Tsuji-Wacker-type oxidation beyond methyl ketones: Reacting unprotected carbohydrate based terminal olefins through the “Uemura-system” to hemiketals and α,β-unsaturated diketones

Patrik A. Runeberg*, Patrik C. Eklund*

Johan Gadolin Process Chemistry Centre
Åbo Akademi University
Piispankatu 8, 20500 Turku, Finland
*patrik.runeberg@abo.fi
*paeklund@abo.fi

Table of Contents

1. General information…………………………………………………………………………………………………S2
2. Experimental details and analytical data…………………………………………………………………………S3
3. References………………………………………………………………………………………………………………S14
4. NMR Spectra…………………………………………………………………………………………………………S15
1. General information

1.1 Materials and instruments

All commercially available chemicals were used as supplied by the manufacturers. The Palladium (II) Acetate used was purchased from both Aldrich (now Merck) and Acros Organics. Substrate 4 (4-penten-2-ol) was purchased from Aldrich as a racemic mixture. Isopropanol and pyridine were purchased from Merck. NMR solvents were purchased from Cambridge Isotopes Laboratories (D₂O), and from VWR Chemicals (MeOD, CDCl₃).

All GC samples were silylated using hexamethyldisilazane (HMDS) and chlorotrimethylsilane (TMCS) in pyridine prior to analysis by GC-EIMS. GC-EIMS analyses were performed on an Agilent Technologies 7890A GC-system equipped with a 5975C EIMS-detector and an Agilent J&W HP-5ms GC Column (30 m x 0.25 mm, 0.25 µm film). HRMS of the Na-adducts of the products were recorded on a micrOTOF-Q instrument. ¹H and ¹³C NMR spectra were recorded on a Bruker AV 500 spectrometer at 500 and 125 MHz, respectively. 2D-experiments were recorded using standard pulse sequences, and the chemical shifts are reported downfield from tetramethylsilane.

Column chromatography was done on a Teledyne ISCO CombiFlash® EZ prep UV/ELSD-unit, using RediSep Rf gold silica flash chromatography columns (20-40 µm) and chloroform/methanol or petroleum ether/ethyl acetate as eluent systems.

1.2 General reaction conditions

The Tsuji-Wacker-type oxidation reactions were performed inside a Parr Instrument pressure Vessel connected to an Ashcroft AISI 316 pressure gauge tube socket. The whole pressure vessel was heated to 60 °C on sand bath prior to the reactions. The reactions were stirred by magnetic stirring. In cases where palladium black was formed, the reaction mixture was filtered through filter paper before analysis and work up.
2. Experimental Details

2.1 Allylation of carbohydrates

The substrates 1-3 were prepared at our laboratory according to literature procedure\cite{1-4} through metal mediated allylation of unprotected monosaccharides.

One equivalent carbohydrate or glyceraldehyde was dissolved in deionized water (to a 0.2 M solution). Three equivalents tin powder and two equivalents allyl bromide was added and the reaction mixture was stirred at room temperature overnight. Dilution in ethanol followed by filtration through celite, and finally evaporation of solvents gave the polyol product.

Allylated D-mannose (1) was retrieved as pure threo-isomer through recrystallization in ethanol. Substrate 2 was the racemic mixtures of threo- and erythro-isomers of the terminal olefin originated from D-glucose, whereas substrate 3 was a mixture of four isomers formed through allylation of DL-Glyceraldehyde.

For threo-isomer of allylated D-mannose (1), synthesis and additional analytical information can be found in the literature.\cite{2,3}

For allylated D-glucose (2), synthesis, $^1$H and $^{13}$C NMR, and other analytical information can be found in the literature.\cite{3}

For 5-Hexene-1,2,3-triol (3), synthesis, $^1$H and $^{13}$C NMR, and other analytical information can be found in the literature.\cite{4,5}
2.2 Tsuji-Wacker-type oxidation of allylated polyols

The reaction followed literature procedure, but with minor alterations.[6] In a typical experiment, a preheated (60 °C) autoclave was charged with a solution of polyol (1.50 mmol, 1.0 eq), Pd(OAc)$_2$ (0.45 mmol, 0.3 eq) and pyridine (0.90 mmol, 0.6 eq) in isopropanol (10 ml). The autoclave was then filled with molecular oxygen (1 or 2 bar). The reaction mixture was vigorously stirred at 60 °C for 20 hours. Any possible formed black precipitate (palladium black) was filtered off. Evaporation of solvents gave the crude mixture of products (and palladium complexes). GCMS and NMR analyses of the crude mixture were used for calculating the observed conversion and for characterizing the formed products.

