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Late-stage C(sp²)-H and C(sp³)-H glycosylation of C-aryl/alkyl glycopeptides: mechanistic insights and fluorescence labeling†‡

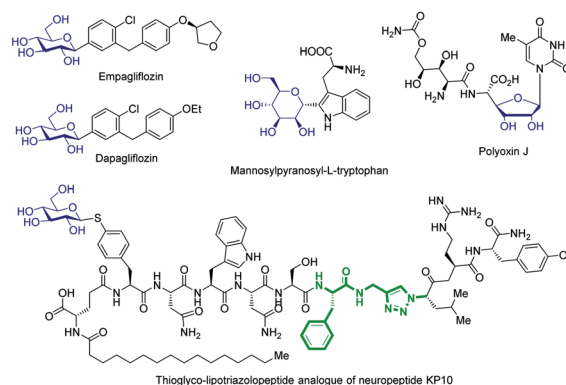
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C(sp³)-H and C(sp²)-H glycosylations of structurally complex amino acids and peptides were accomplished through the assistance of triazole peptide-isosteres. The palladium-catalyzed peptide-saccharide conjugation provided modular access to structurally complex C-alkyl glycoamino acids, glycopeptides and C-aryl glycosides, while enabling the assembly of fluorescent-labeled glycoamino acids. The C-H activation approach represents an expedient and efficient strategy for peptide late-stage diversification in a programmable as well as chemo-, regio-, and diastereo-selective fashion.

Introduction

Glycosylation is a biological function that regulates the structure and activity of a given peptide or protein, introducing considerable structural diversity.¹ The attachment of carbohydrates onto peptides can improve their metabolic stability, water solubility, and protect the peptide backbone from proteolytic attack, while playing key structural roles in numerous biological recognition processes.² As a consequence, glycopeptides have emerged as valuable vaccine candidates and therapeutics.³ However, their chemical and enzymatic instability under physiological conditions limited the utility of *O/N*-glycopeptides as drugs.⁴ In contrast, *C*-glycoside – stabilized isosteres of *O/N*-glycosides⁵ – possess improved metabolic stability towards acids, bases and enzymatic hydrolysis,⁶ thus being promising inhibitors of cell-surface recognition events and regulators of glycoside metabolism (Fig. 1a).⁷ The targeted modification of biologically active peptides is an important strategy for the elucidation of structure-activity relationships (SAR). During the past decade, the direct C-H manipulation⁸ of a peptide side-chain mediated by transition metal catalysis has emerged as a powerful paradigm,⁹ with key contributions from Lavilla/Albericio,¹⁰ Chen,¹¹ Daugulis,¹² Wang,¹³ Shi,¹⁴ Yu,¹⁵ and Ackermann¹⁶ among others.¹⁷ However, efficient methods for

the synthesis of *C*-alkyl/aryl glycopeptides continue to be rare,¹⁸ which contrasts with numerous examples of metal-catalyzed cross-couplings for the construction of *C*-aryl glycoside with two prefunctionalized substrates.¹⁹ Within our program on sustainable C-H activation,²⁰ we herein disclose unprecedented C(sp³)/(sp²)-H glycosylations of amino acids, peptides and (hetero)arenes (Fig. 1b). Notable features of our findings include (1) internal peptide-isosteric click-triazole²¹ as powerful amide surrogates in various bioactive peptidomimetics, (2) modification of terminal and internal peptides by secondary C(sp³)-H alkenylation with remarkable chemo- and diastereo-selectivities, and (3) detailed mechanistic insights by

(a) Selected *C*-aryl glycosides and glycopeptides

(b) This work

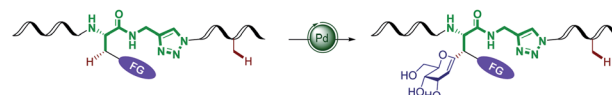


Fig. 1 (a) Selected *C*-aryl glycosides and glycopeptides. (b) C(sp³)-H glycosylation of labeled amino acids and peptides.

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experiment and computation as well as (4) versatile fluorescence labeling with structurally complex glycopeptides.

