}$ = 11.5 Hz, H-6a), 3.96 (dd, 1H, H-6b), 4.14 (m, 1H, $J_{5,6a}$ = 3.8 Hz, $J_{5,6b}$ = 7.6 Hz, H-5), 4.37 (dd, 2H, ^2J = 12.2 Hz, CH_2Ph), 4.60 (dd, 2H, ^2J = 10.9 Hz, CH_2Ph), 4.65 (d, 1H, $J_{1',2'}$ = 8.0 Hz, H-1′), 4.75 (dd, 2H, ^2J = 11.3 Hz, CH_2Ph), 5.21 (d, 1H, $J_{1,2}$ = 10.1 Hz, H-1), 5.37 (dd, 1H, $J_{4,5}$ = 10.0 Hz, H-4), 5.38 (dd, 1H, $J_{2',3'}$ = 8.7

DOI: 10.1021/acs.joc.6b02478
J. Org. Chem. 2017, 82, 1904−1911

Hz, H-2′), 5.51 (dd, 1H, $J_{2,3}$ = 9.7 Hz, H-2), 5.86 (dd, 1H, $J_{3,4}$ = 9.4 Hz, H-3), 7.20−7.95 (m, 39H, aromatic), 10.53 (br. s, 1H, NH) ppm; ^{13}C-NMR (150 MHz, $CDCl_3$): δ, 68.6, 68.7, 69.6, 70.7, 73.5, 73.8, 73.8, 75.3, 75.4 (×2), 77.0, 77.97, 82.6, 84.4, 101.6, 127.9 (×3), 128.1 (×7), 128.4 (×2), 128.5 (×5), 128.6 (×11), 128.7, 128.8 (×2), 129.6, 129.8 (×2), 130.0 (×4), 130.1 (×2), 133.4, 133.5, 133.6, 133.7, 137.8 (×3), 144.8, 165.4 (×2), 165.7, 165.9 ppm; HR-FAB MS $[M+Na]^+$ calcd for $C_{68}H_{60}N_2O_{14}SNa^+$ 1183.3663, found 1183.3634.

*Ethyl 6-O-(2,3,4,6-Tetra-O-benzyl-α/β-D-glucopyranosyl)-2,3,4-tri-O-benzyl-1-thio-β-D-glucopyranoside (**26**).* The title compound was prepared from donor **1** and acceptor **25** in 92% yield (α/β = 1/1.4) in accordance with the general glycosylation procedure in the presence of AgOTf. Analytical data for the title compound was the same as previously described.[20]

Procedure for Competitive Glycosylation. *Methyl 6-O-(2,3,4,6-Tetra-O-benzyl-α/β-D-glucopyranosyl)-2,3,4-tri-O-benzyl-α-D-glucopyranoside (**4**).* A mixture of glycosyl donor **1** (0.045 mmol), glycosyl donor **2** (0.045 mmol), glycosyl acceptor **3** (0.041 mmol), and freshly activated molecular sieves (3 Å, 130 mg), in 1,2-dichloroethane (1.5 mL) was stirred under argon for 1 h. After that, DMTST (0.135 mmol) was added, and the reaction mixture was monitored by TLC. Upon disappearance of the glycosyl acceptor, the solid was filtered off and the filtrate was diluted with CH_2Cl_2 (30 mL), washed with sat. aq. $NaHCO_3$ (10 mL) and water (3 × 10 mL). The organic layer was separated, dried with $MgSO_4$, filtered, and concentrated *in vacuo*. The residue was purified by column chromatography on silica gel.