![Chemical structure](image)

5: White solid. 88 mg isolated yield.

$^1$H NMR (500 MHz, D$_2$O): δ = 3.89-3.96 (ddd, $J = 11.7, 9.2, 5.1$ Hz, 1H, 6), 3.90 (dd, $J = 10.0, 1.2$ Hz, 1H, 4), 3.88 (dd, $J = 11.9, 2.8$ Hz, 1H, 1a), 3.85 (dd, $J = 8.7, 1.2$ Hz, 1H, 3), 3.77 (ddd, $J = 8.7, 6.7, 2.8$ Hz, 1H, 2), 3.66 (dd, $J = 11.9, 6.7$ Hz, 1H, 1b), 3.48 (dd, $J = 10.0, 9.2$ Hz, 1H, 5), 2.17 (dd, $J = 13.3, 5.1$ Hz, 1H, 7a), 1.61 (dd, $J = 13.3, 11.7$ Hz, 1H, 7b), 1.45 (s, 3 H, 9).

$^{13}$C NMR (125 MHz, D$_2$O): δ = 96.8 (8), 70.7 (2), 70.6 (4), 70.5 (5), 69.2 (6), 67.9 (3), 63.2 (1), 41.7 (7), 28.0 (9).

HRMS: found 261.0939 (M-Na$^+$). C$_9$H$_{18}$O$_7$Na$^+$ requires 261.0950.
6: White solid. 76 mg isolated yield.

**1H NMR** (500 MHz, D$_2$O): $\delta = 6.31$ (d, $J = 3.1$ Hz, 1H, 6), 6.05 (dq, $J = 3.0$, 1.1 Hz, 1H, 7), 4.82 (d, $J = 4.7$ Hz, 1H, 4), 3.92 (dd, $J = 6.7$, 4.7 Hz, 1H, 3), 3.75 (dd, $J = 11.8$, 3.1 Hz, 1H, 1a) 3.68 (ddd, $J = 6.9$, 6.7, 3.1 Hz, 1H, 2), 3.58 (dd, $J = 11.8$, 6.9 Hz, 1H, 1b), 2.27 (d, $J = 1.1$ Hz, 3H, 9) ppm.

**13C NMR** (500 MHz, D$_2$O): $\delta = 152.7$ (8), 151.7 (5), 108.6 (6), 106.1 (7), 73.2 (3), 71.4 (2), 66.8 (4), 62.4 (1), 12.5 (9) ppm.

**HRMS**: found (weak signal) 241.0545 (M-Na$^+$). C$_9$H$_{14}$O$_6$Na$^+$ requires 241.0688.

7a: Clear oil. 51 mg isolated yield (in equilibrium with 7b).

**1H NMR** (500 MHz, D$_2$O): $\delta = 4.52$ (d, $J_{5,4}$ = 7.8 Hz, 1 H, 5), 3.88-3.96 (2 H, 2 and 1a), 3.63-3.69 (2 H, 3 and 1b), 3.53 (d, $J_{6,7}$ = 3.8 Hz, 1 H, 6), 3.52 (dd, $J_{4,3}$ = 10.1 Hz, $J_{4,5}$ = 7.8 Hz, 1 H, 4), 3.26 (d, $J_{7,6}$ =3.8 Hz, 1 H, 7), 1.51 (s, 3 H, 9) ppm.

**13C NMR** (125 MHz, D$_2$O): $\delta = 96.8$ (5), 93.8 (8), 72.4 (3), 71.8 (4), 63.2 (1), 59.8 (2), 57.6 (6) 53.5 (7), 24.1 (9) ppm.

**HRMS** (7a and 7b): found 259.0797 (M-Na$^+$). C$_9$H$_{16}$O$_7$Na$^+$ requires 259.0794.

As the spectra of the two isomers 7a and 7b were overlapping the coupling constants for some signals of isomer A were not solved. However, the chemical shifts for $^1$H and $^{13}$C signals for the two isomers were solved using, in addition to $^1$H and $^{13}$C NMR, 2D-experiments (HSQC, HMBC, COSY) and 1D-TOCSY experiments.
7b: Clear oil. 51 mg isolated yield (in equilibrium with 7a).

