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Galactopyranoside-Substituted *N*-Heterocyclic Carbene Gold(I) Complexes: Synthesis, Stability, and Catalytic Applications to Alkyne Hydration

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Cite This: *ACS Omega* 2022, 7, 21788−21799

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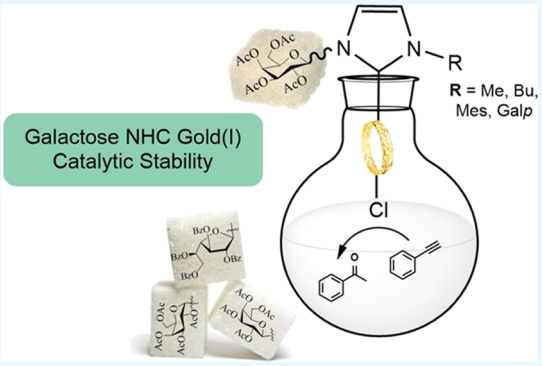
ABSTRACT: A series of novel gold(I) complexes bearing galactopyranoside-based *N*-heterocyclic carbene ligands have been synthesized via transmetalation of the corresponding Ag(I) complex. Gold(I) complexes have been characterized by NMR, Fourier transform infrared (FTIR), and elemental analysis. An exhaustive NMR analysis shows that the complexes are not stable when hydroxyl groups are deprotected. Catalytic studies, using the alkyne hydration as a model reaction, indicate that the synthesized complexes are active and reusable.



INTRODUCTION

Gold has been used for therapeutic and/or catalytic purposes for decades.[1] The current concern is to achieve higher stability of the compounds that carry metals, for which coordination with *N*-heterocyclic carbene (NHC) ligands has been an excellent strategy.[2] For a long time, NHCs were considered transient species; in 1968, independently, Wanzlick and Öfele synthesized mercury(II) and chromium(0) complexes containing NHC ligand, respectively.[3] However, in 1991, when Arduengo et al.[4] isolated the first free carbene, the interest in NHC started to grow up to the present. This neutral monodentate ligand has a series of advantages, such as stability and tolerance to a variety of functional groups. Furthermore, NHCs have contributed to significant advances in water-soluble transition-metal complexes for aqueous phase applications.[5] The most common and simple route to access the NHC is through commercial or synthesized imidazolium salts, using a large number of methodologies.[6,7] Finally, by treatment with a strong Brønsted base (KH, NaH, BuLi, etc.), free carbene is accessed.

Carbohydrates are the most abundant biological molecules on the planet and perform numerous functions in the organism;[8] they are mainly responsible for signaling processes and cellular recognition, being crucial for the proper functioning of the immune system, fertilization, pathogenicity, coagulation, and growth.[9] Despite this, their use as therapeutic agents is very limited.[10] They have received particular interest in organic synthesis as building blocks in the construction of biologically active compounds and as chiral auxiliaries in asymmetric synthesis.[11] Taking into account the property of carbohydrates to function as a site of recognition or anchoring of molecules through a hydrogen bridge,[12] as well as their solubility in water, they become attractive and versatile ligands.[13] In particular, carbohydrate-substituted NHCs and their metal complexes are promising in catalysis and medicinal chemistry.[14] Despite this, examples of their use as ligands bound to NHC complexes are recent. The groups of Kinoshita and Glorius independently synthesized the first examples of imidazolium salts with glycosidic ligands and their metal−NHC complexes.[15] Since those beginnings, complexes have been synthesized, with different transition metals, that include N−C1 [Ag, Pd, Ni, Ir, Ru, Rh],[15,16] N−C2 [Ru],[17] N−C3 [Rh],[18] or N−C6 [Ag, Pd]-pyranosic bonds,[19] generally using D-glucose as a model carbohydrate or metal−carbohydrate bonds.[20] D'Amora et al.[21] reported the first glucopyranoside-incorporated NHC containing gold(I) complexes and their biological activity on PC-3 prostate cancer cells and on a panel of human tumor cell lines. In our group, we have recently achieved very encouraging results by synthesizing and characterizing silver complexes using chitooligosaccharides and glucosamine, through *N*-heterocyclic carbenes, as a

Received: March 28, 2022
Accepted: June 1, 2022
Published: June 14, 2022

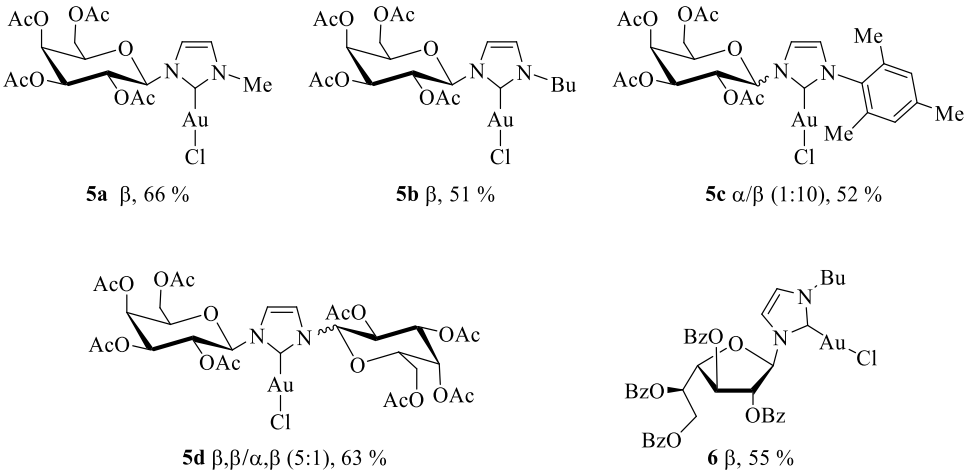
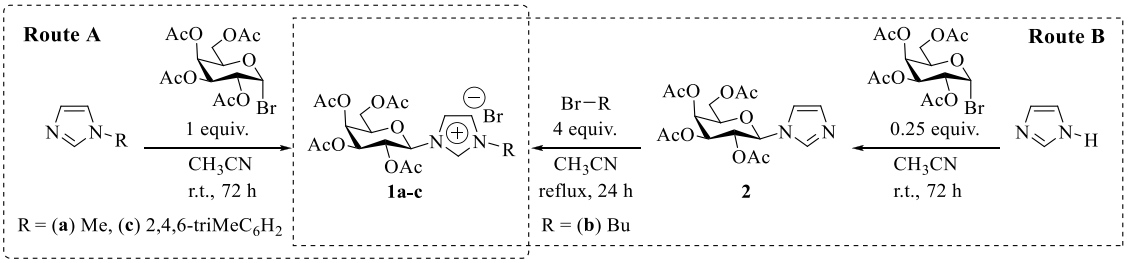


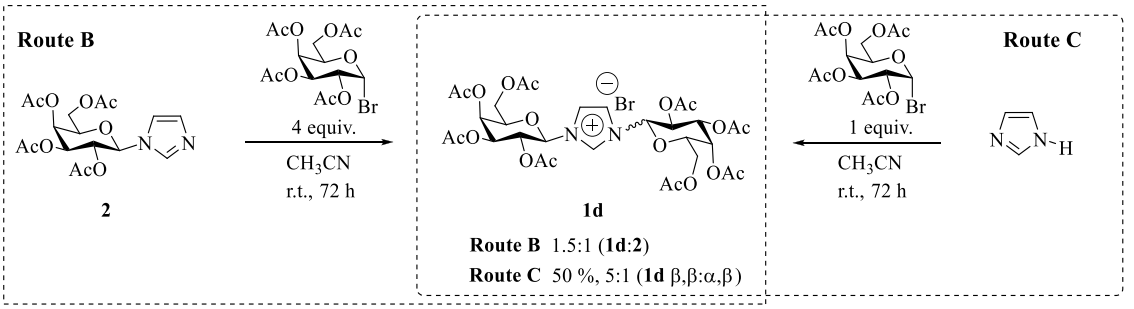
Figure 1. Structure of glycosidic ligand-substituted NHC gold(I) complexes synthesized.

Scheme 1. General Procedures for the Preparation of Glycosyl Imidazolium Salts[a]



[a]Route (A) from alkyl or aryl imidazole; route (B) from *β*-d-galactopyranosyl imidazole.

Scheme 2. Procedures for the Preparation of Bis-Glycosyl Imidazolium Salts



ligand.[22] On the other hand, surprisingly, we found only one example of the use of a C6-furanosic ligand [Rh].[23]

Based on our work in the synthesis and catalytic application of sulfonated Au(I)−NHC complexes[24] and inspired by literature reports,[14,21] we decided to carry out the first catalytic study applying sugar-incorporated Au(I)−NHC complexes (Figure 1). The selection of the D-galactose derivatives is based on their commercial availability and their almost unexplored application in this topic. On the other hand, the substituents on the imidazole nitrogen will allow us to understand correlations between complex structures and catalyst activities. Catalytic studies, using the alkyne hydration as a model reaction,[25] indicate that the synthesized complexes are active and reusable. It is important to mention that a comprehensive NMR analysis was performed to identify the deprotection reaction products of the corresponding gold complexes.

RESULTS AND DISCUSSION

Synthesis and Characterization. *Imidazolium Salts.* A galactopyranoside-substituted NHC precursor has been synthesized in two different ways (Scheme 1).