Mechanistic Studies, Intermediate/Aglycone Isolation/Characterization. *(N-Thiomethyl)benzimidazol-2-yl 2,3,4,6-Tetra-O-benzoyl-1-thio-β-D-glucopyranoside (**15**).* Dimethyl(thiomethyl)-sulfonium triflate (0.024 g, 0.094 mmol) was added to a stirred solution of benzimidazol-2-yl 2,3,4,6-tetra-*O*-benzoyl-1-thio-β-D-glucopyranoside (0.035 g, 0.047 mmol) in 1,21-dichloroethane (1.0 mL). The resulting reaction mixture was allowed to stir for 2 h. Then triethylamine (~0.25 mL) was added. The resulting mixture was then diluted with CH_2Cl_2 (100 mL) and subsequently washed water (10 mL). The organic phase was separated, dried with Na_2SO_4 and concentrated *in vacuo*. The crude residue was then used to obtain ^{1}H-NMR and ^{13}C-NMR Selected analytical data for **15**: R_f = 0.66 (ethyl acetate/toluene, 1/5, v/v); ^{1}H-n.m.r.: δ, 2.44 (s,3H, SCH_3), 4.50 (m, 2H, $J_{5',6b}$ = 4.9 Hz, $J_{6a',6b}$ = 14.3 Hz, H-5, 6a), 4.62 (dd, 1H, H-6b), 5.76 (dd, 1H, $J_{4',5}$ = 9.5 Hz, H-4), 5.84 (dd, 1H, $J_{2',3}$ = 9.4 Hz, H-2), 6.15 (dd, 1H, $J_{3',4}$ = 9.4 Hz, H-3), 6.36 (d, 1H, $J_{1,2}$ = 10.4 Hz, H-1), 7.18−7.88 (m, 24H, aromatic) ppm; ^{13}C-n.m.r.: δ, 23.0, 63.3, 69.6, 70.9, 74.3, 83.9, 110.2, 119.0, 123.2, 128.4 (×2), 128.5 (×4), 128.6 (×3), 128.8 (×2), 128.9, 129.7, 129.8 (×3), 129.9 (×2), 130.0 (×2), 130.1 (×2), 133.1, 133.5, 133.6, 133.7, 138.7, 143.9, 155.3, 165.4 (×2), 165.6, 165.8 ppm; HR-FAB MS $[M+H]^+$ calcd for $C_{42}H_{35}N_2O_9S_2^+$ 775.1784, found 775.1773.

*2-Methylsulfanyl-1H-benzimidazole (**20**).* The title compound was isolated from a reaction between donor **1** and acceptor **3** in the presence of MeI. The identity of **20** was confirmed by comparison with the authentic commercial sample.

*1-Methyl-2-methylthio-1H-benzimidazole (**21**).* The title compound was isolated as colorless crystals from a reaction between donor **18** and acceptor **3** in the presence of MeI. Selected analytical data for **21**: R_f = 0.43 (ethyl acetate/hexane, 1/1, v/v); mp 121−124 °C (dichloromethane/toluene, 1/1, v/v); ^{1}H-n.m.r.: δ, 2.80 (s, 3H, SCH_3), 3.67 (s, 3H, NCH_3), 7.15−7.71 (m, 4H, aromatic) ppm; ^{13}C-n.m.r.: δ, 14.8, 30.1, 108.5, 118.2, 121.9 (x2), 137.1, 143.6, 153.4 ppm; HR-FAB MS $[M+H]^+$ calcd for $C_9H_{11}N_2S^+$ 179.0643, found 179.0645.

X-ray Structure Determination of Compound 21. Crystals of appropriate dimension were obtained by slow evaporation of a mixture of dichloromethane and toluene (1/1, v/v). A crystal of approximate dimensions of 0.576 × 0.119 × 0.041 mm^3 was mounted on MiTeGen cryoloops in a random orientation. Preliminary examination and data collection were performed using a X8 Kappa Apex II Charge Coupled Device (CCD) Detector system single crystal X-ray diffractometer equipped with an Cryostream LT device. All data were collected using graphite monochromated Mo Kα radiation (λ= 0.71073 Å) from a fine focus sealed tube X-ray source. Preliminary unit cell constants were determined with a set of 36 narrow frame scans. Typical data sets consist of combinations of ϖ and ϕ scan frames with typical scan width of 0.5° and counting time of 15 s/frame at a crystal to detector distance of 4.0 cm. The collected frames were integrated using an orientation matrix determined from the narrow frame scans. Apex II and SAINT software packages were used for data collection and data integration. Analysis of the integrated data did not show any decay. Final cell constants were determined by global refinement of reflections harvested from the complete data set. Collected data were corrected for systematic errors using TWINABS based on the Laue symmetry using equivalent reflections.

Crystal data and intensity data collection parameters are listed in Table 3S of the Supporting Information (SI). Structure solution and refinement were carried out using the SHELXTL- PLUS software package.[51] The structure was solved by direct methods and refined successfully in the space group P $\bar{1}$. Data from one of the two twin components were used for structure refinement (data from the minor component were ignored, HKLF 4 data used). Full matrix least-squares refinements were carried out by minimizing $\sum w(F_o^2-F_c^2)^2$. The non-hydrogen atoms were refined anisotropically to convergence. The NH H atom was located and refined freely. All other hydrogen atoms were treated using appropriate riding model (AFIX m3). The final residual values and structure refinement parameters are listed in Table 3S (see SI). The I^- anion was disordered in this structure. The disorder was modeled with partial occupancy atoms (99:1%) and displacement parameter constraint, EADP.