^1H NMR (500 MHz, D$_2$O): $\delta = 4.20$ (dd, $J_{4.3} = 8.9$ Hz, $J_{4.5} = 8.5$ Hz, 1 H, 4), 4.13 (d, $J_{7.6} = 3.0$ Hz, 1 H, 7), 3.94 (dd, $J_{5.4} = 8.5$ Hz, $J_{5.6} = 1.1$ Hz, 1 H, 5), 3.87 (dd, $J_{1a.1b} = 11.9$ Hz, $J_{1a.2} = 2.8$ Hz, 1 H, 1a), 3.85 (d, $J_{6.7} = 3.0$ Hz, 1 H, 6), 3.79 (m, 1 H, 2), 3.67 (dd, $J_{1b.1a} = 11.9$ Hz, $J_{1a.2} = 6.4$ Hz, 1 H, 1b), 3.62 (dd, $J_{3.4} = 8.9$ Hz, $J_{3.2} = 1.1$ Hz, 1 H, 3), 1.51 (s, 3 H, 9) ppm.

^13C NMR (125 MHz, D$_2$O): $\delta = 102.0$ (8), 75.6 (4), 70.6 (2), 69.9 (3), 68.0 (5), 63.1 (1), 59.2 (6), 56.9 (7), 20.6 (9) ppm.

HRMS: (7a and 7b): found 259.0797 (M-Na$^+$). C$_9$H$_{16}$O$_7$Na$^+$ requires 259.0794.

12: White solid. 1 mg isolated yield.

^1H NMR (500 MHz, D$_2$O): $\delta = 4.68$ (m, 1 H, 5), 4.28 (dd, $J_6.7a = 6.7$ Hz, $J_6.7b = 1.7$ Hz, 1 H, 6), 3.77-3.82 (m, 2 H, 1a and 4), 3.61-3.66 (m, 2 H, 1b and 2), 3.54 (dd, $J = 4.3$ Hz, $J = 7.8$ Hz, 1 H, 3), 2.36 (dd, $J_{7a.7b} = 13.7$ Hz, $J_{7a.6} = 6.7$ Hz, 1 H, 7a), 1.68 (s, 3 H, 9), 1.63 (ddd, $J_{7b.7a} = 13.7$, $J_{7b.6} = 1.7$ Hz, $J_{7b.5} = 1.4$ Hz, 1 H, 7b) ppm.

^13C NMR (125 MHz, D$_2$O): $\delta = 108.7$ (8), 83.9 (5), 75.2 (4), 71.7 (6), 71.5 (2), 71.1 (3), 62.6 (1), 46.2 (7), 16.8 (9) ppm.

Product 12 was very unstable and had completely reacted to a mixture of products before HRMS analysis. However, HRMS was done after acetylation to 19 (look at page S13).
**13**: seen as a five membered ring in the crude reaction mixture when NMR run in chloroform. Once the product is in an aqueous environment, an equilibrium between a six membered (4 enantiomeric pairs) ring and open chain (two enantiomeric pairs) methyl ketone (in a 4:3 ratio between ring and open chain) is seen. It was a clear oil with 24 mg isolated yield. Due to overlapping signals in $^1$H NMR when run in D$_2$O, coupling constants for all signals could not be distinguished.

**Five membered ring of 13 seen in CDCl$_3$:**

$^1$H NMR (500 MHz, CDCl$_3$): $\delta =$ 4.63 (ddd, $J_{3,4a} = 7.0$ Hz, $J_{3,4b} = 5.5$ Hz, $J_{3,2} = 5.5$ Hz, 1 H, 3), 4.08 (dd, $J_{2,3} = 5.5$ Hz, $J_{2,1} = 3.7$ Hz, 1 H, 2), 3.90 (d, $J_{1,2} = 3.7$ Hz, 2 H, 1), 2.39 (dd, $J_{4a,ab} = 13.6$ Hz, $J_{4a,3} = 7.0$ Hz, 1 H, 4a), 1.85 (dd, $J_{4b,4a} = 13.6$ Hz, $J_{4b,3} = 5.5$ Hz, 1 H, 4b), 1.52 (s, 3 H, 6) ppm.

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta =$ 107.0 (5), 79.8 (2), 73.6 (3), 61.6 (1), 49.7 (4), 23.7 (6) ppm.