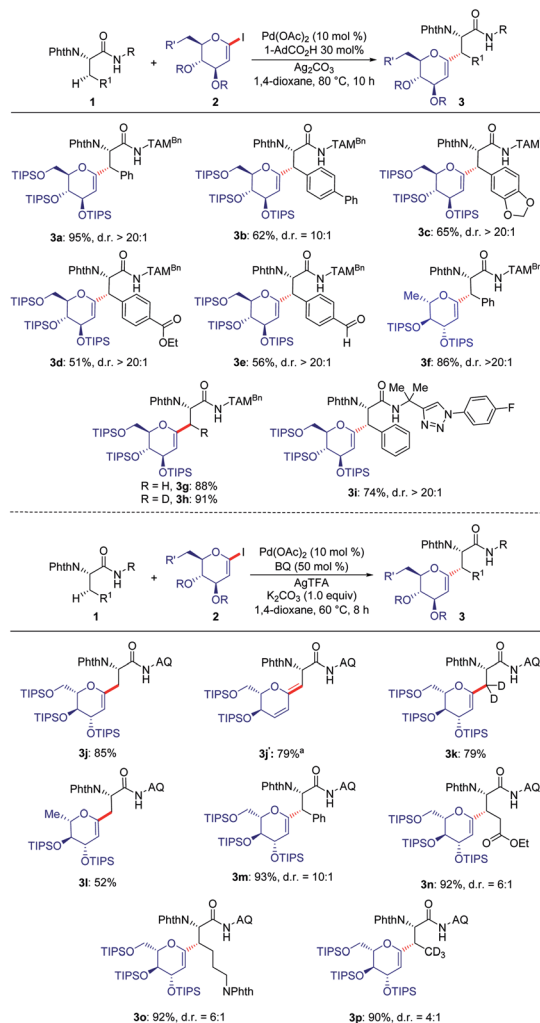
Results and discussion

Optimization of reaction conditions

We initiated our studies by exploring reaction conditions for the challenging secondary C(sp³)-H glycosylation of triazolyldimethylmethyl (TAM) amide **1a** (Table 1). Preliminary optimization indicated that 60 °C was a less suitable temperature, whilst a slight increase led to the formation of product **3a** in 85% yield with Pd(TFA)₂ as the catalyst, 1,4-dioxane as the solvent and AgOAc as the additive. When replacing AgOAc by other silver salts (AgTFA, Ag₂CO₃, and AgBF₄), Ag₂CO₃ stood out, providing glycopeptide **3a** in 95% yield (entries 3–5). Notably, further optimization indicated that 1,4-dioxane was the solvent of choice, and DCE, PhMe, or THF provided diminished or trace amounts of the desired product **3a** (entries 6–8). When 8-aminoquinoline (AQ) was employed, which was independently utilized by Liu for the synthesis of C-alkyl glycoamino acids,²² the reaction also proceeded efficiently, albeit under slightly modified reaction conditions. Under otherwise identical reaction conditions the use of 2-iodo-glycals provided as of yet unsatisfactory results.

Substrate scope

With the optimized reaction conditions for the challenging C(sp³)-H glycosylation in hand, we subsequently examined its versatility. Phenylalanine derivatives **1** bearing a variety of functional groups, such as esters or aldehydes, were well tolerated, leading to the formation of products **3a–e** with high diastereoselectivities (Scheme 1a). Besides the substrate **2a**, the reaction of rhamnose-derived glycal **2b** also occurred efficiently. In addition, primary C(sp³)-H bonds of deuterated or non-deuterated Ala-TAM [D₃]-**1f** and **1f** were likewise converted,



Scheme 1 Scope of glycosylation with TAM and AQ as auxiliaries. (a) 100 °C.

Table 1 Optimization of C(sp³)-H glycosylation^a

Entry	[Ag]	Solvents	T/°C	Yield ^b /%
1	AgOAc	1,4-Dioxane	60	49
2	AgOAc	1,4-Dioxane	80	85
3	AgTFA	1,4-Dioxane	80	Trace
4	Ag ₂ CO ₃	1,4-Dioxane	80	95
5	AgBF ₄	1,4-Dioxane	80	Trace
6	Ag ₂ CO ₃	DCE	80	45
7	Ag ₂ CO ₃	PhMe	80	28
8	Ag ₂ CO ₃	THF	80	<5%