Complete listings of positional and isotropic displacement coefficients for hydrogen atoms, anisotropic displacement coefficients for the non-hydrogen atoms are included as the Supporting Information (Tables 4S, 6S, and 7S). Table of calculated and observed structure factors are available in electronic format.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b02478.

X-ray crystallography data for compound **21** (CIF)

^{1}H and ^{13}C NMR spectra for all new compounds and comparative glycosylation data (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*demchenkoa@umsl.edu

ORCID

Alexei V. Demchenko: 0000-0003-3515-212X

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by awards from the NIGMS (GM077170 and GM111835). We thank funding from the NSF-MRI (CHE-0420497) for the purchase of the Apex-II diffractometer. We also thank Dr. Rensheng Luo (UM—St. Louis) for acquiring spectral data using 600 MHz NMR spectrometer that was purchased thanks to the NSF (award CHE-0959360). Dr. Winter and Mr. Kramer (UM—St. Louis) are thanked for HRMS determinations.

■ REFERENCES

(1) Smoot, J. T.; Demchenko, A. V. *Adv. Carbohydr. Chem. Biochem.* **2009**, *62*, 161.

(2) Bouhall, S. K.; Sucheck, S. J. *J. Carbohydr. Chem.* **2014**, *33*, 347.

(3) Yasomanee, J. P.; Demchenko, A. V. *Trends Glycosci. Glycotechnol.* **2013**, *25*, 13.