**Major enantiomeric pair of six membered ring of 13:**

$^1$H NMR (500 MHz, D$_2$O): $\delta =$ 3.84 (ddd, $J_{3,4b} = 11.7$, $J_{3,2} = 9.1$, $J_{3,4a} = 5.1$ Hz, 1 H, 3), 3.72 (dd, $J_{1a,1b} = 11.1$, $J_{1a,2} = 5.6$ Hz, 1 H, 1a), 3.62 (1H, 1b), 3.52 (ddd, $J_{2,1a} = 10.7$, $J_{2,3} = 9.1$, $J_3 = 5.6$ Hz, 1 H, 2), 2.16 (dd, $J_{4a,4b} = 13.3$, $J_{4a,3} = 5.1$ Hz, 1 H, 4a), 1.59 (dd, $J_{4b,4a} = 13.3$, $J_{4b,3} = 11.7$ Hz, 1 H, 4b), 1.45 (s, 3 H, 6) ppm.

$^{13}$C NMR (125 MHz, D$_2$O): $\delta =$ 97.3 (5), 70.8 (2), 68.8 (3), 62.3 (1), 41.7 (4), 27.7 (6) ppm.

The three other enantiomeric pairs of the six membered ring of 13 had too weak and overlapping signals for identification.
Major enantiomeric pair of open chain methyl ketone of 13:

$^1$H NMR (500 MHz, D$_2$O): $\delta = 4.16$ (ddd, $J_{3,4a} = 8.4$, $J_{3,4b} = 8.0$, $J_{5,2} = 4.0$ Hz, 1 H, 3), 3.54-3.74 (m, 3 H, 1a, 1b, 2), 2.70-2.90 (4a, 4b), 2.65 (6) ppm.

$^{13}$C NMR (125 MHz, D$_2$O): $\delta = 213.5$ (5), 73.7 (2), 67.3 (3), 62.5 (1), 46.5 (4), 29.9 (6) ppm.

Minor enantiomeric pair of open chain methyl ketone of 13:

$^1$H NMR (500 MHz, D$_2$O): $\delta = 4.12$ (3), 3.54-3.74 (1a, 1b, 2), 2.70-2.90 (4a, 4b), 2.65 (6) ppm.

$^{13}$C NMR (125 MHz, D$_2$O): $\delta = 213.8$ (5), 74.2 (2), 66.9 (3), 62.5 (1), 46.4 (4), 30.0 (6) ppm.

HRMS: found 171.0619 (M-Na$^+$). C$_6$H$_{12}$O$_4$Na$^+$ requires 171.0628.

14:

$^1$H NMR (500 MHz, CDCl$_3$): $\delta = 6.16$ (d, $J_{3,4} = 3.0$ Hz, 1 H), 5.91, (d, $J_{4,3} = 3.0$ Hz, 1 H), 4.54 (s, 2 H), 2.28 (s, 3 H) ppm. $^{13}$C NMR (125 MHz, CDCl$_3$): $\delta = 152.5$, 151.7, 108.8, 106.3, 61.6, 13.7 ppm. Spectral data is in accordance with literature data.[7]

15:

$^1$H NMR (500 MHz, CDCl$_3$): $\delta = 4.23$ (ddd, $J_{2,3b} = 9.0$ Hz, $J_{2,1} = 6.3$ Hz, $J_{2,3a} = 3.0$ Hz, 1 H, 4), 2.63 (dd, $J_{3a,3b} = 17.7$ Hz, $J_{3a,2} = 3.0$ Hz, 1 H, 3a), 2.55 (dd, $J_{3b,3a} = 17.7$ Hz, $J_{3b,2} = 9.0$ Hz, 1 H, 3b), 2.18 (s, 3 H, 1), 1.19 (d, $J_{1,2} = 6.3$ Hz, 1 H, 5) ppm. Spectral data is in accordance with literature data.[8]
Product 16 was formed through olefin migration. Similar Pd(II)-catalyzed olefin migrations have been reported, also for the formation of 16 from 4.\textsuperscript{[10,11]}

### 2.3 Additional investigations into the Tsuji-Wacker-type oxidation

The reaction with 1 was also performed under argon atmosphere, in the absence of oxygen, using 2-propanol, Pd(OAc)\(_2\), and allylated polyol which had been flushed with argon for one hour to remove oxygen. Interestingly, the reaction had an observed conversion of 60 % after 24 hour of stirring at 60 °C, and products 5 and 6 were formed in a 3:4 ratio.