Initially, adapting the synthetic strategies reported in the literature,[15] we carried out the synthesis of **1a** and **1c** from methyl and mesitylimidazole with 2,3,4,6-tetra-*O*-acetyl-*α*-D-galactopyranosyl bromide, respectively (Scheme 1; route A). Salt **1a** was obtained as a *β* anomer in a 60% yield, while **1c** was obtained in a 57% yield as a mixture of *α* and *β* anomers (*α*/*β*, 1:5). On the other hand, adapting the synthetic method described by Zhou et al.[16d] the imidazolium salt **1b** was synthesized from *β*-D-galactopyranosyl imidazole (**2**) and butyl bromide (Scheme 1; route B) in a 62% yield as a pure *β* anomer. These two synthetic routes make it possible to obtain the desired salts in good to excellent yields. Next, with the intention of obtaining a derivative with two glycosidic units, alt **1d** was synthesized by two different routes (Scheme 2). First,

https://doi.org/10.1021/acsomega.2c01878
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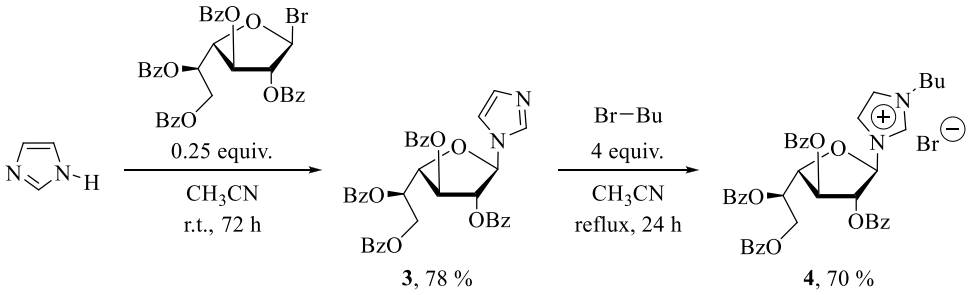
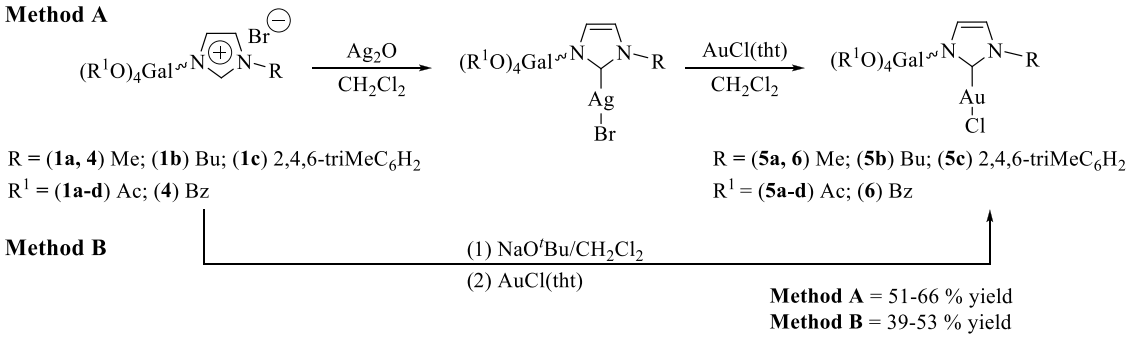
Scheme 3. General Procedures for the Preparation of Glycosyl Imidazolium Salts from β-D-Galactofuranosyl Imidazole



Scheme 4. General Procedures for the Preparation of NHC gold(I) Complexes



by the adaptation of route B, using **2** and glycosyl bromide in a 1:4 ratio (Scheme 2; route B). After 72 h, the reaction gave an inseparable mixture of **2** and two anomers of **1d** (*β*,*β* and *α*,*β*). An experiment carried out for 120 h gave similar results. Furthermore, heating under reflux for 24 h did not cause beneficial effects. On the other hand, the use of an equimolar ratio of glycosyl bromide and imidazole, at room temperature, for 72 h gave **1d** as a mixture of *β*,*β* and *α*,*β* anomers (5:1) in a 50% yield (Scheme 2; route C).

Finally, we present the first report regarding the synthesis of C1-galactofuranoside-substituted NHC ligand (**4**) through a two-step technique (Scheme 3). At first, we synthesized the corresponding *β*-galactofuranosyl imidazole (**3**) from imidazole and 2,3,4,6-tetra-*O*-benzoyl-*β*-D-galactofuranosyl bromide in a 76% yield. Later, using **3** and butyl bromide, salt **4** was obtained in a 70% yield as a pure *β* anomer (see the Experimental Section).

For all salts synthesized, the resonances of the sugar protons were assigned according to both their expected chemical shifts and the coupling constant. The configuration at the anomeric position was determined using ^{1}H NMR spectroscopy due to the neighboring group participation. Coupling constant ^{3}J for *β* anomer is greater than for the *α* (8 and 2 Hz, respectively).

Gold(I) Complexes. Based on our previous experience,[24] gold(I) complexes **5a−d** and **6** (Figure 1) were synthesized from the corresponding imidazolium salts (**1a−d** and **4**) through the silver oxide route developed by Lin and coworkers[26] and based on [Ag−NHC−Cl] complexes as NHC transfer agents[27] employing [AuCl(tht)][28] (tht = tetrahydrothiophene) as a metal precursor (Scheme 4, method A; see the Experimental Section for details). This route turned out to be more effective (51−66% of the isolated complex) compared with the direct method (Scheme 4, method B). In both cases, the formation of the respective bis-carbene complexes [Au(I)−(NHC)$_2$]$^+$ or byproducts containing gold has not been observed. In addition, under these conditions, deprotection of the acetyl group or anomeric isomerization of galactose units was not observed. It is important to mention that the selection of complexes was carried out to evaluate the influence of structural characteristics (symmetric and asymmetric) in catalytic studies as well as their stability and potential solubility in an aqueous medium.

Gold(I)−carbene complexes (**5a−d** and **6**) were fully characterized by ^{1}H and ^{13}C NMR, Fourier transform infrared (FTIR) spectroscopy, and elemental analysis (see the Experimental Section for details). The ^{1}H NMR data unambiguously confirmed the metal coordination by the disappearance of the proton signal of the imidazole ligands (**1a−d** and **4**, singlet at *δ* 10.98−10.57 ppm). In addition, the configuration at the anomeric position for all complexes was determined according to both their expected chemical shifts and the coupling constant. It is important to mention, as expected, that the configuration of the sugar in the complex is the same as in the respective imidazolium salt (see Synthesis of imidazolium salt). Finally, the ^{13}C NMR spectra display the characteristic signals of the carbene carbon bound to a metal with values around 175.0−171.0 ppm, shifted to higher ppm, relative to the starting salts (138.4−136.4 ppm). All gold(I) complexes were found to be stable in air and can be stored for prolonged periods when they are protected from light (even after a period of 9 months without accessing the laboratory due to the restrictions associated with the COVID-19 pandemic) and up to 3 days at 100 °C. The surface plasmon resonance absorption spectrum (SPR) of Au−NPs is at λ_{max} = 545 nm;[24,29] none of the synthesized complexes presents the mentioned band, showing the stability of the Au−C2$_{Imi}$ bond (see the Supporting information).

Stability of Deprotected Complexes. In catalysis, the use of a carbohydrate moiety provides chirality and potential water solubility. Thus, it might be a cheap and simple way of achieving both asymmetric catalysis and catalysis in an aqueous medium. To improve the water solubility of the complexes, we

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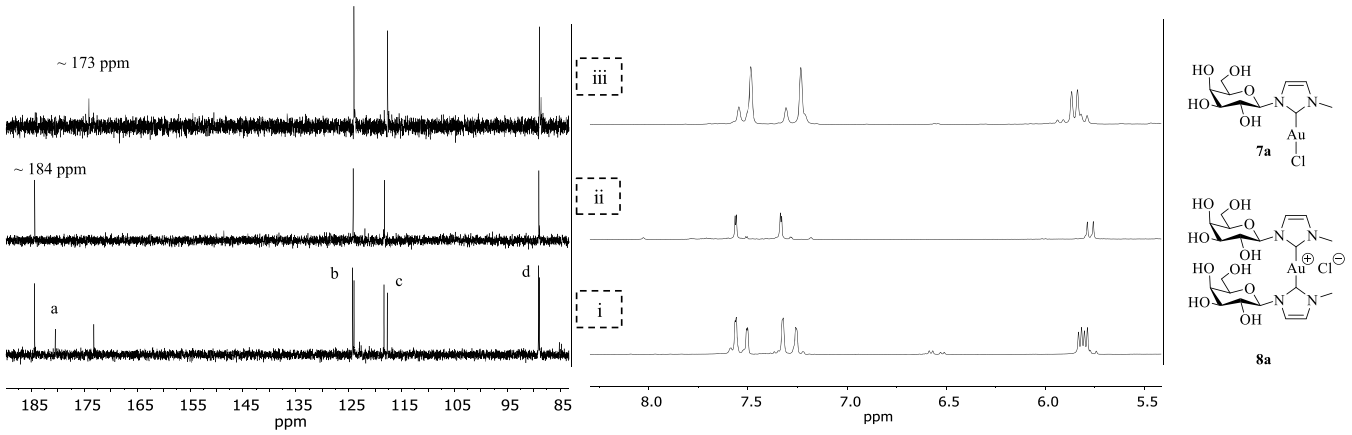

Figure 2. NMR spectra comparison from deprotection conditions (i)−(iii). The signal at 173 ppm corresponding to $C2_{Imi}$ from **7a** and 184 ppm to $C2_{Imi}$ from **8a**; (a) the CO signal from $CH_3CO_2CH_3$; (b) and (c) four signals from $C4_{Imi}$ and $C5_{Imi}$; and (d) two anomeric signals.