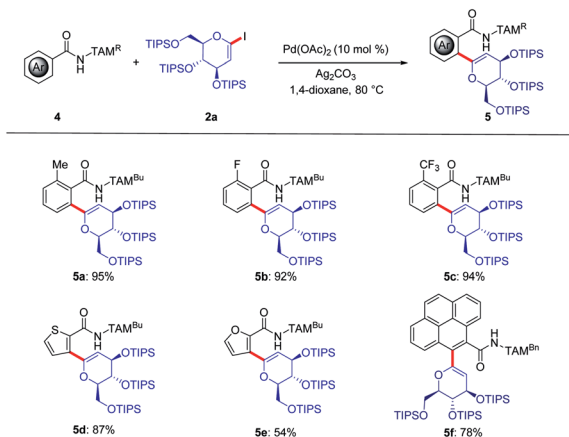
^a Reaction conditions: **1a** (0.10 mmol), **2a** (0.15 mmol), Pd(TFA)₂ (10 mol%), Ag₂CO₃ (0.20 mmol), 1,4-dioxane (0.5 mL) at 80 °C for 10 h. ^b Yield of isolated products.

giving product **3g** and **3h** in 88% and 93% yields respectively, without racemization of the stereogenic centers (see Pages S46–S47 of the ESI†). The optimized glycosylation proved amenable to substrate **1h** with an *N*-aryl substituent. Similarly, we also proved the reactivity of substrates **1h–j** with 8-amino quinoline as a terminal auxiliary. We were pleased to find that glycosylation of primary and secondary C(sp³)-H bonds of alanine, phenylalanine, glutamic acid and even lysine proved to be viable. Interestingly, when the reaction temperature was raised to 100 °C, 1,3-diene **3j'** was isolated because of the elimination of the OTIPS group.

When deuterated L-α-aminobutyramide [D₃]-**1f** was employed as the substrate, deuterium-labeled glycopeptide **3p** was obtained.

Due to the unique role of C-aryl glycosides as privileged glycomimetics,^{19a} we next probed the TAM-assisted C(sp²)-H glycosylation by palladium catalysis (Scheme 2). Hence, arenes **4a–c** with electron-donating or electron-withdrawing substituents were compatible, furnishing the desired products **5a–5c** in 92% to 97% yields. It was found that the heteroarenes furan and thiophene



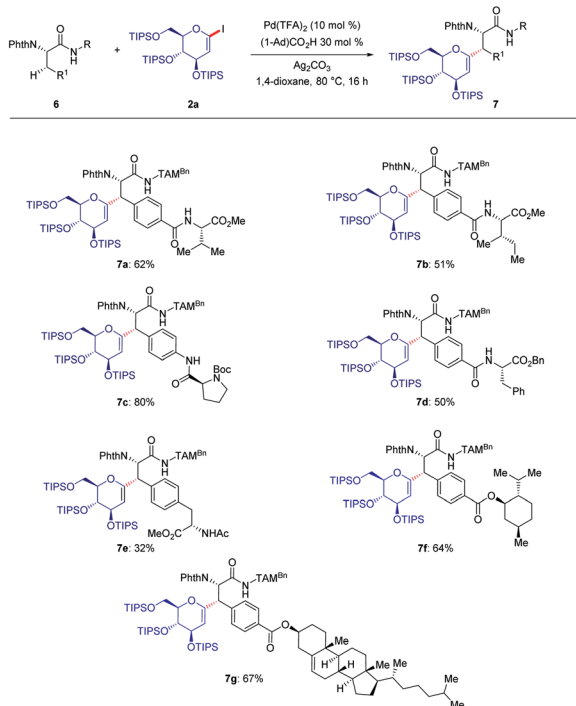
Scheme 2 Scope of C(sp²)-H glycosylation to C-aryl glycosides.

were likewise tolerated by the versatile palladium catalyst to deliver conjugate saccharides. Moreover, the fluorescent label pyrene could be successively attached to the glycoside **5f**.

Next, we studied the bio-conjugation to form versatile glycopeptides and the hybrids derived thereof (Scheme 3). Various terminal peptides and peptide-natural product hybrids were employed, and late-stage modified peptides **7a–g** were obtained by C–H glycosylation. Thereby, the possibilities for accessing structurally complex peptides for drug discovery were showcased.

Mechanistic studies

As shown in Fig. 2, a minor deuterium kinetic isotope effect (KIE) with deuterated and non-deuterated Ala-TAM [**D**₃]-**1f** and



Scheme 3 Scope of glycosylation of terminal peptides and hybrids.

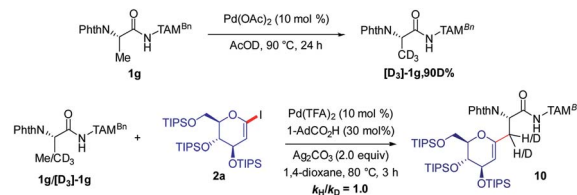


Fig. 2 H/D exchange and KIE experiments.

