Flack, *Acta Crystallogr. Sect. A* **1983**, *39*, 876–881) of about 0.5, which could not be reduced upon inversion of the parameter set. Therefore the final structure refinement was performed by assuming racemic twinning. All non-hydrogen atoms were refined with anisotropic displacement parameters. The hydrogen atoms attached to alcoholic oxygen atoms were refined isotropically, whereas all other hydrogen atoms were treated by using the appropriate riding model. Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-161491 (**1a**) and CCDC-161490 (**2a**). Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB21EZ, UK (fax: (+44)1223-336-033; e-mail: deposit@ccdc.cam. ac.uk).

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A Transition Metal Complex of D-Glucose**

Peter Klüfers* and Thomas Kunte

Special attention is paid to the carbohydrates as the most abundant biogenic raw materials when establishing benign chemical syntheses as a part of sustainable development. In order to overcome the "overfuctionalization" of the carbohydrates, which bear a number of very similar functionalities rather than a large number of functionalities, classical carbohydrate chemistry often uses multistep reaction sequences. Due to by-products and an extensive use of auxiliary agents, carbohydrate chemistry is by no means "green", despite the usage of biogenic raw materials.[1] One approach to solve this problem is reaction steering by metal catalysis. To plan catalysis in a rational way, basic information is needed; in particular, how the substrate reacts with a metal in a specified oxidation state.[2] To what extend the fundamentals are lacking in that area is illustrated by the statement that, to the best of our knowledge, up to now not a single transition-metal complex of D-glucose, as the most important monosaccharide, has been characterized structurally. One of the reasons for this might be the high reactivity of the reducing sugars. Not only the ease of oxidation and their instability in alkaline solution must be accounted for, even the monosaccharides themselves are mixtures in solution. When a coordinating metal moiety is exposed to glucose, for example, it is not predictable whether the sugar will react through its α- or β-furanose, α- or β-pyranose, or a less stable form (Scheme 1; neither open-chain nor septanose forms are considered). For the epimeric D-mannose, it was demonstrated that coordination to a metal can establish β-D-mannofuranose as the main species, although this isomer is unimportant in the normal solution equilibrium of the aldose.[3]
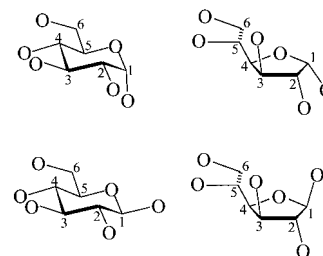
Scheme 1. Oxygen atom pattern of the common α- (top) and β-D-glucose isomers (bottom): Pyranoses with $^4C_1$ conformation (left) and furanoses (right).

Herein, we report on the characterization of a transition metal complex of D-glucose in solution and the solid state. The metal is the good oxidant palladium(II)—oxidation of the aldose, however, could be avoided to such an extent that even crystallization became possible. The starting point of the experiments was the unexpected behaviour of "Pd-en", an aqueous solution of $[(en)Pd(OH)_2]$ (en = ethylenediamine), towards cellulose. Pd-en is a coordinating cellulose solvent, which dissolves the polysaccharide with formation of a metal complex.[4] On investigating largely hydrolyzed cellulose (degree of polymerization approximately 30, compared with about 3000 for native cellulose), our attention was attracted since even with these short chained and hence end-group rich celluloses, there was no enhanced precipitation of palladium(0) due to oxidation of the reducing end groups. Hence monosaccharides—the "pure" reducing end groups—were dissolved in Pd-en and it became apparent that simply cooling the mixtures to about 5 °C suffices to obtain stable solutions without metal precipitation (as expected, no *N*-glycoside formation of the en ligands was observed at the low temperatures applied[5]). Since palladium(II) complexes with an N_2O_2 ligand set are sufficiently inert and diamagnetic, the mixture of isomers can be investigated by NMR spectroscopy in solution. Figure 1 shows the spectrum of a solution with a 3:1 molar ratio of palladium and the sugar. The signals, assigned by $^1H/^{13}C$ correlated spectra, indicated an anomeric mixture made up of two parts α- and one part β-pyranose

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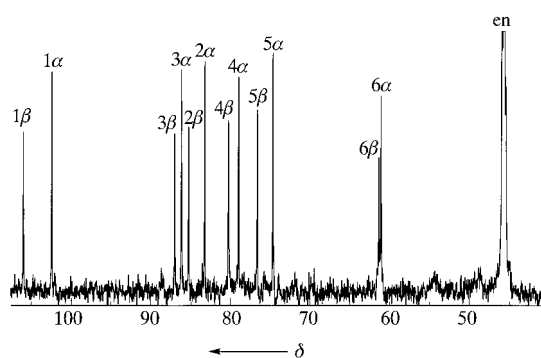Fax: (+49)89-2180-7407
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Figure 1. ^{13}C NMR spectra of a solution of D-glucose in Pd-en (see also Table 1). The atom numbering corresponds to Scheme 1 left. Labels α und β relate to the respective anomer of the pyranose form.
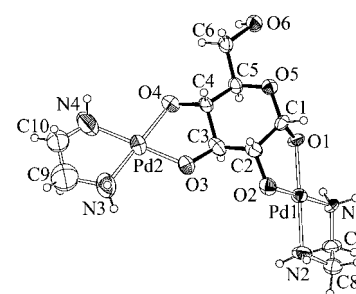