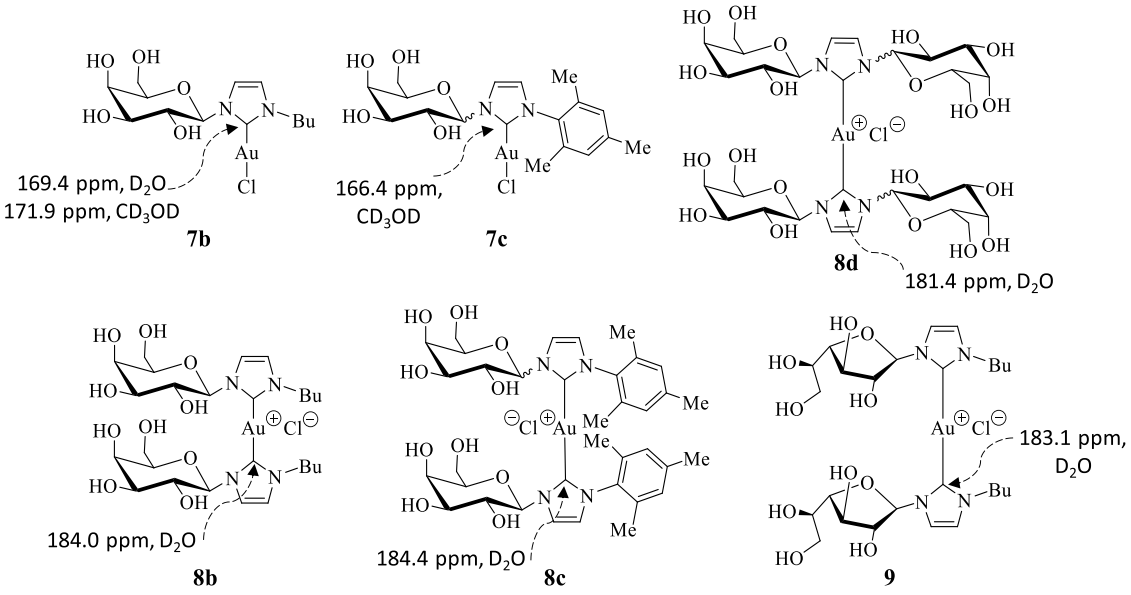

Figure 3. Identification of $C2_{Imi}$ from mono- and bis-carbene complexes by ^{13}C NMR spectroscopy.

carried out a study of the deprotection of the carbohydrate unit. We started with **5a** as a model complex under three different deprotection conditions at room temperature: (i) $Et_3N/H_2O/MeOH$, 30 min;[30] (ii) $NaOMe/MeOH/CH_2Cl_2$, 1 h;[31] and (iii) $K_2CO_3/MeOH/CH_2Cl_2$, 1 h.[32] All attempts to deprotection led to a decomposition of the complex, obtaining a mixture of the corresponding deprotected complex (**7a**) and the bis-carbene complex (**8a**), determined by the signal pattern of the imidazole portion and the presence of two anomeric signals in the NMR spectra in D_2O. The deprotection condition (iii) allowed obtaining complex **7a** as the majority species (Figure 2).

Conditions (ii) and (iii) were applied on **5b**,**c**, obtaining similar results to **5a**. On the other hand, when the methodologies were applied on **5d** and **6**, only **8d** and **9** were obtained, respectively. The identity of **7b**,**c**, **8b**−**d**, and **9** was made with the same criteria explained above (Figure 3). It is important to note that for **7b**,**c** it was necessary to change the solvent because in D_2O the $C2_{Imi}$ signal is difficult to identify.

Although **7b**,**c** could be isolated, both were not stable for a long time. Experiments carried out in an NMR tube at 25 °C evidenced the formation of the bis-carbene species (**8b**,**c**, respectively) together with a violet coloration at 48 h. A study at 100 °C showed, in less than 5 h, the characteristic bis-carbene signal being the only species present after 10 h.

Catalytic Study. All gold(I) complexes (**5a**−**d** and **6**) and their respective imidazolium salts (**1a**−**d** and **4**) were examined in the hydration of phenylacetylene in H_2O, MeOH, and H_2O/MeOH mixtures.

Based on our experience in the NHC−Au(I) activation and according to the stability of the protected complexes, we decided to initiate the catalytic study working at 100 °C with the addition of 1 mol % of catalyst. Under these reaction conditions, acetophenone was not obtained after 20 h in H_2O with any complexes (Table 1, entry 1). In addition, to increase the solubility of complexes in an aqueous medium, we studied the effect of the addition of K_2CO_3. However, no reaction was observed and bis-carbene was detected, regardless of the reaction medium used (entry 2). The same results were obtained with the respective imidazolium salts (entry 3).

Next, we decided to continue the study in the H_2O/MeOH mixture using **5c**, as a model system, working at 80 °C with the addition of 1 mol % of catalyst. Under these reaction

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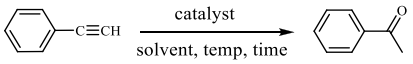
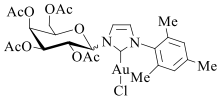
Table 1. Hydration of Phenylacetylene: Initial Study[abcee]



Entry	Catalyst	Solvent	Base	AgX (1mol%)	Temp (°C)	Time (h)	Yield (%)[b]
1	**5a-d** and **6**	H_2O	-	-	100	20	0
2	**5a-d** and **6**	H_2O or H_2O/MeOH or MeOH[c]	K_2CO_3	-	100	20	0
3	**1a-d** and **4**	H_2O or H_2O/MeOH	-	-	100	20	0
4		H_2O/MeOH	-	-	80	20	64
5		H_2O/MeOH	-	-	100	20	17
6		MeOH[c]	-	-	80	20	82
7		MeOH[c]	-	-	100	20	100
8		MeOH[c]	-	SCN	100	4	21
9		MeOH[c]	-	NO_3	100	4	40
10		MeOH[c]	-	OTs	100	1	100
11	**5c**	MeOH[c]	-	OTs	80	1	10
12		MeOH[c]	-	OTs	30	20	0
13[d]		MeOH[c]	-	-	100	20	60
14[d]		MeOH[c]	-	OTs	100	1	23
15[e]		MeOH[c]	-	-	100	20	86
16[e]		MeOH[c]	-	OTs	100	1	50

[a]A typical experiment: 0.5 mmol of phenylacetylene, 1 mol % of catalyst (1.66 mM), H_2O or MeOH (3 mL), or H_2O/MeOH (1.5/1.5 mL). [b]Determined by GC-MS. [c]A stoichiometric amount of pure H_2O. [d]0.25 mol % [Au] (0.42 mM). [e]0.25 mol % [Au] (1.66 mM).

conditions, acetophenone was obtained in a 64% yield after 20 h (entry 4). Furthermore, an increase in temperature at 100 °C caused no benefits to the reaction, showing a decline in the catalytic activity (entry 5). Taking into account that the reactions in H_2O are null or slower than in a H_2O/MeOH mixture, we carried out a reaction in MeOH, adding a stoichiometric amount of pure H_2O. This reaction was faster than in H_2O/MeOH, giving 82 and 100% of ketone after 20 h at 80 and 100 °C, respectively (entries 6 and 7). The results obtained in two experiments carried out in the shortest reaction times (2−5 h) enable us to propose the generation of the ketone through the hydrolysis of a ketal intermediate.[24b,33] Despite the stability of deprotected complex **7c** at 80 °C, we performed phenylacetylene hydration experiments with it. As expected, the results were not satisfactory.

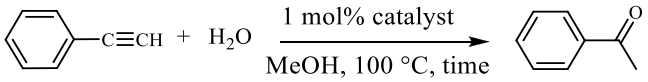
Next, with the main goal of reducing the reaction time, we studied the effect of the addition of silver salt.[34] The results summarized in Table 1 show that the addition of 1 mol % of silver salt was effective and the best yield was obtained with AgOTs, even in a shorter reaction time (entries 8−10). Meanwhile, the addition of 1 mol % of AgOTs caused no benefits to the reaction carried out at 80 °C for 20 h, giving the desired product in a 10% yield (entry 11). Moreover, in an experiment carried out at 30 °C, phenylacetylene was recovered quantitatively (entry 12). The same result was obtained using the silver salts at 100 °C in the absence of the gold complex. Our result confirms that there is a cooperative effect between the addition of silver salt and the temperature. Finally, a series of experiments were performed in MeOH, reducing the catalyst loading to 0.25 mol % with and without the addition of AgOTs at 100 °C. As can be seen, the catalyst turned out to be active in all cases. However, an influence of the catalyst concentration on the yields is observed. A higher yield is achieved, working with a catalyst concentration of 1.66 mM (entries 15 and 16) compared to 0.42 mM (entries 13 and 14).