1f ($k_{\text{H}}/k_{\text{D}} = 1.0$) indicated that the C(sp³)-H bond cleavage is not likely a kinetically relevant step of the palladium catalysis. In order to gain further insights into the mechanism of the palladium-catalyzed C–H glycosylation DFT calculations were hence performed at the ω B97X-D/6-311++G(d,p), SDD(Pd, I, Ag) + SMD(1,4-dioxane)// ω B97X-D/6-31G(d), LANL2DZ(Pd, I, Ag) level of theory.²³ The calculated barrier for the initial C–H activation is 19.4 kcal mol^{−1} (see Fig. S1 of the ESI[†]), which is in good agreement with our previous studies.^{16f} Subsequent to the C–H activation, the dissociation of acetic acid and association of substrate **2a** lead to the intermediate **I1'**, which could be further stabilized by Ag₂CO₃ to afford the stable intermediate **I1**.²⁴ This process is highly exergonic by 36.8 kcal mol^{−1}, thus making the step irreversible. In **I1** as shown in Fig. 3, C–I bond cleavage occurs with the assistance of silver *via* the transition state **TS1–2** to afford the oxidized palladium(IV) intermediate **I2**, with a barrier of 19.3 kcal mol^{−1} with respect to **I1**. In this transition state, it is possible to observe attractive dispersive interactions between the imide of the substrate and Ag₂CO₃, which subsequently becomes evident by the bond distances between both moieties as shown in Fig. 4. This could be further confirmed by visualizing the NCI (non-covalent interactions) plot. The reaction continues with the reductive elimination *via* the transition state **TS2–3** with a barrier of 18.8 kcal mol^{−1} to

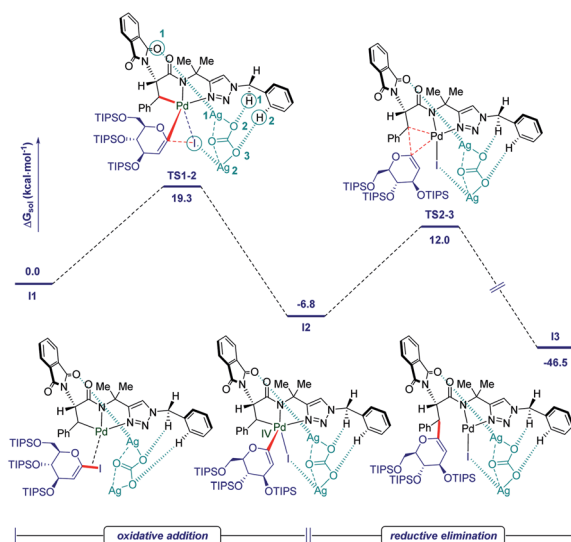


Fig. 3 Calculated Gibbs free energy profiles for the oxidative addition and reductive elimination steps in kcal mol^{−1} at the ω B97X-D/6-311++G(d,p), SDD(Pd, I, Ag) + SMD(1,4-dioxane)// ω B97X-D/6-31G(d), LANL2DZ(Pd, I, Ag) level of theory.



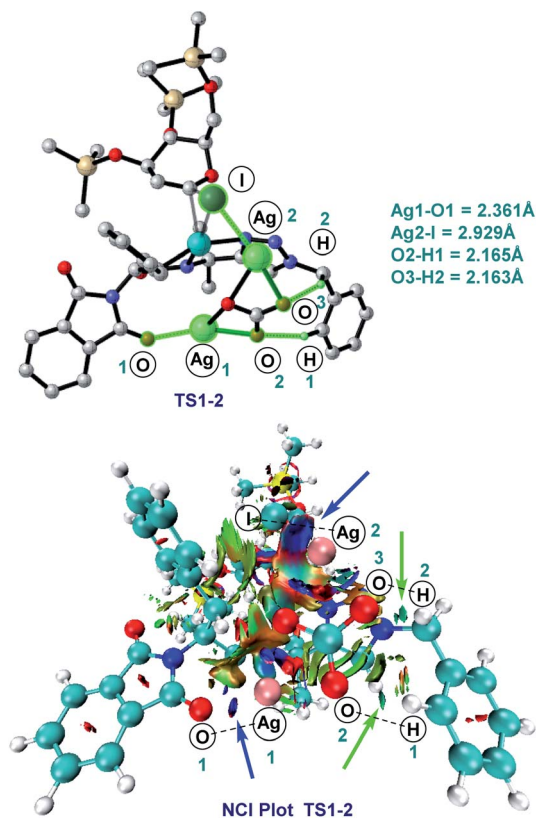
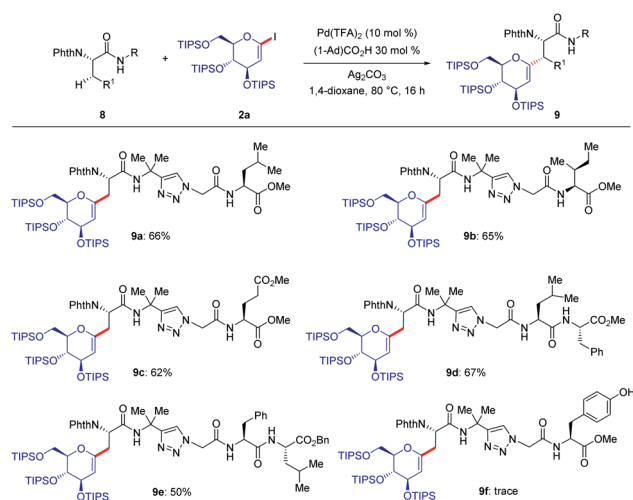