Figure 2. The molecular structure of **1** in the crystal. Thermal ellipsoids are drawn at 40 % probability (C9 and C10 are refined isotropically). Distances [pm]: from Pd1-O1 199.5(11), Pd1-O2 199.9(12), Pd1-N1 202.4(13), Pd1-N2 204.0(14), Pd2-O3 197.6(13), Pd2-N3 200.9(18), Pd2-N4 203(2), Pd2-O4 204.0(13); bonding angles [°]: O1-Pd1-O2 83.5(5), O3-Pd2-O4 84.2(5); torsion angles [°]: O1-C1-C2-O2 43(2), O2-C2-C3-O3 68(2), O3-C3-C4-O4 −50(2).

Table 1. Signal positions in the ^{13}C NMR spectrum of a 0.35 M solution of D-glucose in 1 M Pd-en. In addition to the chemical shift the coordination-induced shift $(\delta_{Complex} - \delta_{Reference})$[a] is tabulated. CIS values indicating palladium bonding are printed in bold. The relative amount of the anomers was detected (^{1}H NMR) as 2:1 in favor of the α form.

	C1	C2	C3	C4	C5	C6
α-D-glucopyranose in Pd-en:						
δ [ppm]	102.6	83.4	86.3	79.1	74.8	61.2
CIS [ppm]	**9.0**	**10.4**	**12.1**	**8.0**	1.9	− 0.9
β-D-glucopyranose in Pd-en:						
δ [ppm]	106.2	85.4	87.2	80.4	76.8	61.5
CIS [ppm]	**8.8**	**9.8**	**10.0**	**9.3**	− 0.6	− 0.8

[a] The reference is an about 0.6 M solution of D-glucose in water.[8]

(compare the 1:2 equilibrium mixture of an aqueous glucose solution). The bonding sites of palladium are indicated by their characteristic "coordination-induced shift" (CIS), which is a downfield shift of about 10 ppm for those carbon atoms that are bonded to metal-coordinating oxygen atoms. As a result, the four oxygen atoms 1–4 (for atom numbers see Scheme 1 top left) are bonded to palladium, hence the hemiacetal function is also part of a palladium-coordinating entity. Since the Pd(en) fragment provides a bonding site for one diolato ligand, a binuclear complex should be present with both anomers. The spectra remain the same when the molar ratio of Pd and D-glucose is reduced to 2:1. A further decrease to a 1:1 ratio results in a mixture of monometallated glucoses. The 1,2-metallated species are of particular significance, as may be expected owing to the maximum acidity of the hydroxy group at C1.

We did not succeed in the preparation of crystals of satisfying size. However, a small crystal was obtained from a solution with a 3:1 Pd:D-glucose molar ratio. X-ray analysis[6] proved the crystal to be composed of the main solution species, the α anomer. According to the formula [(en)$_2$Pd$_2$-(α-D-Glcp1,2,3,4H$_{-4}$)]·7H$_2$O **1** (Glcp = glucopyranose), the spectroscopically determined metal-binding sites were found entirely deprotonated. Figure 2 shows the O1–O4 deprotonated α-D-glucopyranose tetraanion, which is coordinated as a bis(chelate) ligand to two palladium(II) central atoms. Owing to the weakly scattering crystal it was not possible to locate the hydrogen sites experimentally. However, O−O and O−N distances clearly indicate that all alkoxo oxygen atoms are acceptors in two hydrogen bonds each, with O−H groups as the donors. N−H functions contribute to the hydrogen bond structure as parts of cooperative chains. With this structural features, the glucose complex fits in the series of polyol complexes with the (en)Pd^{II} fragment.[4]

The oxygen atom pattern of a carbohydrate may match the pattern of free coordination sites of a metal thus forming stable aggregates. With a reducing sugar, the first structure analysis with a transition metal complex—a molybdate(VI) with the β-lyxofuranose ligand[7]—shows that the pentose sugar is able to provide an O$_4$ rhomb. A later analysis showed that the O$_5$ pattern provided by β-mannofuranose turned out to be an ideal building block of M$_2$O$_{10}$ double octahedra of binuclear metallates(III).[3] On the other hand, the oxygen atom patterns of the most important monosaccharide, D-glucose, in any of its hemiacetal forms do not exceed the simple O$_2$ diol pattern (a consequence is the epimerization reaction of glucose to β-mannofuranose in the presence of trivalent metal ions[3a]). In this work, this steric restriction is taken into account by providing exclusively the (en)Pd^{II} moiety, which is a diol chelator. However, despite the low hapticity, the stability of the complexes is large enough that no signals but those of the doubly metallated species are observed in stoichiometrically composed solutions. Current work is directed towards the issue of making use of the modulated reactivity of the complexed reducing sugars.