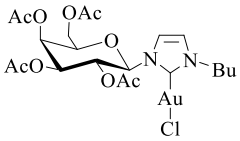
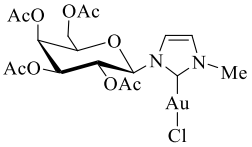
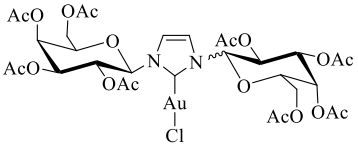
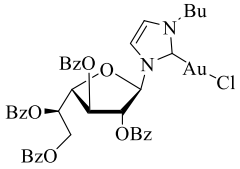
To evaluate the effect caused by the substituents attached to the nitrogen atoms on the catalytic activity, we studied the hydration of phenylacetylene in the presence of 1 mol % of **5a**,**b**,**d** and **6**. All reactions were performed in MeOH with a stoichiometric amount of pure H_2O, with and without the addition of silver salt, at 100 °C. Table 2 summarizes the relevant results obtained.

As can be seen, all complexes turned out to be active in both reaction conditions. The complex containing the bulkiest substituent (**5d**) gives the best yields compared to their methyl (**5a**) and butyl (**5b** and **6**) analogues. Regarding butyl analogue complexes, the galactofuranoside unit is not exerting a different effect than its pyranose analogue, showing the highest efficiency at 1 h with the addition of silver salt (entries

https://doi.org/10.1021/acsomega.2c01878
ACS Omega 2022, 7, 21788−21799

Table 2. Hydration of Phenylacetylene Catalyzed by 5a,b,d and 6 at Optimal Conditions[ab]



Entry	Catalyst	AgX (1mol%)	Time (h)	Yiled (%)[b]
1		-	20	70
2	**5a**	OTs	1	87
3		-	20	61
4	**5b**	OTs	1	63
5		-	20	89
6	**5d**	OTs	1	90
7		-	20	68
8	**6**	OTs	1	85

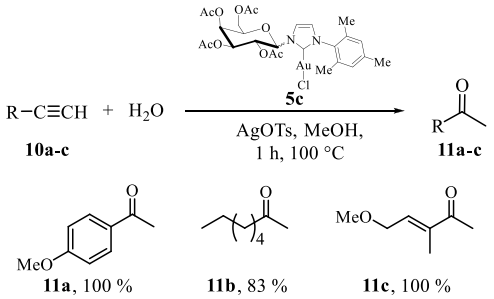
[a]A typical experiment: 0.5 mmol of phenylacetylene, 1 mol % of [Au] (1.66 mM), and MeOH (3 mL) with a stoichiometric amount of pure H_2O. [b]Determined by GC-MS.

2 and 8). Summarizing, the complexes show a catalytic activity trend, depending on the substituents attached to the imidazole nitrogen in the following order: Mes > $(AcO)_4$Gal*p* > Bu > Me.

Afterward, we decided to examine the recovery and reuse of the catalysts. We started the recycling experiment using **5b,c** at optimal hydration conditions with AgOTs, and each experiment was repeated until the catalyst was almost inactive. These essays showed that **5c** suffered significant activity losses after the initial cycles (1st cycle 100%, 2nd cycle 20%, 3rd cycle 7% yield), while **5b** was not recoverable, indicating that the substituent attached to the imidazole ring is a determining factor in the recycling. Taking into account the solubility of the complexes in an organic medium, it is probable that they are lost in the extraction processes. To improve the reuse of the complexes, recharges of the alkyne were carried out without product extractions using **5c** as a model catalyst. The results show that this complex was active for five cycles (1st cycle 100%, 2nd cycle 92%, 3rd cycle 80%, 4th cycle 71%, and 5th cycle 57%), decreasing notably after the fifth cycle.

Next, considering the higher catalytic activity and stability shown by **5c**, we studied the reactivity of selected terminal alkynes in methanol at 100 °C in the presence of AgOTs (Scheme 5). All of the terminal alkynes were oxidized to the corresponding ketone in excellent or quantitative yields, according to Markovnikov's rule. Despite promising results with the protected complexes in the hydration of alkynes, less than 100 turnovers were achieved, which is lower than the best values reported in the literature.[35,36] This motivates us to continue our studies and explore other activation methods that work in aqueous environments.[37]

Scheme 5. Alkyne Hydration Catalyzed by 5c in MeOH



CONCLUSIONS

We have developed different procedures for the preparation of glycosyl imidazolium salts from alkyl, aryl, or β-D-galactosyl

https://doi.org/10.1021/acsomega.2c01878
ACS Omega 2022, 7, 21788−21799

imidazole. These precursors were used to synthesize five new stable gold(I) complexes, in good yield, through the silver oxide route employing AuCl(tht) as a metal precursor. Moreover, we report the first synthesis of the C1-galactofuranoside-substituted NHC metal complex. All attempts to deprotect led to a decomposition of the complexes, obtaining a mixture of the corresponding deprotected complex and the bis-carbene species.

Catalytic studies indicate that the synthesized protected complexes are active and reusable in the alkyne hydration reaction using MeOH with a stoichiometric amount of pure H_2O at 100 °C. However, attempts to deprotect the acetylated carbohydrate moiety *in situ* were unsuccessful. The synthesis of new complexes with other transition metals and the incorporation of sugars in the NHC structure are currently in progress in our laboratories.

EXPERIMENTAL SECTION

General Procedures. The solvents used were distilled-dried and stored according to standard procedures.[38] Unless otherwise stated, reagents were obtained from commercial sources and were used as received. α-D-Galactopyranosyl bromide[39] and β-D-galactofuranosyl bromide[40] were prepared according to the literature procedures and were used without further purification. 1-Mesitylimidazole[41] and AuCl(tht)[28] were prepared according to reported procedures. ^{1}H, ^{13}C NMR, and two-dimensional (2D) (^{1}H COSY and HSQC) spectra were recorded with a Bruker Advance 300 spectrometer. Chemical shifts (δ) are reported in ppm with the residual solvent resonance signal: δ H/C 7.27:77.2 for $CDCl_3$; δ H 4.79 for D_2O; and δ H/C for CD_3OD 4.87/49; coupling constants (*J*) are reported in hertz. Melting points were determined on a Reichert−Kofler hot-stage microscope and were uncorrected. UV−visible spectra were recorded in a Carey 60 version 2.0 instrument with a quartz 5 mL cell. Microanalytical data were obtained using an Exeter Analitycal Inc. CE-440 microanalyzer. Infrared spectra were collected on an FTIR spectrometer Nicolet Nexus-470. Alkyne hydration reaction mixtures were analyzed by gas-liquid chromatography (GLC) in an instrument equipped with a flame-ionization detector and a HP5 capillary column (30 m × 0.25 mm × 0.25 μm).

Route A: General Procedure for the Preparation of Imidazolium Salts from Alkyl or Aryl Imidazole. In a 25 mL round-bottom flask equipped with a nitrogen inlet and a magnetic stirrer loaded with D-galactosyl bromide (1 mmol) and dry CH_3CN (9 mL) was added the imidazole precursor (1 mmol). The mixture was stirred at room temperature for 72 h and then concentrated in vacuum. The residue was dissolved in CH_2Cl_2 (20 mL) and washed with a 10% citric acid aqueous solution (5 mL). It was purified by flash chromatography on silica gel (CH_2Cl_2/MeOH 94:6) and concentrated in vacuum to give the desired imidazolium salt.

*1-Methyl-3-(2,3,4,6-tetra-O-acetyl-D-β-galactopyranosyl)-imidazolium Bromide (**1a**).* Prepared from 2,3,4,6-tetra-*O*-acetyl-α-D-galactopyranosyl bromide and 1-methylimidazole. The imidazolium salt **1a** was obtained in a 60% yield as a colorless foam; R_f = 0.72 (CH_2Cl_2/MeOH 9:1). ^{1}H NMR (300 MHz, $CDCl_3$) δ 10.85 (br s, 1H, $H2_{Imi}$); 7.57 (br s; 1H, $H4_{Imi}$); 7.39 (br s, 1H, $H5_{Imi}$); 6.47 (s, *J* = 6.7 Hz, 1H, H1); 5.56 (br s, 1H, H4); 5.38−5.36 (m, 2H, H2,3); 4.50 (t, *J* = 6.3 Hz, 1H, H5); 4.22−4.09 (m, 5H, H6, CH_3N); 2.19, 2.10, 2.05, 1.98 (4s, 12H, CH_3CO). ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.5, 170.4, 169.8, 169.4 (CO); 138.4 ($C2_{Imi}$); 123.8 ($C4_{Imi}$); 119.6 ($C5_{Imi}$); 84.6 (C1); 74.4 (C5); 70.5 (C3); 68.2 (C2); 67.1 (C4); 61.1 (C6); 37.6 (CH_3N); 21.1, 20.9, 20.8, 20.5 (CH_3CO). FTIR (neat): 3162.3; 3101.0; 1748.5; 1643.5; 1578.0; 1552.3; 1437.9; 1360.3; 1221.3; 1057.9; 956.3; 914.9. Elemental analysis calcd for $C_{18}H_{25}BrN_2O_9$: C 43.83, H 5.11, N 5.68; found C 43.80, H 5.09, N 5.70.