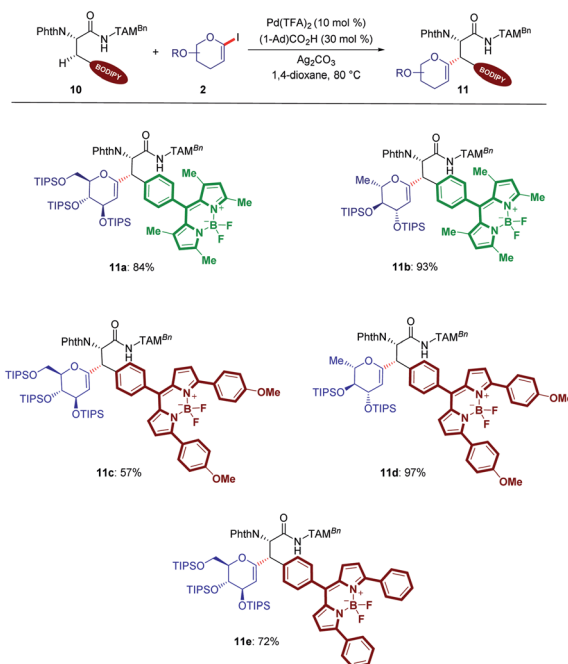
Fig. 4 The 3D structures and the non-covalent interactions visualized through NCI-plots of the transition state TS1-2 (strong and weak attractive interactions are given in blue and green, respectively, while red corresponds to strong repulsive interactions).

finalize the C–C formation process, followed by subsequent protonation to release the desired product.

In order to illustrate the robustness of our C(sp³)–H activation, we explored the unprecedented late-stage glycosylation of internal peptides (Scheme 4). With the sterically congested *gem*-disubstituted substrates **8a–8e** various peptides **9a–9e** were



Scheme 4 Scope of glycosylation of terminal peptides.



Scheme 5 Scope of BODIPY labeled glycoamino acids.

converted into value-added glycopeptides under exceedingly mild reaction conditions. When unprotected peptide Phth-Ala-Tzl-Tyr-OMe was employed, only trace amounts of product **9f** were observed. Here, the peptidomimetic Tzl scaffold set the stage for expedient site-selective peptide late-stage glycosylations.

Intrigued by the unique potential of BODIPYs as bio-compatible fluorescent probes,^{16e,25} glycosylation of different BODIPY labeled amino acids was explored for our C(sp³)–H activation process (Scheme 5). Hence, the C–H activation enabled the unprecedented preparation of BODIPY labeled glycoamino acids (**11a–11e**).

Conclusion

In summary, we have reported a versatile C(sp³)–H/C(sp²)–H glycosylation strategy enabled by peptide isosteric click-triazoles. Thus, the *de novo* synthesis of structurally complex C-alkyl glycoamino acids, glycopeptides and C-aryl glycosides was achieved by palladium-catalyzed C(sp³)–H/C(sp²)–H activation with excellent levels of regio-, chemo- and diastereoselectivities. The synthetic utility of our strategy was reflected *inter alia* by the assembly of BODIPY fluorescent labeled glycoamino acids and the racemization-free late-stage diversification of structurally complex molecules. Our approach holds major potential for the preparation of C-alkyl and C-aryl glycosyl amino acid building blocks for their subsequent use in glycopeptide assembly and molecular labeling.

Conflicts of interest

There are no conflicts to declare.



Acknowledgements

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