

## EDGE ARTICLE

Cite this: *Chem. Sci.*, 2022, 13, 5588

All publication charges for this article have been paid for by the Royal Society of Chemistry

## P(v) intermediate-mediated E1cB elimination for the synthesis of glycols†

Fen Liu, Haiyang Huang,<sup>1</sup> Longgen Sun, Zeen Yan, Xiao Tan, Jing Li, Xinyue Luo, Haixin Ding and Qiang Xiao<sup>1\*</sup>

Glycols are highly versatile and useful building blocks in the chemistry of carbohydrate and natural products. However, the practical synthesis of glycols remains a long-standing and mostly unsolved problem in synthetic chemistry. Herein, we present an unprecedented approach to make a variety of glycols using phosphonium hydrolysis-induced, P(v) intermediate-mediated E1cB elimination. The method provides a highly efficient, practical and scalable strategy for the synthesis of glycols with good generality and excellent yields. Furthermore, the strategy was successfully applied to late-stage modification of complex drug-like molecules. Additionally, the corresponding 1-deuterium-glycols were produced easily by simple <sup>t</sup>BuONa/D<sub>2</sub>O-hydrolysis-elimination. Mechanistic investigations indicated that the oxaphosphorane intermediate-mediated E1cB mechanism is responsible for the elimination reaction.

Received 10th March 2022  
Accepted 22nd April 2022

DOI: 10.1039/d2sc01423h

rsc.li/chemical-science

### Introduction

As one of the most fundamental and well-established reactions in phosphorus chemistry, the hydrolysis of phosphonium salts is commonly recognized as proceeding *via* oxaphosphorane P(v)-intermediates, which typically results in a phosphine oxide and alkane or arene.<sup>1</sup> Although an abnormal hydrolysis mode has been observed in specialized 7-phosphanorborenium salts (Fig. 1a),<sup>2</sup> the application of alkaline hydrolysis of phosphonium salts in practical synthetic chemistry is rare.<sup>3</sup> Fortunately, conventional P(v)-intermediates have demonstrated promising and unanticipated reactivities in recent years. McNally *et al.* described for the first time the phosphorus ligand-coupling reaction of oxaphosphorane P(v)-intermediates (Fig. 1b),<sup>4</sup> which was further exploited for contractive C–C bonding reactions of pyridine derivatives.<sup>5</sup> However, the more reactive deprotonated oxanionic phosphorane can rapidly release a carbanion-like fragment that is quickly quenched by H<sub>2</sub>O in the hydrolysis system.<sup>6</sup> Therefore, the use of a carbanion-like intermediate to facilitate further conversions has been a long-standing conundrum.<sup>7</sup> We hypothesized that because the oxaphosphorane-anion intermediate can provide an adjacent carbanion-like center, an E1cB-type elimination<sup>8</sup> could be triggered by a suitably leaving group at its β-position to form a double bond.<sup>9</sup> We are aware that glucosylphosphonium **2a**

meets the structural requirements and the hydrolysis-mediated elimination could afford the corresponding glycol (Fig. 1c).

Glycols are a class of versatile chiral building blocks that have been extensively used in the synthesis of oligosaccharides and other biologically important molecules.<sup>10,11</sup> Although considerable effort has been devoted to developing a practical synthetic methodology for glycols, several serious issues persist in the currently available protocols, including the use of a toxic and excessive amount of reducing metal, poor generality, and the complicated preparation of the corresponding appropriate precursor (Fig. S1†).<sup>10,12</sup> Until now, the reductive metal-induced elimination reaction of peracetylated glycosyl bromide (Fischer–Zach method) has been the dominant approach for synthesizing glycols (Fig. 1d).<sup>10,12,13</sup> Therefore, the growing demand for diverse glycols necessitates the development of novel and scalable strategies for their preparation. In this article, we demonstrated how to synthesize glycols using an oxaphosphorane-anion-mediated E1cB-like elimination reaction of glucosylphosphonium (Fig. 1e).

### Results and discussion

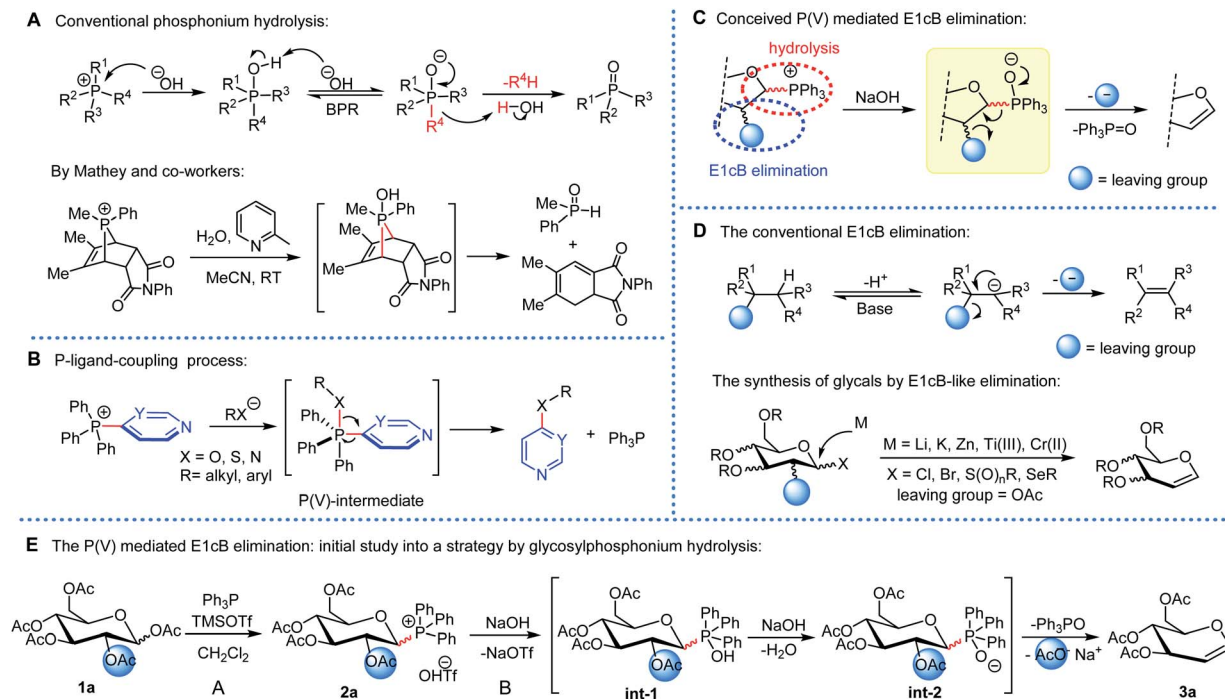
#### Development of an elimination reaction

Fig. 1e depicts the test system. This strategy is based on the alkaline hydrolysis of glucosylphosphonium salt **2a** (Scheme S2†), which firsts form a C1-anion-like center followed by an E1cB-like elimination to afford glycol. Indeed, the formation of the C=C π-bond *via* phosphonium hydrolysis has been previously observed, but the reported abnormal process is a result of a high tension of 7-phosphanorborenium salts (Fig. 1a).<sup>2</sup> 1,2,3,4,6-Penta-*O*-acetyl-β-*D*-glucopyranose **1a** was chosen as the model substrate since it is commercially accessible (Table S1†).