*1-Mesityl-3-(2,3,4,6-tetra-O-acetyl-α/β-D-galactopyranosyl)imidazolium Bromide (**1c**).* Prepared from 2,3,4,6-tetra-*O*-acetyl-α-D-galactopyranosyl bromide and 1-mesitylimidazole. The imidazolium salt **1c** was obtained in a 57% yield (α/β 1:5) as a light brown foam; R_f = 0.56 (CH_2Cl_2/MeOH 9:1). ^{1}H NMR (300 MHz, $CDCl_3$) δ 10.71 (br s, 5H, $H2_{Imi}\beta$); 10.62 (s, 1 H, $H2_{Imi}\alpha$); 7.91 (t, *J* = 1.8 Hz, 5H, $H5_{Imi}\beta$); 7.84 (t, *J* = 1.8 Hz, 1H, $H5_{Imi}\alpha$); 7.69 (d, *J* = 2.4 Hz, 1H, H1α); 7.29 (t, *J* = 1.8 Hz, 5H, $H4_{Imi}\beta$); 7.27 (t, *J* = 1.8 Hz, 1H, below $CDCl_3$ signal, $H4_{Imi}\alpha$); 7.10 (d, *J* = 8.3 Hz, 5H, H1β); 6.97 (s, 10H, H_{Ar}); 6.95 (s, 2H, H_{Ar}); 5.56 (dd, 5.55; *J* = 5.1 Hz, 2.4 Hz; 1H, H2α); (dd, *J* = 2.9 Hz, 1.2 Hz, 5H, H4β), 5.49 (m, 1H, H3α); 5.41−5.34 (m, 10H, H2,3β); 4.60 (m, 1H, H5α); 4.51 (t, *J* = 6.8 Hz, 5H, H5β); 4.16 (m, 10H, H6β); 4.01 (m, 2H, H6α); 2,30 (s, $CH_{3Ar}\beta$); 2.26 (s, $CH_{3Ar}\alpha$); 2.16 (2s, $CH_3CO\beta$); 2.06 (s, $CH_{3Ar}\beta$); 2.01 (2s, $CH_3CO\beta$); 1.98 (s, $CH_{3Ar}\beta$); 1.94 (s, $CH_3CO\beta$); other hydrogen signals from $CH_{3Ar}\alpha$ and $CH_3CO\alpha$ cannot be individualized. ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.6 ($CO\alpha$); 170.4 ($CO\alpha$); 170.3 ($CO\beta$); 170.2 ($CO\beta$); 169.8 ($CO\alpha$); 169.7 ($CO\beta$); 169.2 ($CO\beta$); 168.5 ($CO\alpha$); 141.7 ($C_{Ar}\beta$); 141.4 ($C_{Ar}\alpha$); 137.7 ($C2_{Imi}\beta$); 137.6 ($C2_{Imi}\alpha$); 135.0 ($C_{Ar}\alpha$); 134.2 ($C_{Ar}\beta$); 133.7 ($C_{Ar}\beta$); 130.4 ($C_{Ar}\alpha$); 130.2 ($C_{Ar}\beta$); 130.1 ($CH_{Ar}\beta$); 129.9 ($CH_{Ar}\beta$); 129.2 ($CH_{Ar}\alpha$); 124.0 ($C5_{Imi}\beta$); 123.2 ($C5_{Imi}\alpha$); 120.9 ($C4_{Imi}\alpha$); 120.5 ($C4_{Imi}\beta$); 84.1 (C1β); 79.4 (C1α); 74.3 (C5α); 74.1 (C5β); 70.2 (C2β); 68.7 (C3β); 68.5 (C2α); 67.3 (C3α); 66.9 (C4β); 64.6 (C4α); 60.9 (C6β); 60.2 (C6α); 21.5−20.4 ($CH_3CO\alpha/\beta$, $CH_{3Ar}\alpha/\beta$); 17.7 ($CH_{3Ar}\beta$); 17.5($CH_{3Ar}\alpha$); 17.3 ($CH_{3Ar}\alpha$); 17.2 ($CH_{3Ar}\beta$). FTIR (neat): 2959.1; 2917.3; 2847.8; 1749.1; 1540.8; 1491.7; 1442.7; 1365.1; 1214.0; 1066.9; 1013.8; 919.9; 801.4; 730.9. Elemental analysis calcd for $C_{26}H_{33}BrN_2O_9$: C 52.27, H 5.57, N 4.69; found C 52.13, H 5.08, N 4.63.

Route B: General Procedure for the Preparation of Imidazolium Salts from Glycosyl Imidazole. In a 25 mL round-bottom flask equipped with a nitrogen inlet and a magnetic stirrer loaded with β-D-galactosyl imidazole (1 mmol) and dry CH_3CN (11 mL) was added butyl bromide (4 mmol). The mixture was stirred at reflux for 24 h and then concentrated in vacuum. it was purified by flash chromatography on silica gel (CH_2Cl_2/MeOH 9:1) and concentrated in vacuum to give the desired imidazolium salt.

*1-Butyl-3-(2,3,4,6-tetra-O-acetyl-D-β-galactopyranosyl)-imidazolium Bromide (**1b**).* Prepared from 2,3,4,6-tetra-*O*-acetyl-β-D-galactopyranosyl imidazole. The imidazolium salt **1b** was obtained in a 62% yield as a colorless foam; R_f = 0.5 (CH_2Cl_2/MeOH 9:1). ^{1}H NMR (300 MHz, $CDCl_3$) δ 10.57 (br, 1H, $H2_{Imi}$); 7.71 (s, 1H, $H4_{Imi}$); 7.56 (s, 1H, $H5_{Imi}$); 6.43 (d, *J* = 8.1 Hz, 1H, H1); 5.46 (d, *J* = 1.6 Hz, 1H, H4); 5.33−5.23 (m, 2H, H2, 3); 4.44 (t, *J* = 6.3 Hz, 1H, H5); 4.36 (t, *J* = 7.2 Hz, 2H, NCH_2); 4.08 (qd, *J* = 11.5 Hz, 6.3 Hz, 2H, H6); 2.12, 1.96 (×2), 1.89 (4s, 12H, CH_3CO); 1.83 (m, 2H, NCH_2CH_2); 1.27 (qd, *J* = 7.9 Hz, 4.0 Hz, 2H, CH_2CH_3); 0.88 (t, *J* = 7.3 Hz, 3H, CH_3). ^{13}C NMR (75 MHz, CDCl3) δ 170.3, 169.9, 169.8, 169.4 (CO); 136.8 ($C2_{Imi}$); 123.1 ($C4_{Imi}$); 119.6 ($C5_{Imi}$); 84.2 (C1); 74.0 (C5); 70.2 (C3); 68.3 (C2);

https://doi.org/10.1021/acsomega.2c01878
ACS Omega 2022, 7, 21788−21799

66.9 (C4); 61.0 (C6); 50.2 (NCH_2); 32.0 (NCH_2CH_2); 20.7, 20.6 (×2), 20.4 (CH_3CO); 19.2 (CH_2CH_3); 13.4 (CH_3). FTIR (neat): 3374.8; 2962.2; 2925.4; 2851.9; 1749.1; 1553.0; 1463.1; 1438.6; 1369.2; 1214.0; 1160.9; 1062.8; 1017.9; 919.9; 797.3. Elemental analysis calcd for $C_{21}H_{31}BrN_2O_9$: C 47.11, H 5.84, N 5.23; found C 46.98, H 6.01, N 5.24.

*1-Butyl-3-(2,3,5,6-tetra-O-acetyl-D-β-galactofuranosyl)-imidazolium Bromide (**4**).* Prepared from 2,3,4,6-tetra-*O*-acetil-β-D-galactofuranosyl imidazole. The imidazolium salt **4** was obtained in a 70% yield as a colorless foam; R_f = 0.76 (CH_2Cl_2/MeOH 9:1). ^{1}H NMR (300 MHz, $CDCl_3$) δ 10.98 (s, 1H, $H2_{Imi}$); 8.10 (d, *J* = 7.5 Hz, 2H, H_{Ar}); 8.03 (d, *J* = 7.6 Hz, 2H, H_{Ar}); 7.92 (d, *J* = 7.6 Hz, 2H, H_{Ar}); 7.80−7.75 (m, 4 H, $H4,5_{Imi}/H_{Ar}$); 7.57 (t, *J* = 7.4 Hz, 1H, H_{Ar}); 7.52−7.41 (m, 6H, H_{Ar}); 7.34 (t, *J* = 7.6 Hz, 4H, H_{Ar}); 7.21 (t, *J* = 7.7 Hz, 2H, H_{Ar}); 6.56 (s, 1H, H1); 6.12 (dt, *J* = 7.7 Hz, 3.8 Hz, 1H, H5); 5.90 (br s, 1H, H3); 5.72 (s, 1H, H2); 5.65 (t, *J* = 3.8 Hz, 1H, H4); 5.02 (dd, *J* = 12.2 Hz, 3.7 Hz, 1H, H6a); 4.82 (dd, *J* = 12.1 Hz, 7.6 Hz, 1H, H6b); 4.52 (t, *J* = 7.4 Hz, 2H, NCH_2); 1.89 (p, *J* = 7.5 Hz, 2H, NCH_2CH_2); 1.35 (m, 2H, CH_2CH_3); 0.89 (t, *J* = 7.4 Hz, 3H, CH_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.3, 166.2, 166.0, 165.5 (CO); 136.8 ($C2_{Imi}$); 134.1 (×2), 133.6, 133.3, 130.2 (×2), 130.1, 129.8 (CH_{Ar}); 129.4, 128.9 (C_{Ar}); 128.8, 128.7, 128,6, 128.5 (CH_{Ar}); 128.1, 127.5 (C_{Ar}); 123.5 ($C4_{Imi}$); 119.2 ($C5_{Imi}$); 93.2 (C1); 86.0 (C4); 83.5 (C2); 77.9 (C3); 70.9 (C5); 63.7 (C6); 50.3 (NCH_2); 32.3 (NCH_2CH_2); 19.5 (CH_2CH_3); 13.6 (CH_3). FTIR (neat): 2958.1; 2921.4; 2843.8; 1720.5; 1446.8; 1316.1; 1254.8; 1181.3; 1099.6; 1066.9; 1022.0; 707.5. Elemental analysis calcd for $C_{41}H_{39}BrN_2O_9$: C 62.84, H 5.02, N 3.57; found C 62.76, H 5.06, N 3.49.