When a mixture of erythro- and threo-isomers of 1 reacted in the oxidation system using 2 bar molecular oxygen, a mixture of erythro- and threo-isomers of the products were retrieved (5, 7a and 7b). The mixture was acetylated, and the products were separated by column chromatography using petroleum ether and ethyl acetate as eluents. [See NMR for the epoxides 17 and erythro-17]

### 2.4 Acetylation of reaction mixtures

The acetylation reaction followed literature procedure.\textsuperscript{[12]} The crude reaction mixture was dissolved in pyridine. Acetic anhydride (15 mmol, 10 eq) was added and the reaction was
vigorously stirred at room temperature for 3 hours. The reaction was quenched by addition of methanol (1 ml), and the solvents were evaporated.

During the acetylation reaction, any ring closed product (except 6) was opened to the corresponding open chain ketone derivative. The epoxides 7a and 7b gave the single product 17 when ring opened. Additionally the open chain methyl ketone derivatives of 5 and 12 were further hydrolyzed to α-unsaturated methyl ketones (18 and 19).
17: Clear oil. 34 mg isolated yield.

\(^1\)H NMR (500 MHz, CDCl\(_3\), 25 °C): \(\delta = 5.40\) (dd, \(J_{3,2} = 9.3\) Hz, \(J_{3,4} = 2.0\) Hz, 1 H, 3), 5.38 (dd, \(J_{4,5} = 9.6\) Hz, \(J_{4,3} = 2.0\) Hz, 1 H, 4), 5.09 (ddd, \(J_{2,3} = 9.3\) Hz, \(J_{2,ib} = 5.3\) Hz, \(J_{2,ia} = 2.7\) Hz, 1 H, 2), 4.88 (dd, \(J_{5,4} = 9.6\) Hz, \(J_{5,6} = 9.0\) Hz, 1 H, 5), 4.18 (dd, \(J_{1a,ib} = 12.6\) Hz, \(J_{1a,2} = 2.7\) Hz, 1 H, 1a), 4.03 (dd, \(J_{ib,1a} = 12.6\) Hz, \(J_{ib,2} = 5.3\) Hz, 1 H, 1b), 3.41 (d, \(J_{7,6} = 4.8\) Hz, 1 H, 7), 3.33 (dd, \(J_{6,5} = 9.0\) Hz, \(J_{6,7} = 4.8\) Hz, 1 H, 6), 2.30 (s, 3 H, OAc), 2.13 (s, 3 H, OAc), 2.07 (s, 3 H, OAc), 2.06 (s, 3 H, OAc), 2.05 (s, 3 H, OAc) ppm.

\(^{13}\)C NMR (500 MHz, CDCl\(_3\), 25 °C): \(\delta = 204.7\) (8), 170.7 (OAc), 170.7 (OAc), 169.8 (OAc), 169.8 (OAc), 68.1 (3), 67.7 (2), 67.3 (5), 66.8 (4), 62.0 (1), 58.7 (7), 57.3 (6), 27.5 (9), 20.9 (OAc), 20.9 (OAc), 20.8 (OAc), 20.7 (OAc), 20.6 (OAc) ppm. The proposed stereochemistry is supported by NOESY-experiment, giving couplings from H-9 to H-5; from H-6 to H-4; from H-4 to H-1b.

HRMS: found 469.1326 (M-Na\(^+\)). \(C_{19}H_{26}O_{12}Na^+\) requires 469.1322

Erythro isomer of 17 (erythro-17): Clear oil. 16 mg isolated yield.

\(^1\)H NMR (500 MHz, CDCl\(_3\), 25 °C): \(\delta = 5.55\) (dd, \(J_{4,5} = 7.8\) Hz, \(J_{4,3} = 2.8\) Hz, 1 H, 4), 5.51 (dd, \(J_{3,2} = 9.1\) Hz, \(J_{3,4} = 2.8\) Hz, 1 H, 3), 5.18 (ddd, \(J_{2,3} = 9.1\) Hz, \(J_{2,ia} = 5.0\) Hz, \(J_{2,ib} = 2.8\) Hz, 1 H, 2), 4.54, (dd, \(J_{5,6} = 8.1\) Hz, \(J_{5,4} = 7.8\) Hz, 1 H, 5), 4.22 (dd, \(J_{1ib,1a} = 12.5\) Hz, \(J_{1ib,2} = 2.8\) Hz, 1 H, 1b), 4.10 (dd, \(J_{1a,ib} = 12.5\) Hz, \(J_{1a,2} = 5.0\) Hz, 1 H, 1a), 3.51 (d, \(J_{7,6} = 4.4\) Hz, 1 H, 7), 3.30 (dd, \(J_{6,5} = 8.1\) Hz, \(J_{6,7} = 4.4\) Hz, 1 H, 6), 2.25 (s, 3 H, 9), 2.15 (s, 3 H, OAc), 2.10 (s, 3 H, OAc), 2.08 (s, 3 H, OAc), 2.06 (s, 3 H, OAc), 2.03 (s, 3 H, OAc) ppm.
$^{13}$C NMR (500 MHz, CDCl$_3$, 25 °C): $\delta = 201.8$ (8), 170.6 (OAc), 170.5 (OAc), 169.8 (OAc), 169.8 (OAc), 169.2(OAc), 69.1 (4), 67.8 (2), 67.2 (3), 67.0 (5), 61.9 (1), 56.6 (7), 55.7 (6), 28.2 (9), 20.5 – 20.8 (5 x OAc) ppm.