Key Laboratory of Organic Chemistry, Institute of Organic Chemistry, Jiangxi Science & Technology Normal University, Nanchang 330013, Jiangxi Province, China. E-mail: huanghaiyang1209@163.com; xiaoqiang@tsinghua.org.cn

† Electronic supplementary information (ESI) available. CCDC 2142375. For ESI and crystallographic data in CIF or other electronic format see <https://doi.org/10.1039/d2sc01423h>





**Fig. 1** E1cB elimination and phosphonium hydrolysis. (a) The mechanism of phosphonium salt hydrolysis. (b) P-ligand coupling reaction via a P(v)-intermediate. (c) Our conceived P(v) mediated E1cB elimination. (d) The E1cB elimination and its application in the synthesis of glycols. (e) Test system for the synthesis of glycols via P(v)-mediated E1cB elimination.

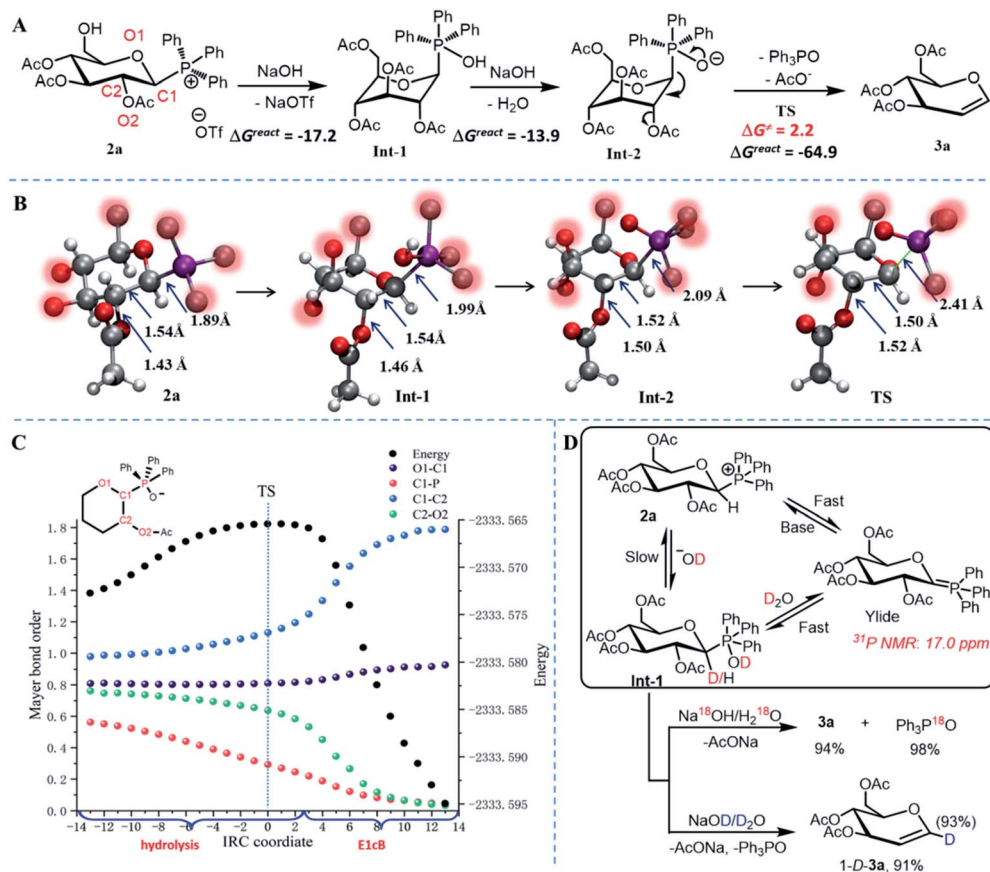
Initially, we developed a facile synthesis of  $\beta$ -D-glucosylphosphonium salt **2a** (previously prepared using corresponding glycosyl bromide and  $\text{PPh}_3$  with moderate yield<sup>14</sup>), by treating compound **1a** and  $\text{PPh}_3$  with trimethylsilyl trifluoromethanesulfonate (TMSOTf, 1.1 equivalents) in  $\text{CH}_2\text{Cl}_2$  at room temperature (stage A).<sup>15</sup> Following that, alkaline hydrolysis of phosphonium ion **2a** resulted in the formation of glycol **3a** via P(v) intermediates **Int-1** and **Int-2** (stage B). The reaction solvents, temperatures, and duration of the reaction were evaluated in detail. To our delight, the desired product **3a** could be obtained in two steps under the optimized conditions in 94% total isolated yield (Table S1,† entry 10). The screening results indicated that THF, toluene, or  $\text{CH}_3\text{CN}$  all inhibit the synthesis of phosphonium **2a** primarily because TMSOTf and  $\text{Ph}_3\text{P}$  can precipitate as a  $[\text{TMSOTf} \cdot \text{Ph}_3\text{P}]$  complex in these solvents. Additionally, we discovered that increasing the temperature (80 °C) and concentration of NaOH (3 M) may deprotect the acetyl groups, resulting in a lower yield. Therefore, the optimal conditions are dichloromethane ( $\text{CH}_2\text{Cl}_2$ ) as the solvent, aqueous NaOH (1 M) as the base, and room temperature (entry 10) for 2 hours in a mild two-phase hydrolysis system.

### Mechanistic investigation

We performed a series of experimental and computational studies to gain insight into the phosphonium hydrolysis-mediated E1cB-like process. Firstly, we attempted to monitor the hydrolysis process using  $^{31}\text{P}$  NMR spectroscopy, however, due to its high reactivity, no P(v) intermediates were detected (Fig. S4 and S5†). Therefore, we hypothesized that

decomposition of the P(v) intermediate is a rapid process rather than a rate-determining step. Computational studies revealed that the P(v) intermediate **Int-2** underwent P–C bond cleavage through the transition states with a very low barrier ( $\Delta G^\ddagger$ ), 2.2 kcal mol<sup>-1</sup> for **TS** ( $\beta$ -configurations, Fig. 2a) and 6.6 kcal mol<sup>-1</sup> for **TS'** ( $\alpha$ -configurations, Fig. S6†). These findings indicate that the addition of NaOH/ $\text{H}_2\text{O}$  to glycosylphosphonium is the rate-limiting step. We discovered that the rate of hydrolysis was proportional to the base concentration and depended on the type of solvent, confirming the preceding result. The  $\Delta G$  values indicated that each step of the process was significantly exergonic.