Route C: Synthesis of 1-(2,3,4,6-tetra-*O*-acetyl-β-D-galactopyranosyl)-3-(2,3,4,6-tetra-*O*-acetyl-α/β-D-galactopyranosyl)imidazolium Bromide (1d). In a 25 mL round-bottom flask equipped with a nitrogen inlet and a magnetic stirrer loaded with imidazole (1 mmol) and dry CH_3CN (5 mL) was added 2,3,4,6-tetra-*O*-acetyl-α-D-galactopyranosyl bromide (1 mmol). The mixture was stirred at room temperature for 72 h and then concentrated in vacuum. The residue was dissolved in CH_2Cl_2 (20 mL) and washed with a 10% citric acid aqueous solution (5 mL). Purification by flash chromatography on silica gel (CH_2Cl_2/MeOH 9:1) gave **1d** in a 50% yield (β,β/α,β anomers 5/1) as a colorless foam; R_f = 0.54 (CH_2Cl_2/MeOH 9:1). ^{1}H NMR (300 MHz,) δ 10.92 (s, 1H, H2-α,β); 10.84 (s, 5H, H2-β,β); 7.64 (d, *J* = 1.3 Hz, 10H, $H2_{Imi}$-β,β); 7.59 (s, 1H, $H2_{Imi}$-α,β); 7.07 (d, *J* = 2.8 Hz, 1H, H1α-α,β); 6.69 (d, *J* = 8.8 Hz, 10H, H1β- β,β); 6.44 (d, *J* = 8.8 Hz, 1H, H1β-α,β); 5.55−5.53 (m, 1H, H2- α,β); 5.50 (dd, *J* = 3.2 Hz, 1.2 Hz, 10H, H4-β,β); 5.43−5.29 (m, H4,3,2-α,β/3,2-β,β); 4.59 (t, *J* = 6.4 Hz, 10H, H5-β,β); 4.54−4.05 (m, H5,6-α,β/6-β,β); 2.20 (s, CH_3CO-α,β); 2.16 (s, CH_3CO-β,β); 2.14 (s, CH_3CO-α,β); 2.11 (s, CH_3CO-α,β); 2.06 (s, CH_3CO-α,β); 2.03 (s, CH_3CO-β,β); 2.01 (s, CH_3CO-α,β); 2.00 (×2, s, CH_3CO-α,β); 1.99 (s, CH_3CO-β,β); 1.93 (s, CH_3CO-β,β). ^{13}C NMR (75 MHz, $CDCl_3$) δ 173.5, 170.7, 170.6 (CO-α,β); 170.4, 170.1, 170.0 (CO-β,β); 169.8 (×2), 169.6 (CO-α,β); 169.5 (CO-β,β); 169.4, 168.9 (CO-α,β); 137.7 ($C2_{Imi}$-β,β); 136.9 ($C2_{Imi}$-α,β); 121.2 ($C4_{Imi}$-α,β); 120.1 ($C4,5_{Imi}$-β,β); 119.1 ($C5_{Imi}$-α,β); 84.7 (C1β-α,β); 84.6 (C1β-β,β); 80.2 (C1α-α,β); 74.2 (C5-β,β); 73.6 (C5-α,β); 70.2 (C3-β,β); 70.2 (C3-α,β); 68.3 (C2-α,β); 68.2 (C2-β,β); 68.0 (C2-α,β); 67.0 (C4-β,β); 64.9 (C4-α,β); 61.1 (C6-α,β); 61.0 (C6-β,β); 60.0 (C6-α,β); 21.3−20.5 (CH_3CO).[42] FTIR (neat): 2970.4; 2925.4; 1753.2; 1548.9; 1430.4; 1369.2; 1214.0; 1062.8; 944.4; 915.8. Elemental analysis calcd for $C_{31}H_{41}BrN_2O_{18}$: C 45.99, H 5.10, N 3.46; found C 45.91, H 5.14, N 3.39.

General Procedure for the Preparation of D-Galactosyl Imidazole. In a 25 mL round-bottom flask equipped with a nitrogen inlet and a magnetic stirrer loaded with D-galactosyl bromide (1 mmol) and dry CH_3CN (8 mL) was added imidazole (4 mmol). The mixture was stirred at room temperature for 72 h and then concentrated in vacuum. it was purified by flash chromatography on silica gel (hexane/ethyl acetate 4:1) and concentrated in vacuum to give the desired D-galactosyl imidazole.

*1-(2,3,4,6-Tetra-O-acetyl-β-D-galactopyranosyl)imidazole (**2**).* Prepared from 2,3,4,6-tetra-*O*-acetyl-α-D-galactopyranosyl bromide. Imidazole **2** was obtained in a 68% yield as a colorless foam; R_f = 0.30 (ethyl acetate). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.65 (s, 1H, $H2_{Imi}$); 7.12 (s, 1 H, $H4_{Imi}$); 7.09 (s, 1H, $H5_{Imi}$); 5.55−5.49 (m, 2H, H2,4); 5.26 (d, *J* = 9.3 Hz, 1H, H1); 5.17 (dd, *J* = 10.3, 3.3, 1H, H3); 4.18−4.12 (m, 3H, H5,6); 2.21, 2.04, 2.00, 1.88 (4s, 12H, CH_3CO). ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.5, 170.2, 170.0, 168.9 (CO); 136.8 ($C2_{Imi}$); 130.3 ($C5_{Imi}$); 117.1 ($C4_{Imi}$); 84.3 (C1); 73.8 (C5); 71.2 (C3); 68.3 (C2); 67.1 (C4); 61.4 (C6); 20.8 (×2), 20.6, 20.4 (CH_3CO). FTIR (neat): 3117.4; 2962.1; 2921.2; 1744.4; 1495.1; 1425.6; 1368.4; 1229.5; 1057.9; 947.6; 923.0; 800.4; 735.1. Elemental analysis calcd for $C_{17}H_{22}N_2O_9$: C 51.26, H 5.57, N 7.03; found C 51.19, H 5.54, N 7.06.

*1-(2,3,5,6-Tetra-O-benzoyl-β-D-galactofuranosyl)-imidazole (**3**).* Prepared from 2,3,5,6-tetra-*O*-benzoyl-β-D-galactofuranosyl bromide. Imidazole **3** was obtained in a 76% yield as a colorless foam; R_f = 0.70 (ethyl acetate). ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.01 (d, *J* = 7.7 Hz, 2H, H_{Ar}); 7.89−7.83 (m, 6H, $H2_{Imi}/H_{Ar}$); 7.55−7.43 (m, 4H, H_{Ar}); 7.40−7.19 (m, 10H, $H5_{Imi}/H_{Ar}$); 7.12 (s, 1H, $H4_{Imi}$); 6.13 (s, 1H, H1); 6.01 (td, *J* = 6.3 Hz, 4.0 Hz, 1H, H5), 5.83 (d, *J* = 2.9 Hz, 1H, H2); 5.73 (s, 1H, H3); 4.86−4.78 (m, 2H, H4,6a); 4.67 (dd, *J* = 12.1 Hz, 6.6 Hz, 1H, H6b). ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.2, 165.9, 165.6, 165.5 (CO); 135.8 ($C2_{Imi}$); 134.1, 134.0, 133.6, 133.4 (CH_{Ar}); 130.5 ($C4_{Imi}$); 130.1, 130.0, 129.9, 129.8 (CH_{Ar}); 129.4, 129.3 (C_{Ar}); 128.8, 128.7, 128.6, 128.5 (CH_{Ar}); 128.4, 128.2 (C_{Ar}); 116.8 ($C5_{Imi}$); 91.3 (C1); 84.6 (C4); 82.7 (C2); 78.1 (C3); 70.7 (C5); 63.4 (C6). FTIR (neat): 2953.9; 2921.2; 2839.5; 1719.9; 1450.2; 1311.2; 1258.1; 1311.2; 1258.1; 1176.4; 1102.8; 1090.6; 1070.2; 1017.0; 702.4. Elemental analysis calcd for $C_{37}H_{30}N_2O_9$: C 68.72, H 4.68, N 4.33; found C 68.61, H 4.72, N 4.36.

General Two-Step One-Pot Procedure for the Preparation of Carbohydrate-Substituted NHC Gold(I) Complexes *via* a Silver Oxide. In a 25 mL round-bottom flask, equipped with a nitrogen inlet, was prepared a solution of [Ag(I)-NHC-Br], from the imidazolium salt (0.4 mmol) and silver oxide (0.2 mmol), in dry CH_2Cl_2 (4 mL). The reaction mixture was stirred at room temperature for 4 h in the dark. Then, AuCl(tht) (0.6 mmol) was added and the mixture was stirred at room temperature for 18 h. The solution was filtered through a pad of celite and then the solvent was partially removed in vacuum to a remaining volume of 1 mL. The gold complex was precipitated with ethyl ether (**5a**) or hexane (**5b−d**, **6**), separated by filtration, and dried under vacuum.