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Heterocycles through Domino Reactions with Trimethyl Aconitate, a Versatile Synthetic Building Block[**]

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Dedicated to Professor Dieter Hoppe on the occasion of his 60th birthday

Selective C−C bond formations require building blocks of opposite reactivity, that is donors and acceptors. Anionic donors, which are soluble in methanol, simplify thereby the performance of the reaction. Trimethyl aconitate (**1**), a C$_6$ building block, is of interest in this regard. It possesses five functional groups: one donor, namely the acidic methylene group of a vinylogous malonate and four acceptors, namely the electrophilic double bond and three ester groups. Furthermore aconitic acid is a renewable raw material, which can be extracted from sugar molasses or be obtained by dehydration of citric acid. In spite of these favorable presuppositions **1** has up to now been rarely used in synthesis.[1] First systematic investigations demonstrate that the functional groups in **1** can be used for Michael additions,[2] Diels–Alder cycloadditions,[3] Knoevenagel condensations,[4] and cyclodimerizations.[5] Here we report on domino reactions[6] of the donor(*d*) and acceptor(*a*) groups of **1** with imines.

Stirring equimolar amounts of **1** with the imine **2** in methanol leads to the dihydropyrrolones **3** and **4** [Eq. (1)]. The isomer **4** was shown by AM1 and PM3 calculations to be thermodynamically more stable than **3**. For the product
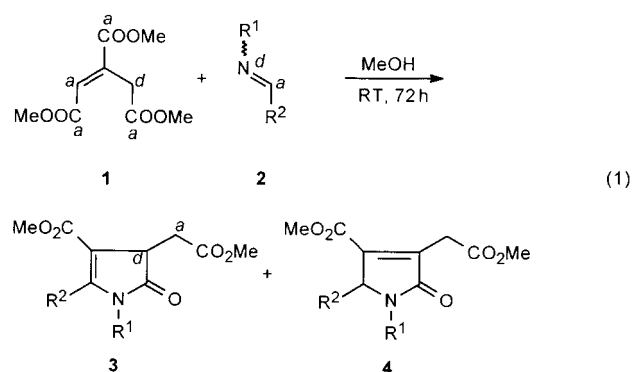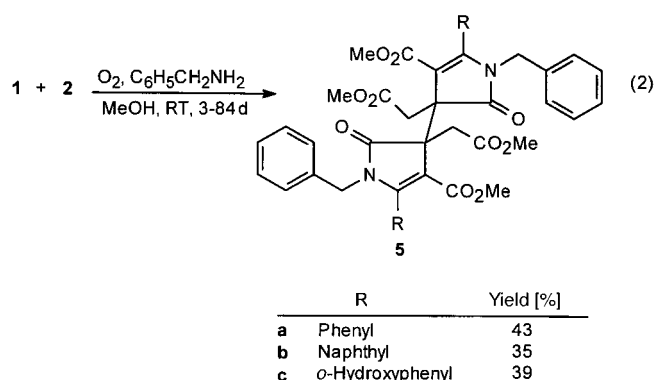

	R^1	R^2	Yield [%]	3:4
a	Benzyl	Phenyl	57	100:0
b	Benzyl	Naphthyl	55	0:100
c	Benzyl	*o*-Hydroxyphenyl	28	38:62
d	2-Furylmethyl	Phenyl	52	100:0
e	Methyl	Phenyl	46	41:59

formation the following reaction path appears plausible: **1** reacts with one equivalent of imine in a domino reaction, which consists of a nucleophilic addition, an intramolecular acylation, and a shift of the exocyclic double bond, to form the 2,5-dihydropyrrolone **3**. The subsequent base-catalyzed double bond shift leading to **4** is evidently kinetically controlled by the substituents R^1 and R^2.

2,5-Dihydropyrrolones **3** are components of herbicides[7] and structural motifs of natural products.[8] They are usually prepared by reaction of enaminoesters or imines, respectively, with dialkyl maleates or maleic anhydride leading to N1−C2 and C4−C5 connections.[9] The alternative N1−C2 and C4−C5 connection established here using **1** and imines allows a simpler variation of the C5 substituent in the dihydropyrrolone.

The reaction of **1** with the imine **2a** in the presence of benzylamine leads to the bisdihydropyrrolone **5a** [Eq. (2)], which is obtained nearly exclusively as the racemate as shown by the crystal structure analysis.

	R	Yield [%]
a	Phenyl	43
b	Naphthyl	35
c	*o*-Hydroxyphenyl	39

As the reaction does not occur when using triethylamine, benzylamine evidently acts as redox-mediator and not as base. Benzylamine is possibly oxidized by air to the cation radical, which is deprotonated to the benzylamino radical. This radical could abstract a hydrogen atom from the simultaneously

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