Fig. 2b depicts the computed structures of glycosylphosphonium **2a**, P(v) intermediates, and transition state **TS**. The hydrolysis reaction was characterized by an increase in the length of the P–C1 bond and C2–O bonds, but a decrease in the C1–C2 bond length as the reactions proceeded from **2a** to **TS**. However, the magnitude of the changes in P–C1 bonds was significantly greater than the other two parameters, implying that the carbanion center (C1 of the sugar ring) was formed first with the P(v)-group leaving, followed by the E1cB process (Video S1 and S2†). In the intermediate structure **Int-2**, the glycosyl as a nucleofugality is located at an apical position with a weaker, longer bond ( $d_{\text{P-C(glycosyl)}} = 2.09 \text{ \AA}$ ), whereas anionic oxygen which acts as an electron-donating ligand is placed in an equatorial position, theoretically explaining the observed P–C(glycosyl) cleavage. Additionally, the intrinsic reaction coordinate (IRC; Fig. 2c, Fig. S7 and S8†) demonstrated the formation of the C1=C2  $\pi$ -bond, the breaking of leaving groups (the P-



**Fig. 2** Computational and experimental analysis of P(v) the intermediate-mediated E1cB elimination of glucosyl triphenylphosphonium. (a) The DFT technique was used to determine the proposed reaction process and activation barrier of E1cB elimination at the m06-2x/6-311+G(d, p)/IEF-PCM<sub>DCM</sub>//b3lyp/6-31+G(d, p) level. The energy is expressed as kcal mol<sup>-1</sup>. (b) Optimized structures for **2a**, **Int-1**, **Int-2**, and **TS** demonstrate a stepwise evolution of the main bond lengths and the coordination configurations of the P-group. (c) Calculated variation in the main Mayer bond order and total energy along the IRC coordinate during the elimination process at the B3LYP/6-31G(d, p) level. (d) Hydrolysis conditions for the isotope-labeling experiments are base/H<sub>2</sub>O<sup>18</sup> or D<sub>2</sub>O. The glycosylphosphonium-ylide species can be detected under dry alkaline conditions.

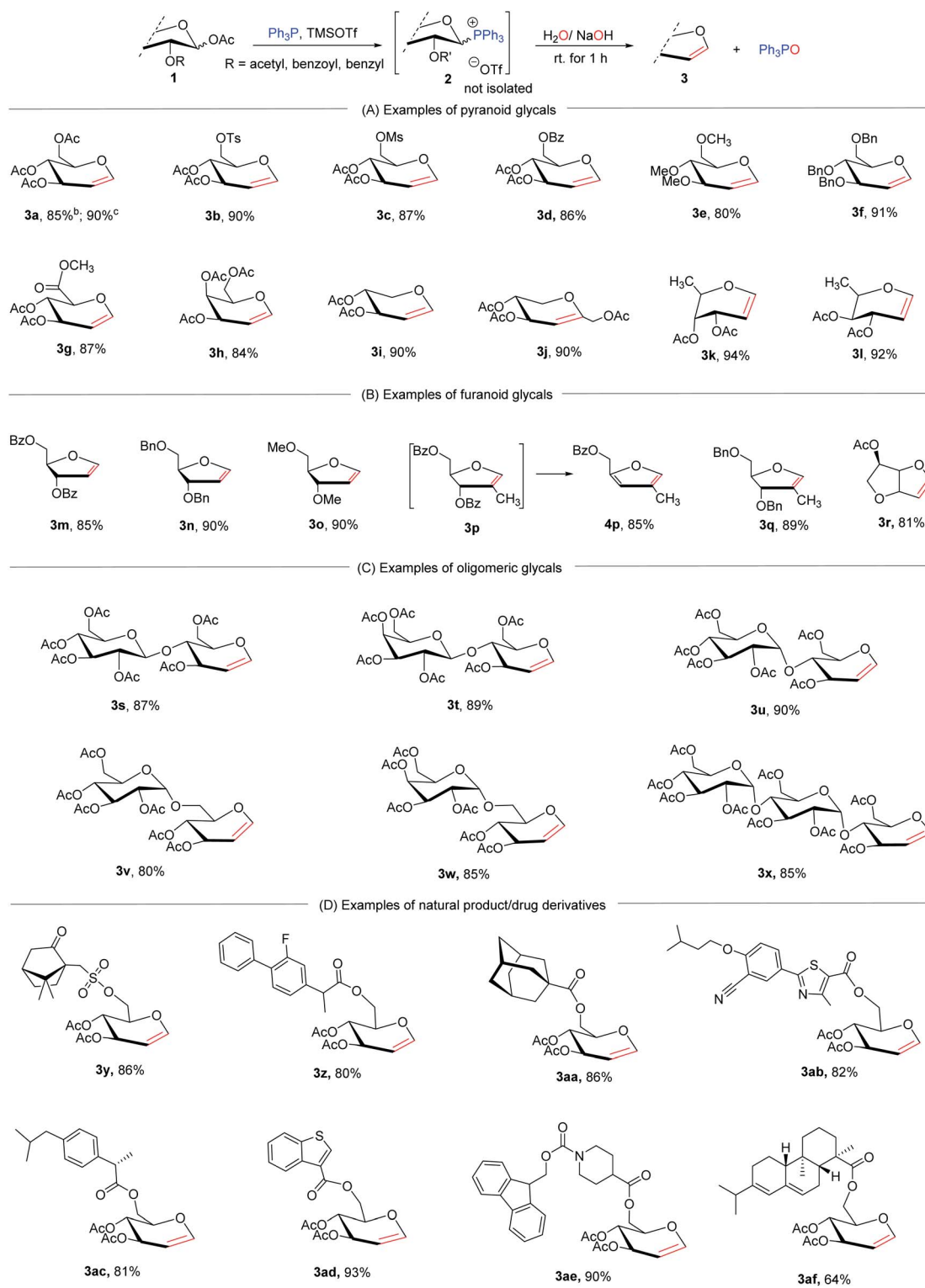
fragment and anionic OAc group), and a slight variation in the C1–O1 bond. With steady expulsion of the P-group, the Mayer bond order (MBO) values of C1–C2 and C2–O2 bonds evolve slowly at first and then reduce significantly, demonstrating that the oxaphosphorane-anion induces the formation of an anomeric carbanion-like center and then triggers E1cB elimination. Additionally, the relatively low MBO values of C1–O1 and C2–O2 in the intermediate **Int-2** imply that electron-withdrawing oxygen disperses the partial anionic electron to enhance glycosyl nucleofugality, resulting in a favored P–C<sub>(glycosyl)</sub> bond cleavage.