*1-Methyl-3-(2,3,4,6-tetra-O-acetyl-D-β-galactopyranosyl)-imidazol-2-ylidene Gold(I) Chloro (**5a**).* Colorless solid, 66% yield; Mp 73−74 °C; R_f = 0.18 (hexane/ethyl acetate 1:1). ^{1}H

https://doi.org/10.1021/acsomega.2c01878
ACS Omega 2022, 7, 21788−21799

NMR (300 MHz, $CDCl_3$) δ 7.27 (d, 1H, below $CDCl_3$ signal, $H4_{Imi}$); 6.99 (d, J = 2.1 Hz, 1H, $H5_{Imi}$); 5.98 (d, J = 8.7 Hz, 1H, H1); 5.55 (d, J = 3.1 Hz, 1H, H4); 5.36 (m, 1H, H2); 5.24 (dd, J = 10.3, 3.3 Hz, 1H, H3); 4.25−4.10 (m, 3H, H5,6); 3.85 (s, 3H, CH_3); 2.20, 2.06; 2.02; 2.00 (4s, 12H, CH_3CO). ^{13}C NMR (75 MHz, $CDCl_3$) δ 175.2 ($C2_{Imi}$); 170.3, 169.8, 169.7, 169.5 (CO); 122.8 ($C5_{Imi}$); 118.0 ($C4_{Imi}$); 86.8 (C1); 73.9 (C5); 70.4 (C3); 68.4 (C2); 66.9 (C4); 61.3 (C6); 38.5 (CH_3N); 20.8, 20.7, 20.6, 20.5 (CH_3CO). FTIR (neat): 3121.5; 2937.7; 1745.0; 1455.0; 1361.0; 1218.1; 1120.0; 1058.8; 915.8; 732.0. Elemental analysis calcd for $C_{18}H_{24}AuClN_2O_9$: C 33.53, H 3.75, N 4.34; found C 33.59, H 3.77, N 4.40.

*1-Butyl-3-(2,3,4,6-tetra-O-acetyl-D-β-galactopyranosyl)-imidazol-2-ylidene Gold(I) Chloro (**5b**).* Colorless solid, 51% yield; Mp 70−72 °C; R_f = 0.30 (hexane/ethyl acetate 1:1). ^1H NMR (300 MHz, $CDCl_3$) δ 7.24 (d, J = 2.0 Hz, 1H, $H4_{Imi}$); 7.00 (d, J = 2.0 Hz, 1H, $H5_{Imi}$); 5.95 (d, J = 8.4 Hz, 1H, H-1); 5.53 (d, J = 3.0 Hz, 1H, H4); 5.35−5.19 (m, 2H); 4.38−3.93 (m, 5H); 2.18, 2.05, 1.98, 1.98 (4s, 12H, CH_3CO); 1.79 (dt, J = 13.9 Hz, 6.9 Hz, 2H, NCH_2CH_2); 1.30 (tt, J = 11.8 Hz, 6.0 Hz, 2H, CH_2CH_3); 0.94 (t, J = 7.3 Hz, 3H, CH_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.8 ($C2_{Imi}$); 170.5, 169.9, 169.6 (×2) (CO); 121.7 ($C5_{Imi}$); 118.1 ($C4_{Imi}$); 87.1 (C1); 74.0 (C5); 70.4 (C3); 68.6 (C2); 67.0 (C4); 61.4 (C6); 51.7 (NCH_2); 33.0 (NCH_2CH_2); 20.9, 20.8, 20.7, 20.6 (CH_3CO); 19.5 (CH_2CH_3); 13.7 (CH_3). FTIR (neat): 2954.0; 2921.4; 2856.0; 1749.1; 1467.2; 1430.5; 1373.3; 1226.2; 1124.1; 1095.5; 1058.8; 919.9; 801.4; 740.2. Elemental analysis calcd for $C_{21}H_{30}AuClN_2O_9$: C 36.72, H 4.40, N 4.08; found C 36.80, H 4.47, N 4.12.

*1-Mesityl-3-(2,3,4,6-tetra-O-acetyl-D-α/β-galactopyranosyl)imidazol-2-ylidene Gold(I) Chloro (**5c**).*[43] Light yellow solid, 52% yield (α/β 1:10); Mp 110−112 °C; R_f = 0.60 (hexane/ethyl acetate 1:1). ^1H NMR (300 MHz, $CDCl_3$) δ 7.45 (d, J = 2.0 Hz, 1H, $H4_{Imi}\beta$); 7.40 (d, J = 2.0 Hz, 0.1 H, $H4_{Imi}\alpha$); 7.01 (s, 0.1H, $H_{Ar}\alpha$); 6.95 (s, 2H, $H_{Ar}\beta$); 6.94 (d, J = 2.0 Hz, 1H, $H5_{Imi}\beta$); 6.88 (d, J = 2.0 Hz, 0.1 H, $H5_{Imi}\alpha$); 6.83 (d, J = 2.8 Hz, 0.1 H, H1α); 6.10 (d, J = 8.7 Hz, 1H, H1β); 5.58 (d, J = 3.2 Hz, 1H, H4β); 5.41 (t, J = 9.5 Hz, 1H, H2β); 5.28 (dd, J = 10.3 Hz, 3.2 Hz, 1H, H3β); 5.16 (dd, J = 10.5 Hz, 3.4 Hz, 0.1H, H3α); 4.29−4.13 (m, 3H, H5,6β); 2.32 (s, 3H, CH_{3Ar}); 2.21, 2.08, 2.03, 2.02 (4s, 12H, CH_3CO); 2.01 (s, 3H, CH_{3Ar}); 1.96 (s, 3H, CH_{3Ar}). ^{13}C NMR (75 MHz, $CDCl_3$) δ 172.3 ($C2_{Imi}$); 170.5, 169.9, 169.7, 169.6 (CO); 140,1, 134.8, 134.5 (×2) (C_{Ar}); 129.7, 129.6 (CH_{Ar}); 123.5 ($C5_{Imi}$); 118.2 ($C4_{Imi}$); 87.2 (C1); 74.0 (C5); 70.5 (C3); 68.7 (C2); 67.0 (C4); 61.3 (C6); 21.2 (CH_{3Ar}); 21.0, 20.8, 20.7, 20.6 (CH_3CO); 18.0, 17.6 (CH_{3Ar}). FTIR (neat): 2962.2; 2917.3; 2843.8; 1749.1; 1365.1; 1218.1; 1120.0; 1062.8; 919.9; 740.2. Elemental analysis calcd for $C_{26}H_{32}AuClN_2O_9$: C 41.70, H 4.31, N 3.74; found C 41.79, H 4.36, N 3.67.

*1-(2,3,4,6-Tetra-O-acetyl-β-D-galactopyranosyl)-3-(2,3,4,6-tetra-O-acetyl-α/β-D-galactopyranosyl)imidazol-2-ylidene Gold(I) Chloro (**5d**).* Colorless solid, 63% yield ($\beta,\beta/\alpha,\beta$ 1:5); Mp 119−121 °C; R_f = 0.47 (hexane/ethyl acetate 3:7). ^1H NMR (300 MHz, $CDCl_3$) δ 7.25 (s, 1H, $H2_{Imi}$-β,β; $H2_{Imi}$-α,β is below); 6.65 (d, J = 2.6 Hz, 1H, H1α-α,β); 5.91 (d, J = 9.0 Hz, 10H, H1β-β,β; H1β-α,β is below); 5.54 (d, J = 3.2 Hz, 10H, H4-β,β), 5.49−5.45 (m, 1H, H4-α,β); 5.42 (t, J = 9.7 Hz, 10H, H2-β,β; H2,3-α,β are below); 5.22 (dd, J = 10.2 Hz, 3.3 Hz, 10H, H3-β,β; H2,3-α,β are below); 4.59 (dd, J = 12.2 Hz, 8.7 Hz, 1H, H6-α,β), 4.53−4.44 (m, 1H, H5-α,β), 4.30 (dd, J = 12.3 Hz, 3.1 Hz, 1H, H6-α,β); 4.22−4.07 (m, H5,6-β,β,/H5,6-α,β); 2.22 (s, CH_3CO-α,β); 2.21 (s, CH_3CO-β,β), 2.18, 2.13 (s, CH_3CO-α,β), 2.05 (s, CH_3CO-β,β); 2.00 (s, CH_3CO-α,β); 1.99, 1.98 (s, CH_3CO-β,β). ^{13}C NMR (75 MHz, $CDCl_3$) δ 172.6 ($C2_{Imi}$-α,β); 172.6 ($C2_{Imi}$-β,β); 170.7, 170.5 (CO-α,β); 170.4 (CO-β,β); 170.1 (CO-α,β); 170.0 (CO-β,β); 169.8, 169.7 (CO-α,β); 169.6, 169.5 (CO-β,β); 169.3, 168.5 (CO-α,β); 120.2 ($C4_{Imi}$-α,β); 119.2 ($C4,5_{Imi}$-β,β); 117.7 ($C5_{Imi}$-α,β); 87.6 (C1β-β,β); 87.5 (C1β-α,β); 80.8 (C1α-α,β); 74.1 (C5-β,β); 74.1, 73.5 (C5-α,β); 70.6 (C3-β,β); 70.4, 69.7 (C3-α,β); 68.2 (C2-α,β); 68.1 (C2-β,β); 67.6 (C2-α,β); 67.0 (C4-α,β); 66.9 (C4-β,β); 64.9 (C4-α,β); 61.5 (C6-α,β); 61.3 (C6-β,β); 59.5 (C6-α,β); 21.0−20.4 (CH_3CO).[40] FTIR (neat): 2970.3; 2925.3; 1744.4; 1437.9; 1368.4; 1217.2; 1127.4; 1062.0; 919.0; 735.1. Elemental analysis calcd for $C_{31}H_{40}AuClN_2O_{18}$: C 38.74, H 4.20, N 2.91; found C 38.80, H 4.26, N 2.88.