DOI: 10.1021/acs.joc.6b02478
J. Org. Chem. 2017, 82, 1904−1911

(4) Szeja, W.; Grynkiewicz, G. In *Handbook of Chemical Glycosylation*; Demchenko, A. V., Ed.; Wiley-VCH: Weinhein, Germany, 2008; p 329.
(5) Hasty, S. J.; Demchenko, A. V. *Chem. Heterocycl. Compd.* **2012**, *48*, 220.
(6) Hasty, S. J.; Kleine, M. A.; Demchenko, A. V. *Angew. Chem., Int. Ed.* **2011**, *50*, 4197.
(7) Roy, R.; Andersson, F. O.; Letellier, M. *Tetrahedron Lett.* **1992**, *33*, 6053.
(8) Fraser-Reid, B.; Udodong, U. E.; Wu, Z. F.; Ottosson, H.; Merritt, J. R.; Rao, C. S.; Roberts, C.; Madsen, R. *Synlett* **1992**, *1992*, 927.
(9) Boons, G. J.; Isles, S. *Tetrahedron Lett.* **1994**, *35*, 3593.
(10) Kim, K. S.; Kim, J. H.; Lee, Y. J.; Lee, Y. J.; Park, J. *J. Am. Chem. Soc.* **2001**, *123*, 8477.
(11) Kim, K.-S.; Jeon, H.-B. In *Handbook of Chemical Glycosylation*; Demchenko, A. V., Ed.; Wiley-VCH: Weinheim, Germany, 2008; p 185.
(12) Hinklin, R. J.; Kiessling, L. L. *J. Am. Chem. Soc.* **2001**, *123*, 3379.
(13) Huang, L.; Wang, Z.; Huang, X. *Chem. Commun.* **2004**, 1960.
(14) Wang, P.; Haldar, P.; Wang, Y.; Hu, H. *J. Org. Chem.* **2007**, *72*, 5870.
(15) Dara, S.; Saikam, V.; Yadav, M.; Singh, P. P.; Vishwakarma, R. A. *Carbohydr. Res.* **2014**, *391*, 93.
(16) Xiao, X.; Zhao, Y.; Shu, P.; Zhao, X.; Liu, Y.; Sun, J.; Zhang, Q.; Zeng, J.; Wan, Q. *J. Am. Chem. Soc.* **2016**, *138*, 13402.
(17) Fraser-Reid, B.; Wu, Z.; Udodong, U. E.; Ottosson, H. *J. Org. Chem.* **1990**, *55*, 6068.
(18) Kuester, J. M.; Dyong, I. *Justus Liebigs Ann. Chem.* **1975**, *1975*, 2179.
(19) Ranade, S. C.; Kaeothip, S.; Demchenko, A. V. *Org. Lett.* **2010**, *12*, 5628.
(20) Kaeothip, S.; Pornsuriyasak, P.; Demchenko, A. V. *Tetrahedron Lett.* **2008**, *49*, 1542.
(21) Zhong, W.; Boons, G.-J. In *Handbook of Chemical Glycosylation*; Demchenko, A. V., Ed.; Wiley-VCH: Weinheim, Germany, 2008; p 261.
(22) Kaeothip, S.; Demchenko, A. V. *Carbohydr. Res.* **2011**, *346*, 1371.
(23) Kaeothip, S.; Demchenko, A. V. *J. Org. Chem.* **2011**, *76*, 7388.
(24) Kanie, O.; Ito, Y.; Ogawa, T. *J. Am. Chem. Soc.* **1994**, *116*, 12073.
(25) Ito, Y.; Kanie, O.; Ogawa, T. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 2510.
(26) Paulsen, H. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1432.
(27) Kanie, O. In *Carbohydrates in Chemistry and Biology*; Ernst, B., Hart, G. W., Sinay, P., Eds.; Wiley-VCH: Weinheim, NY, 2000; Vol. *1*, p 407.
(28) Kanie, O.; Ohtsuka, I.; Ako, T.; Daikoku, S.; Kanie, Y.; Kato, R. *Angew. Chem., Int. Ed.* **2006**, *45*, 3851.
(29) Demchenko, A. V.; Pornsuriyasak, P.; De Meo, C.; Malysheva, N. N. *Angew. Chem., Int. Ed.* **2004**, *43*, 3069.
(30) Pornsuriyasak, P.; Demchenko, A. V. *Chem. - Eur. J.* **2006**, *12*, 6630.
(31) Kaeothip, S.; Pornsuriyasak, P.; Rath, N. P.; Demchenko, A. V. *Org. Lett.* **2009**, *11*, 799.
(32) Vidadala, S. R.; Thadke, S. A.; Hotha, S. *J. Org. Chem.* **2009**, *74*, 9233.
(33) Premathilake, H. D.; Demchenko, A. V. *Beilstein J. Org. Chem.* **2012**, *8*, 597.
(34) Demchenko, A. V.; De Meo, C. *Tetrahedron Lett.* **2002**, *43*, 8819.
(35) Lopez, J. C.; Uriel, C.; Guillamon-Martin, A.; Valverde, S.; Gomez, A. M. *Org. Lett.* **2007**, *9*, 2759.
(36) Mydock, L. K.; Demchenko, A. V. *Org. Lett.* **2008**, *10*, 2103.
(37) Mydock, L. K.; Demchenko, A. V. *Org. Lett.* **2008**, *10*, 2107.
(38) Premathilake, H. D.; Mydock, L. K.; Demchenko, A. V. *J. Org. Chem.* **2010**, *75*, 1095.
(39) Kumar, R. V.; Gopal, K. R.; Seshu Kumar, K. V. S. R. *J. Heterocycl. Chem.* **2005**, *42*, 1405.
(40) Yavo, E. A.; Kakou-Yao, R.; Coulibaly, S.; Abou, A.; Tenon, A. J. *Acta Crystallogr., Sect. E: Struct. Rep. Online* **2007**, *63*, o4551.
(41) Ranade, S. C.; Demchenko, A. V. *J. Carbohydr. Chem.* **2013**, *32*, 1.
(42) Ranade, S. C.; Hasty, S. J.; Demchenko, A. V. *J. Carbohydr. Chem.* **2013**, *32*, 360.
(43) Fei, C.; Chan, T. H. *Acta Chim. Sin.* **1989**, *7*, 258.
(44) Andersson, F.; Fugedi, P.; Garegg, P. J.; Nashed, M. *Tetrahedron Lett.* **1986**, *27*, 3919.
(45) Lemieux, R. U. In *Methods in Carbohydrate Chemistry*; Whistler, R. L., Wolform, M. L., Eds.; Academic Press Inc.: New York and London, 1963; Vol. *2*, p 226.
(46) Ekborg, G.; Glaudemans, C. P. J. *Carbohydr. Res.* **1984**, *129*, 287.
(47) Khan, A. T.; Ghosh, S.; Choudhury, L. H. *Eur. J. Org. Chem.* **2004**, *2004*, 2198.
(48) Majumdar, D.; Zhu, T.; Boons, G.-J. *Org. Lett.* **2003**, *5*, 3591.
(49) Garcia, B. A.; Gin, D. Y. *J. Am. Chem. Soc.* **2000**, *122*, 4269.
(50) Nguyen, H. M.; Chen, Y. N.; Duron, S. G.; Gin, D. Y. *J. Am. Chem. Soc.* **2001**, *123*, 8766.
(51) Sheldrick, G. M. *Acta Crystallogr., Sect. A: Found. Crystallogr.* **2008**, *64*, 112.

DOI: 10.1021/acs.joc.6b02478
J. Org. Chem. 2017, 82, 1904−1911