To elucidate the mechanism of the reaction further, we performed isotope-labeling (D and O<sup>18</sup>) experiments (Fig. S4 and S5<sup>†</sup>). The deuteration reactions demonstrated that the 1,2-elimination of glycosylphosphonium salt to form glycosylphosphonium-ylide species (<sup>31</sup>P NMR = 17.0 ppm, Fig. S5<sup>†</sup>) was easier and faster than the straightforward nucleophilic attack by a hydroxyl anion in the presence of base/H<sub>2</sub>O, which is consistent with previous reports (Fig. 2d).<sup>16</sup> This kinetically regulated process results in the synthesis of 1-D-glycal with an extremely high deuterated ratio (93% for 1-D-**3a**, Scheme S3

and Fig. S2<sup>†</sup>). Additionally, the findings of the treatment of phosphonium **2a** with NaO<sup>18</sup>H/H<sub>2</sub>O<sup>18</sup> (generated from NaO<sup>t</sup>Bu and H<sub>2</sub>O<sup>18</sup> *in situ*) demonstrated that the oxygen in triphenylphosphine oxide is derived from H<sub>2</sub>O<sup>18</sup> (Scheme S4 and Fig. S3<sup>†</sup>), confirming that the novel elimination reaction is mediated by a phosphonium-mediated hydrolysis mechanism (Scheme S5<sup>†</sup>).

### Exploration of the substrate scope

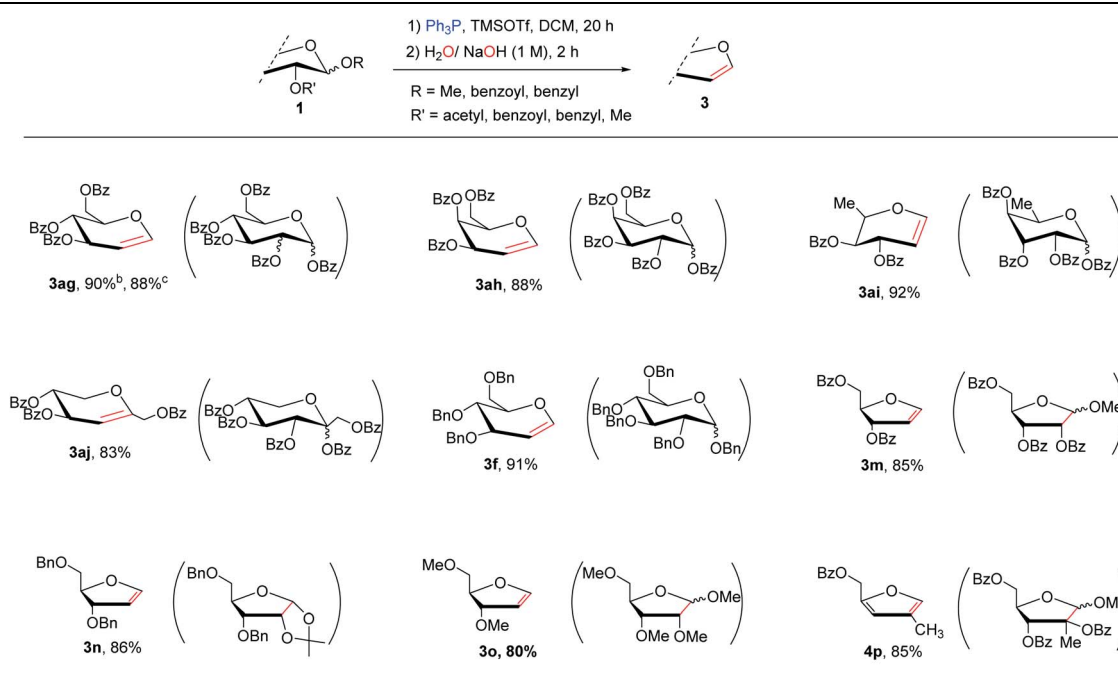
To examine the scope tolerance of P(v)-mediated E1cB elimination, we used a series of commercially available 1-O-acetyl sugars as substrates (Table 1). We first examined the general applicability of pyranoses for this transformation under optimized conditions (Table 1a). We were ecstatic to discover that a wide variety of pyranoid glycols containing various protected groups, including acetyl, benzyl, benzoyl, sulfonyl, and ester groups, were obtained in excellent yields (**3a–3l**). Notably, substrates with BnO- or MeO-groups as adjacent leaving groups were also feasible (**3e**, **3f**), demonstrating that the stable ether linkage does not impair reactivity. In addition, we found that the other configuration at the C2-position, such as penta-O-

Table 1 Substrate scope of P(v)-mediated E1cB elimination of 1-O-acetyl sugars<sup>a</sup>

<sup>a</sup> Reactions conditions: compounds **1** (1 mmol), Ph<sub>3</sub>P (1.1 mmol) and TMSOTf (1.1 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (15 ml) at rt for 5 h, then the aqueous NaOH/H<sub>2</sub>O (1 M, 0.5 ml) at rt for 2 h; Isolated yields. <sup>b</sup> Penta-O-acetyl glucose as the substrate. <sup>c</sup> Penta-O-acetyl mannose as the substrate.

acetyl mannose (**3a<sup>c</sup>**) and penta-O-benzoyl mannose (**3ag<sup>c</sup>** in Table 2), had little effect on the rate and yield of the reaction, implying that the E1cB process is suitable for different C-2

configurations as leaving groups. Following that, we extended our reaction to the ever-challenging synthesis of furanoid glycols (Table 1b), which are difficult to synthesize using the

Table 2 Substrate scope for the elimination of other common sugar derivatives<sup>a</sup>

<sup>a</sup> Reactions conditions: compounds **1** (1 mmol),  $\text{Ph}_3\text{P}$  (1.1 mmol) and TMSOTf (1.1 mmol) in  $\text{CH}_2\text{Cl}_2$  (15 ml) at 50 °C for 10 h, then the aqueous  $\text{NaOH}/\text{H}_2\text{O}$  (1 M, 0.5 ml) at rt for 2 h; Isolated yields; the starting materials in parentheses. <sup>b</sup> Penta-*O*-acetyl glucose as the substrate. <sup>c</sup> Penta-*O*-acetyl mannose as the substrate.

Fischer–Zach method.<sup>10,13</sup> The different protected furanoid glycols can be easily synthesized using this alkali hydrolysis-induced E1cB process (**3m–3r**). Meanwhile, we discovered that some of the generated furanoid glycols can easily undergo further elimination to form furans (**3m**, **3p**) during workup. This additional elimination, however, can be avoided by using benzyls or methyl as protecting groups (**3n**, **3o**, and **3q**).