*1-Butyl-3-(2,3,5,6-tetra-O-acetyl-D-β-galactofuranosyl)-imidazol-2-ylidene Gold(I) Chloro (**6**).* Colorless solid, 55% yield; Mp 68−70 °C; R_f = 0.30 (toluene/ethyl acetate 9:1). ^1H NMR (300 MHz, $CDCl_3$) δ 8.23−8.20 (m, 2H, H_{Ar}); 8.06 (d, J = 7.0 Hz, 2H); 7.97 (d, J = 7.1 Hz, 2H, H_{Ar}); 7.70 (d, J = 7.1 Hz, 2H, H_{Ar}); 7.68−7.55 (m, 3H, H_{Ar}); 7.59−7.40 (m, 3H, H_{Ar}); 7.41−7.36 (m, 3H, H_{Imi}/H_{Ar}); 7.22 (t, J = 7.8 Hz, 2H, H_{Ar}); 7.11−7.02 (m, 2H, H_{Imi}/H1); 6.16 (ddd, J = 7.2 Hz, 5.2 Hz, 2.6 Hz, 1H, H5); 5.85 (dd, J = 5.3 Hz, 3.1 Hz, 1H, H2); 5.66 (t, J = 3.1 Hz, 1H, H3); 4.94 (t, J = 3.0 Hz, 1H, H4); 4.78 (dd, J = 11.8 Hz, 5.2 Hz, 1H, H6a); 4.70 (dd, J = 11.8 Hz, 6.9 Hz, 1H, H6b); 4.19 (m, 2H, NCH_2); 1.85 (p, J = 7.3 Hz, 2H, NCH_2CH_2); 1.38 (m, 2H, CH_2CH_3); 0.95 (t, J = 7.3 Hz, 3H, CH_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.6 ($C2_{Imi}$); 166.2, 165.9, 165.8, 165.6 (CO); 134.1, 133.9, 133.8, 133.3, 130.2, 130,1, 130.0, 129.9 (CH_{Ar}); 129.5 (C_{Ar}), 129.4, 128.8 (CH_{Ar}); 128.6 (×2, C_{Ar}); 128, 6 (×2, CH_{Ar}), 127.8 (C_{Ar}), 122.1 ($C4_{Imi}$); 117.2 ($C5_{Imi}$); 93.9 (C1); 84.0 (C4); 81.7 (C2); 79.5 (C3); 72.0 (C5); 63.0 (C6); 52.0 (NCH_2); 33.0 (NCH_2CH_2); 19.7 (CH_2CH_3); 13.7 (CH_3). FTIR (neat): 2958.1; 2917.3; 2847.8; 1720.5; 1597.9; 1581.6; 1446.8; 1312.0; 1267.1; 1173.1; 1087.4; 1066.9; 1022.0; 711.6. Elemental analysis calcd for $C_{41}H_{38}AuClN_2O_9$: C 52.66, H 4.10, N 3.00; found C 52.71, H 4.14, N 3.04.

General Two-Step One-Pot Procedure for the Preparation of Carbohydrate-Substituted NHC Gold(I) Complexes *via* a Sodium *tert*-butoxide. In a 25 mL round-bottom flask, equipped with a nitrogen inlet, imidazolium salt (0.4 mmol) and AuCl(tht) (0.4 mmol) were dissolved in dry CH_2Cl_2 (4 mL) at 0 °C (ice bath). The system was purged with nitrogen by means of three vac-refill cycles. Then, sodium *tert*-butoxide (0.57 mmol) was added and the mixture was stirred at room temperature for 18 h. At this point, the mixture was processed as the silver oxide methodology. The gold complexes were obtained in acceptable yields with the same stereochemistry and isomeric ratio: **5a**, 53%; **5b**, 39%; **5c**, 42%; **5d**, 48%; **6**, 42%.

General Procedure for Gold(I) Complex Deprotection. In a 25 mL round-bottom flask, 0.1 mmol of gold(I) complex was dissolved in CH_2Cl_2 (2 mL) and MeOH (2 mL). Then, 6 mg of K_2CO_3 was added and the mixture was stirred at room temperature for 1 h. The mixture was filtered through a pad of celite and concentrated in vacuum to give the desired deprotected complex.

*1-Butyl-3-(D-β-galactopyranosyl)imidazol-2-ylidene Gold-(I) Chloro (**7b**).* Pale brown solid. ^1H NMR (300 MHz, D_2O) δ

https://doi.org/10.1021/acsomega.2c01878
ACS Omega 2022, 7, 21788−21799

7.47 (s, 1H, $H4_{Imi}$); 7.30 (s, 1H, $H5_{Imi}$); 5.78 (d, J = 9.1 Hz, 1H); 4.15 (t, J = 7.2 Hz, 2H, NCH_2); 4.05 (br s, 1H, H4); 4.02−3.92 (m, 2H, H2, 5); 3.84 (dd, J = 9.5 Hz, 2.4 Hz, 1H, H3); 3.74 (m, 2H, H6); 1.79 (p, J = 7.2 Hz, 6.6 Hz, 2H, NCH_2CH_2); 1.28 (h, J = 7.2 Hz, 2H, CH_2CH_3); 0.88 (t, J = 7.2 Hz, 3H, CH_3). ^{13}C NMR (75 MHz, D_2O) δ 168.9 ($C2_{Imi}$); 122.8 ($C5_{Imi}$); 117.9 ($C4_{Imi}$); 89.2 (C1); 77.8 (C5); 73.1 (C3); 70.2 (C2); 68.6 (C4); 60.7 (C6); 51.3 (NCH_2); 32.5 (NCH_2CH_2); 19.1 (CH_2CH_3); 13.1 (CH_3). ^{13}C NMR (75 MHz, CD_3OD) δ 171.9 ($C2_{Imi}$); 123.0 ($C5_{Imi}$); 119.4 ($C4_{Imi}$); 91.5 (C1); 79.8 (C5); 75.1 (C3); 71.7 (C2); 70.4 (C4); 62.4 (C6); 52.3 (NCH_2); 34.2 (NCH_2CH_2); 20.6 (CH_2CH_3); 14.0 (CH_3).

1-Mesityl-3-(D-α/β-galactopyranosyl)imidazol-2-ylidene Gold(I) Chloro (7c).[44] Pale brown solid. ^{1}H NMR (300 MHz, CD_3OD) δ 7.65 (s, 1H); 7.08 (s, 1H): 6.89 (s, 2H, H_{Ar}); 5.99 (d, J = 8.5 Hz, 1H, H1); 4.31 (t, J = 8.8 Hz, 1H, H2); 3.92 (br s, 1H, H4); 3.84−3.65 (m, 3H, H5, 6); 3.59 (dd, J = 9.1 Hz, 3.1 Hz, 1H, H3); 2.20 (s, 3H, CH_3); 1.94 (br s, 6H, CH_3). ^{13}C NMR (75 MHz, CD_3OD) δ 166.4 ($C2_{Imi}$); 140.7, 137.0, 136.7, 136.2 (C_{Ar}); 130.1 (CH_{Ar}); 124.6 ($C5_{Imi}$); 119.6 ($C4_{Imi}$); 94.4 (C1); 80.9 (C5); 80.2 (C3); 77.3 (C2); 70.6 (C4); 62.9 (C6); 21.1, 18.7, 17.9 (CH_{3Ar}).

General Method for the Alkyne Hydration Reactions in MeOH. Catalyst (0.005 mmol) was added to a solution of phenylacetylene (0.5 mmol, 55 μL) in MeOH (3 mL) and pure H_2O (100 μL). In the case of the silver salt methodology, together with the catalyst, 0.005 mmol of AgOTs was added. The mixture was vigorously stirred at 100 °C (oil bath) in an ampoule tube equipped with a PTFE valve for 20 or 1 h (AgOTs methodology). After allowing it to cool down to room temperature, the organic product was extracted with diethyl ether (3 mL × 5 mL); the combined organic layers were dried over $MgSO_4$ and injected on GC to determine the reaction conversion. The aqueous phase was reused, as specified in the Results and Discussion section.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.2c01878.

^{1}H and ^{13}C NMR spectra for compounds **1**−**6** and **7b,c** (PDF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was partially supported by CONICET (PIP 11220170100349) and the Universidad Nacional del Sur (PGI 24/Q108), Bahía Blanca, Argentina. CONICET is thanked for a research fellowship to A.W.H.

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https://doi.org/10.1021/acsomega.2c01878
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(43) NOTE: due to the isomeric ratio only some signals from the *α* anomer are indicated.
(44) NOTE: due to decomposition issues, only *β* anomer NMR spectra are indicated. Traces of the *α* anomer are indicated on the NMR spectra in the Supporting information.

https://doi.org/10.1021/acsomega.2c01878
ACS Omega 2022, 7, 21788−21799