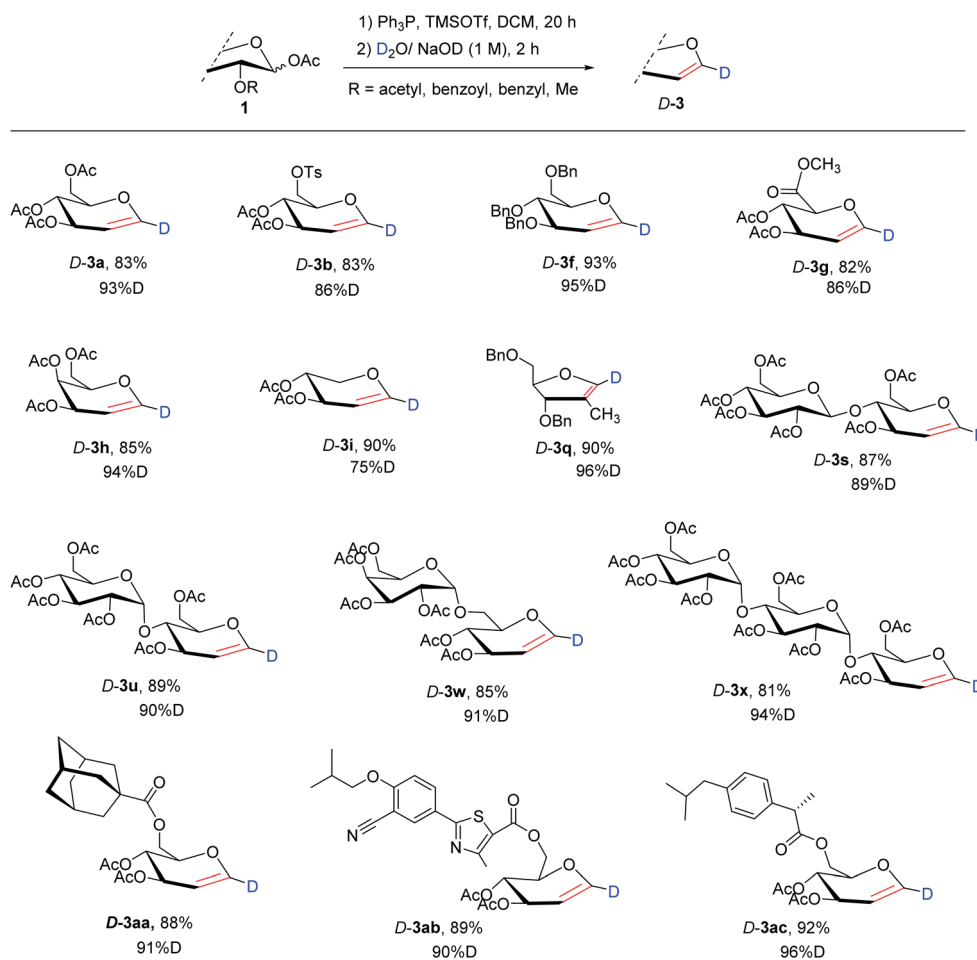
To further test the method's efficacy, some selected peracetylated oligosaccharides, including cellobiose, lactose, maltose, isomaltose, melibiose, and maltotriose, were examined to obtain **3s–3t** respectively (Table 1c). Although their yields were not affected, a longer reaction time (24–36 h) was required to prepare the corresponding phosphonium, probably due to their greater steric hindrance. Additionally, the synthetic value of this process was further enhanced by its suitability for natural product- and drug-conjugated sugar derivatives (Table 1d). For example, under slightly adjusted conditions, the 6-*O*-ester of (+)-10-camphorsulfonic acid, flurbiprofen, adamantancarboxylic acid, febuxostat, (+)-ibuprofen, benzothiophene, Fmoc-isonipecotic acid, and abietic acid smoothly converted to the desired products **3y–3af** (phosphoniuming at 80 °C for 12 h and subsequent elimination using 3 M aqueous NaOH for 3 h).

Next, we examine whether this methodology could be applied to other common sugar derivatives with more stable protecting groups on the anomeric carbon, as well as *O*-glycosides (Table 2). The results indicated that under standard conditions, perbenzoyl sugars can react smoothly to form pyranoid and furanoid glycols. Although the acetonide-, 1-benzyloxy- and methoxy-sugar derivatives required a slightly higher reaction

temperature (50–60 °C) to complete the corresponding phosphonation, all of the desired products were obtained in good yields (**3ag–4p**). Thus, our protocol demonstrated a high degree of generality for the synthesis of a variety of glycols at excellent yields under mild metal-free conditions.

### Synthesis of 1-deuterium-glycols

Due to their importance in chemical, environmental, optical, and biological fields, deuterium-labeled compounds have been extensively studied.<sup>17</sup> Particularly, deuteration using  $\text{D}_2\text{O}$  as the deuterium source has been proposed as one of the most promising and efficient methods due to its economic and environmental benefits.<sup>18</sup> However, the reported synthesis of 1-deuterium-glycols is based on the hydrogen–deuterium exchange of alkyl lithium treatment and so requires a multi-step process (at least 7 steps for 1-D-**3f**, 8 steps for 1-D-**3f**) and a strict requirement on the protecting group (Scheme S1†).<sup>19</sup> Therefore, we anticipated that this protocol can be directly used for the regioselective synthesis of a variety of 1-deuterium-glycols *via*  $^t\text{BuONa}/\text{D}_2\text{O}$ -hydrolysis–elimination ( $\text{D}_2\text{O}$  as the deuterium source). The scope of 1-D-glycol synthesis is shown in Table 3. We investigated the utility of direct one-step synthesis of 1-deuterium-glycols using a variety of different sugar derivatives, including pyranoid and furanoid monosaccharides, disaccharides, trisaccharides, and drug-conjugated sugar derivatives. Therefore, we demonstrated a powerful and facile approach for the synthesis of 1-deuterium-glycols, which may be potentially useful in future chemical and biological applications.

Table 3 The synthesis of 1-deuterium-glycals<sup>a</sup>

<sup>a</sup> Reactions conditions: compounds **1** (1 mmol), Ph<sub>3</sub>P (1.1 mmol) and TMSOTf (1.1 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (15 ml) at rt for 5 h, then the aqueous NaOH/H<sub>2</sub>O (1 M, 0.5 ml) at rt for 2 h; isolated yields; the deuterated ratios given by <sup>1</sup>H NMR.

### Scale-up reaction

To further evaluate the practicability of the currently developed method, 200 grams per-*O*-acetyl glucose **1a** was used as a model substrate (Fig. S9†). Although the yield was unaffected by the air atmosphere, somewhat longer reaction times for phosphoniuming (10 h) and hydrolysis–elimination (5 h) were required. Fortunately, pure glucosylphosphonium **2a** (370 g, 94% yield) can be obtained by simple filtration and crystallization. The glycal **3a** (131 g) was achieved in 94% yield after hydrolysis of the obtained phosphonium, as long as the insoluble triphenylphosphin oxide in diethyl ether was removed. We anticipate that this method developed into a commercially viable method for the synthesis of glycals.

### Conclusions

In summary, we present a novel oxanion phosphorane-mediated E1cB-like elimination method for the synthesis of glycals and 1-deuterium-glycals. This method overcomes the

major limitations of conventional approaches by virtue of the metal-free, mild base-induced conditions and compatibility with pyranoid and furanoid derivatives, particularly complex oligosaccharides and drug-like molecules. Additionally, this method can be easily scaled up to a hundred-gram-scale, allowing for large-scale preparation. This method is advantageous in medicinal chemistry due to its simple protocols, readily available reagents, broad applicability, and scale-up synthesis. Additionally, the currently developed hydrolysis-mediated elimination method enables a new application of anionic phosphorane in synthetic chemistry and encourages chemists to explore further reactivity of phosphoranes.

### Data availability

All experimental and characterization data are available in the ESI.† Crystallographic data for compound **2a'** have been deposited in the Cambridge Crystallographic Data Centre under the accession number CCDC: 2142375.

## Author contributions

H. H. and Q. X. directed the project and co-wrote the manuscript; H. H. conceived the work, designed the experiments, conducted the DFT calculation and analysed the data; F. L., L. S., Z. Y., X. T., J. L., X. L., and H. D. performed the experiments and collected experimental data; all authors have given approval regarding the final version of the manuscript.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 21462019 and 21676131), the Bureau of Science & Technology of Jiangxi Province (No. 20143ACB20012), and the PhD start-up fund (No. 2018BSQD025) and innovation fund (No. YC2020-S563) of Jiangxi Science & Technology Normal University.

## Notes and references

- (a) G. W. Fenton and C. K. Ingold, CCCVII.—Influence of poles and polar linkings on the course pursued by elimination reactions. Part V. The mechanism of thermal decomposition of quaternary phosphonium hydroxides, *J. Chem. Soc.*, 1929, 2342–2357; (b) L. Horner, H. Hoffmann, H. G. Wippel and G. Hassel, Phosphorus organic compounds. X. The course of the cleavage of mixed substituted tetraarylphosphonium hydroxides, *Chem. Ber.*, 1958, **91**, 52–57; (c) G. Asknes and J. Songstad, Kinetic Study of the Reaction between Phosphonium Compounds and Hydroxyl Respectively Alkoxide Ions, *Acta Chem. Scand.*, 1962, **16**, 1426–1432; (d) W. E. McEwen, G. Axelrad, M. Zanger and C. A. Vander Werf, Mechanisms of substitution reactions at phosphorus. XII. A kinetic study of the decomposition of quaternary phosphonium hydroxides, *J. Am. Chem. Soc.*, 1965, **87**, 3948–3952; (e) R. A. McClelland, G. H. McGall and G. Patel, Kinetics and mechanism of the hydrolysis of acyclic oxyphosphonium salts, *J. Am. Chem. Soc.*, 1985, **107**, 5204–5209; (f) P. A. Byrne, Y. Ortin and D. G. Gilheany, First ever observation of the intermediate of phosphonium salt and ylide hydrolysis: P-hydroxytetraorganophosphorane, *Chem. Commun.*, 2015, **51**, 1147; (g) P. A. Byrne, Y. Ortin and D. G. Gilheany, The Mechanism of Phosphonium Ylide Alcoholysis and Hydrolysis: Concerted Addition of the O–H Bond Across the P=C Bond, *Chem.–Eur. J.*, 2016, **22**, 9140–9154; (h) A. W. Johnson, W. C. Kaska, K. A. O. Starzewski and D. A. Dixon, *Ylides and Imines of Phosphorus*; John Wiley & Sons: New York, 1993; (i) H. J. Cristau and F. Plénat, in *The Chemistry of Organophosphorus Compounds*, ed. F. R. Hartley, Wiley, Chichester, 1994, ch. 2, vol. 3, pp. 111–138; (j) L. D. Quin, *A guide to organophosphorus chemistry*. John Wiley & Sons. 2000, ch. 4, pp. 117–122.
- R. Tian, H. Liu, Z. Duan and F. Mathey, The Abnormal Hydrolysis of 7-Phosphanorbornenium Salts: A Case of Phosphonium–Phosphenium Equivalence, *J. Am. Chem. Soc.*, 2009, **131**, 16008–16009.
- (a) D. Valentine Jr, J. F. Blount and K. Toth, Synthesis of phosphines having chiral organic groups ligated to chiral phosphorus, *J. Org. Chem.*, 1980, **45**, 3691–3698; (b) F. Zaragoza, One-step conversion of alcohols into nitriles with simultaneous two-carbon chain elongation. (cyanomethyl)trimethylphosphonium iodide as a reagent with a dual mode of action, *J. Org. Chem.*, 2002, **67**, 4963–4964; (c) P. Calcagno, B. M. Kariuki, S. J. Kitchin, J. M. Robinson, D. Philp and K. D. Harris, Understanding the Structural Properties of a Homologous Series of Bis-diphenylphosphine Oxides, *Chem.–Eur. J.*, 2000, **6**, 2338–2349.
- (a) M. C. Hilton, R. D. Dolewski and A. McNally, Selective functionalization of pyridines *via* heterocyclic phosphonium salts, *J. Am. Chem. Soc.*, 2016, **138**, 13806–13809; (b) R. G. Anderson, B. M. Jett and A. McNally, A unified approach to couple aromatic heteronucleophiles to azines and pharmaceuticals, *Angew. Chem.*, 2018, **130**, 12694–12698; (c) J. L. Koniarczyk, D. Hesk, A. Overgard, I. W. Davies and A. McNally, A general strategy for site-selective incorporation of deuterium and tritium into pyridines, diazines, and pharmaceuticals, *J. Am. Chem. Soc.*, 2018, **140**, 1990–1993.
- (a) M. C. Hilton, X. Zhang, B. T. Boyle, J. V. Alegre–Requena, R. S. Paton and A. McNally, Heterobiaryl synthesis by contractive C–C coupling *via* P(V) intermediates, *Science*, 2018, **362**, 799–804; (b) X. Zhang, K. G. Nottingham, C. Patel, J. V. Alegre–Requena, J. N. Levy, R. S. Paton and A. McNally, Phosphorus-mediated sp<sup>2</sup>–sp<sup>3</sup> couplings for C–H fluoroalkylation of azines, *Nature*, 2021, **594**, 217–222.
- (a) M. Zanger, C. A. WanderWerf and W. E. McEwen, Kinetic study of the decomposition of quaternary phosphonium hydroxides, *J. Am. Chem. Soc.*, 1959, **81**, 3806–3807; (b) G. U. N. N. A. R. Aksnes, J. Songstad, A. M. Olson, T. Briggs, G. A. D. Haslewood and H. Flood, Kinetic Study of the Reaction between Phosphonium Compounds and Hydroxyl Respectively Alkoxide Ions, *Acta Chem. Scand.*, 1962, **16**, 1426–1432; (c) W. E. McEwen, K. F. Kumli, A. Blade-Font, M. Zanger and C. A. WanderWerf, Mechanisms of substitution reactions at phosphorus. X. The Wittig reaction and the decomposition of quaternary phosphonium hydroxides, *J. Am. Chem. Soc.*, 1964, **86**, 2378–2382; (d) B. Siegel, *J. Am. Chem. Soc.*, 1979, **101**, 2265–2268.
- (a) M. Shimada, O. Sugimoto and A. Sato, Preparation and reaction of quinolinyl (or pyridinyl) phosphonium salts with base and pivalaldehyde, *Heterocycles*, 2011, **83**, 837–847; (b) Z. Deng, J. H. Lin and J. C. Xiao, Nucleophilic arylation with tetraarylphosphonium salts, *Nat. Commun.*, 2016, **7**, 10337.

- 8 (a) J. Clayden, N. Greeves and S. Warren, in *Organic Chemistry*, Oxford University Press, Oxford, 2nd edn, 2012, pp. 382–406; (b) A. Krebs and J. Swienty-Busch, in *Eliminations to Form Alkenes, Allenes and Alkynes and Related Reactions*, ed. B. M. Trost and I. Fleming, Pergamon, Oxford, 1991, pp.949–973; (c) G. Köbrich, Eliminations from olefins, *Angew. Chem., Int. Ed.*, 1965, **4**, 49–68; (d) T. I. Crowell, R. T. Kemp, R. E. Lutz and A. A. Wall, an elimination reaction with kinetics characteristic of the E1cB mechanism, *J. Am. Chem. Soc.*, 1968, **90**, 4638–4643.
- 9 (a) C. J. Stirling, Leaving groups and nucleofugality in elimination and other organic reactions, *Acc. Chem. Res.*, 1979, **12**, 198–203; (b) L. Somsák, Carbanionic reactivity of the anomeric center in carbohydrates, *Chem. Rev.*, 2001, **101**, 81–136.
- 10 Book and reviews: (a) W. Priebe, I. Fokt and G. Gryniewicz, Glycal Derivatives, in *Glycoscience*, ed. B. O. Fraser-Reid, K. Tatsuta and J. Thiem, Springer, Berlin, Heidelberg, 2008, pp. 699–735; (b) H. H. Kinfe, Versatility of glycals in synthetic organic chemistry: coupling reactions, diversity oriented synthesis and natural product synthesis, *Org. Biomol. Chem.*, 2019, **17**, 4153–4182; (c) S. J. Danishefsky and M. T. Bilodeau, Glycals in organic synthesis: the evolution of comprehensive strategies for the assembly of oligosaccharides and glycoconjugates of biological consequence, *Angew. Chem., Int. Ed.*, 1996, **35**, 1380–1419.
- 11 Some selected examples: (a) C. Qin, B. Schumann, X. Zou, C. L. Pereira, G. Tian, J. Hu and J. Yin, Total synthesis of a densely functionalized *Plesiomonas shigelloides* serotype 51 aminoglycoside trisaccharide antigen, *J. Am. Chem. Soc.*, 2018, **140**, 3120–3127; (b) S. N. Hess, X. Mo, C. Wirtz and A. Fürstner, Total Synthesis of Limaol, *J. Am. Chem. Soc.*, 2021, **143**, 2464–2469; (c) S. V. Sharma, V. K. Jothivasan, G. L. Newton, H. Upton, J. I. Wakabayashi, M. G. Kane and C. J. Hamilton, Chemical and chemoenzymatic syntheses of bacillithiol: A unique low-molecular-weight thiol amongst low G + C gram-positive bacteria, *Angew. Chem.*, 2011, **123**, 7239–7242; (d) M. Tanaka, A. Nakagawa, N. Nishi, K. Iijima, R. Sawa, D. Takahashi and K. Toshima, Boronic-acid-catalyzed regioselective and 1, 2-*cis*-stereoselective glycosylation of unprotected sugar acceptors via S<sub>N</sub>i-type mechanism, *J. Am. Chem. Soc.*, 2018, **140**, 3644–3651; (e) F. Zhu, J. Rodriguez, T. Yang, I. Kevlishvili, E. Miller, D. Yi and M. A. Walczak, Glycosyl cross-coupling of anomeric nucleophiles: scope, mechanism, and applications in the synthesis of aryl C-glycosides, *J. Am. Chem. Soc.*, 2017, **139**, 17908–17922; (f) R. Xiao, E. L. Dane, J. Zeng, C. J. McKnight and M. W. Grinstaff, Synthesis of altrose poly-amido-saccharides with  $\beta$ -N-(1  $\rightarrow$  2)-*d*-amide linkages: A right-handed helical conformation engineered in at the monomer level, *J. Am. Chem. Soc.*, 2017, **139**, 14217–14223; (g) Y. Nakatsuji, Y. Kobayashi and Y. Takemoto, Direct Addition of Amides to Glycals Enabled by Solvation-Insusceptible 2-Haloazolium Salt Catalysis, *Angew. Chem.*, 2019, **131**, 14253–14257; (h) K. Sakamoto, M. Nagai, Y. Ebe, H. Yorimitsu and T. Nishimura, Iridium-catalyzed direct hydroarylation of glycals via C–H activation: ligand-controlled stereoselective synthesis of  $\alpha$ - and  $\beta$ -C-glycosyl arenes, *ACS Catal.*, 2019, **9**, 1347–1352; (i) C. Palo-Nieto, A. Sau and M. C. Galan, Gold (I)-catalyzed direct stereoselective synthesis of deoxyglycosides from glycals, *J. Am. Chem. Soc.*, 2017, **139**, 14041–14044; (j) M. Liu, K. M. Liu, D. C. Xiong, H. Zhang, T. Li, B. Li and X. S. Ye, Stereoselective Electro-2-deoxyglycosylation from Glycals, *Angew. Chem., Int. Ed.*, 2020, **59**, 15204–15208; (k) G. Zhao and T. Wang, Stereoselective Synthesis of 2-Deoxyglycosides from Glycals by Visible-Light-Induced Photoacid Catalysis, *Angew. Chem., Int. Ed.*, 2018, **57**, 6120–6124; (l) A. Sau, R. Williams, C. Palo-Nieto, A. Franconetti, S. Medina and M. C. Galan, Palladium-Catalyzed Direct Stereoselective Synthesis of Deoxyglycosides from Glycals, *Angew. Chem.*, 2017, **129**, 3694–3698; (m) W. Shang, C. Zhu, F. Peng, Z. Pan, Y. Ding and C. Xia, Nitrogen-Centered Radical-Mediated Cascade Amidoglycosylation of Glycals, *Org. Lett.*, 2021, **23**, 1222–1227.
- 12 (a) P. Pal and A. K. Shaw, The evolution of comprehensive strategies for furanoid glycal synthesis and their applications, *RSC Adv.*, 2017, **7**, 25897–25963; (b) C. L. Cavallaro and J. Schwartz, Rapid preparation of variously protected glycals using titanium (III), *J. Org. Chem.*, 1995, **60**, 7055–7057; (c) B. K. Shull, Z. Wu and M. Koreeda, A convenient, highly efficient one-pot preparation of peracetylated glycals from reducing sugars, *J. Carbohydr. Chem.*, 1996, **15**, 955–964; (d) K. Micskei, Z. Juhász, Z. R. Ratković and L. Somsák, Reactivity of per-*O*-acetylated 1-thioglycosides and glycosyl sulfones towards chromium (II) complexes in aqueous medium, *Tetrahedron Lett.*, 2006, **47**, 6117–6120; (e) A. M. Gómez, M. Casillas, A. Barrio, A. Gawel and J. C. López, Synthesis of pyranoid and furanoid glycals from glycosyl sulfoxides by treatment with organolithium reagents, *Eur. J. Org. Chem.*, 2008, **23**, 3933–3942; (f) O. Boutureira, M. A. Rodríguez, M. I. Matheu, Y. Díaz and S. Castellón, General method for synthesizing pyranoid glycals. A new route to allal and gular derivatives, *Org. Lett.*, 2006, **8**, 673–675.
- 13 (a) E. Fischer and K. Zach, *Sitzber. kgl. preuss. Acad. Wiss.*, 1913, **16**, 311–317; (b) R. Csuk, A. Fürstner, B. I. Glänzer and H. Weidmann, A New, Zinc-promoted Synthesis of 1, 4-(1, 5)-Anhydro-2-deoxy-pent-(hex)-1-enitols (Furanoid and Pyranoid Glycals), *J. Chem. Soc., Chem. Commun.*, 1986, 1149–1150; (c) J. Zhao, S. Wei, X. Ma and H. Shao, A simple and convenient method for the synthesis of pyranoid glycals, *Carbohydr. Res.*, 2010, **345**, 168–171; (d) Y. Xu, W. Wang, Y. Cai, X. Yang, P. G. Wang and W. Zhao, A convenient and efficient synthesis of glycals by zinc nanoparticles, *RSC Adv.*, 2014, **4**, 46662–46665; (e) H. Chen, T. Xian, W. Zhang, W. Si, X. Luo and B. Zhang, An efficient method for the synthesis of pyranoid glycals. J. Zhang, *Carbohydr. Res.*, 2016, **431**, 42–46.
- 14 (a) F. J. Kronzer and C. Schuerch, Use of positively charged, leaving groups in the synthesis of  $\alpha$ -D-linked galactosides. Attempted synthesis of 3-*O*- $\alpha$ -(D-(galactopyranosyl))-D-galactose, *Carbohydr. Res.*, 1974, **33**, 273–280; (b) R. Eby



- and C. Schuerch, The use of positively charged leaving-groups in the synthesis of  $\alpha$ -D-linked glucosides. Synthesis of methyl 2,3,4-tri-O-benzyl-6-O-(2,3,4,6-tetra-O-benzyl- $\alpha$ -D-glucopyranosyl)- $\alpha$ -D-glucopyranoside, *Carbohydr. Res.*, 1975, **39**, 33–38.
- 15 (a) H. Fujioka, A. Goto, K. Otake, O. Kubo, Y. Sawama and T. Maegawa, An unusual reaction of  $\alpha$ -alkoxyphosphonium salts with Grignard reagents under an O<sub>2</sub> atmosphere, *Chem. Commun.*, 2011, **47**, 9894–9896; (b) A. Goto, K. Otake, O. Kubo, Y. Sawama, T. Maegawa and H. Fujioka, Effects of Phosphorus Substituents on Reactions of  $\alpha$ -Alkoxyphosphonium Salts with Nucleophiles, *Chem.–Eur. J.*, 2012, **18**, 11423–11432.
- 16 (a) M. Schlosser, Phosphororganische Verbindungen, I. Eine Methode zur Darstellung selektiv deuterierter Verbindungen, *Chem. Ber.*, 1964, **97**, 3219–3233; (b) A. Schnell, J. G. Dawber and J. C. Tebby, The mechanism of hydrolysis of phosphonium ylides, *J. Chem. Soc., Perkin Trans. 2*, 1976, **6**, 633–636; (c) K. Y. Lee, J. E. Na, M. J. Lee and J. N. Kim, Synthesis of deuterium labeled compounds by KCN-assisted hydrolysis of phosphonium salts, *Tetrahedron Lett.*, 2004, **45**, 5977–5981.
- 17 (a) S. L. Harbeson and R. D. Tung, Deuterium in Drug Discovery and Development, *Annual Reports in Medicinal Chemistry*, Elsevier, 2011, vol. 46, pp. 403–417; (b) J. F. Liu, S. L. Harbeson, C. L. Brummel, R. Tung, R. Silverman and D. Doller, A Decade of Deuteration in Medicinal Chemistry, *Annual Reports in Medicinal Chemistry*, Elsevier, 2017, vol. 50, pp. 519–542; (c) T. Pirali, M. Serafini, S. Cargini and A. A. Genazzani, Applications of Deuterium in Medicinal Chemistry, *J. Med. Chem.*, 2019, **62**, 5276–5297; (d) X. Yang, H. Ben and A. J. Ragauskas, Recent Advances in the Synthesis of Deuterium-Labeled Compounds, *Asian J. Org. Chem.*, 2021, **10**, 2473–2485.
- 18 (a) D. A. Spiegel, K. B. Wiberg, L. N. Schacherer, M. R. Medeiros and J. L. Wood, Deoxygenation of Alcohols Employing Water as the Hydrogen Atom Source, *J. Am. Chem. Soc.*, 2005, **127**, 12513–12515; (b) M. R. Medeiros, L. N. Schacherer, D. A. Spiegel and J. L. Wood, Expanding the Scope of Trialkylborane/Water-Mediated Radical Reactions, *Org. Lett.*, 2007, **9**, 4427–4429; (c) V. Soulard, G. Villa, D. P. Vollmar and P. Renaud, Radical Deuteration with D<sub>2</sub>O: Catalysis and Mechanistic Insights, *J. Am. Chem. Soc.*, 2018, **140**, 155–158; (d) C. Liu, S. Han, M. Li, X. Chong and B. Zhang, Electrocatalytic Deuteration of Halides with D<sub>2</sub>O as the Deuterium Source over a Copper Nanowire Arrays Cathode, *Angew. Chem.*, 2020, **132**, 18685–18689.
- 19 (a) S. Zhang, Y. H. Niu and X. S. Ye, General Approach to Five-Membered Nitrogen Heteroaryl C-Glycosides Using a Palladium/Copper Cocatalyzed C–H Functionalization Strategy, *Org. Lett.*, 2017, **19**, 3608–3611; (b) D. Yi, F. Zhu and M. A. Walczak, Stereoretentive Intramolecular Glycosyl Cross-Coupling: Development, Scope, and Kinetic Isotope Effect Study, *Org. Lett.*, 2018, **20**, 4627–4631.