HRMS: found 469.1258 (M-Na$^+$). C$_{19}$H$_{26}$O$_{12}$Na$^+$ requires 469.1322

18: Clear oil. 25 mg isolated yield.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta = 6.51$ (dd, $J_{6,7} = 16.0$ Hz, $J_{6,5} = 6.6$ Hz, 1 H, 6), 6.21 (d, $J_{7,6}$ = 16.0 Hz, 1 H, 7), 5.49 (dd, $J_{3,2} = 9.0$ Hz, $J_{3,4} = 1.7$ Hz, 1 H, 3), 5.55 – 5.38 (m, 2 H, 4 and 5), 5.12 (ddd, $J_{2,3} = 9.0$ Hz, $J_{2,1a} = 5.1$ Hz, $J_{2,1b} = 2.8$ Hz, 1 H, 2), 4.21 (dd, $J_{1a,1b} = 12.5$ Hz, $J_{1b,2} = 2.8$ Hz, 1 H, 1b), 4.10 (dd, $J_{1a,1b} = 12.5$ Hz, $J_{1a,2} = 5.1$ Hz, 1 H, 1a), 2.25 (s, 3 H, OAc), 2.07 (s, 3 H, OAc), 2.06 (2 x s, 2 x 3 H, 2 x OAc) ppm.

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta = 197.5$ (8), 170.7 (OAc), 169.9 (OAc), 169.8 (OAc), 169.7 (OAc), 169.5 (OAc), 139.0 (6), 133.8 (7), 69.8 (5), 69.7 (4), 68.0 (2), 67.4 (3), 61.9 (1), 27.4 (9), 20.9 (2 x OAc), 20.8 (OAc), 20.7 (2 x OAc) ppm.

HRMS: found 453.1348 (M-Na$^+$). C$_{19}$H$_{26}$O$_{11}$Na$^+$ requires 453.1373.

19: Light orange solid. 19 mg isolated yield.

$^1$H NMR (500 MHz, CDCl$_3$): $\delta = 6.69$ (dd, $J_{6,7} = 16.2$ Hz, $J_{6,5} = 5.2$ Hz, 1 H, 6), 6.19 (d, $J_{7,6}$ = 16.2 Hz, 1 H, 7), 5.55 (dd, $J_{5,4} = 6.4$ Hz, $J_{5,6} = 5.2$ Hz, 1 H, 5), 5.40 (dd, $J_{3,2} = 7.4$, $J_{3,4} = 3.5$ Hz, 1 H, 3), 5.35 (dd, $J_{4,5} = 6.4$ Hz, $J_{4,3} = 3.5$ Hz, 1 H, 4), 5.07 (ddd, $J_{2,3} = 7.4$ Hz, $J_{2,1b} = 5.4$ Hz, $J_{2,1a} = 3.0$ Hz, 1 H, 2), 4.25 (dd, $J_{1a,1b} = 12.5$ Hz, $J_{1a,2} = 3.0$ Hz, 1 H, 1a), 4.10 (dd, $J_{1b,1a} = 12.5$ Hz,
$J_{1b, 2} = 5.4$ Hz, 1 H, 1b, 2.28 (s, 3 H, 9), 2.14 (s, 3 H, OAc), 2.11 (a, 3 H, OAc), 2.09 (s, 3 H, OAc), 2.07 (s, 6 H, 2 x OAc) ppm.

$^{13}$C NMR (125 MHz, CDCl$_3$): $\delta = 197.5$ (8), 170.7 (OAc), 169.9 (OAc), 169.8 (OAc), 169.7 (OAc), 169.5 (OAc), 138.6 (6), 132.4 (7), 70.6 (5), 70.0 (4), 68.6 (2), 68.4 (3), 61.7 (1), 27.8 (9), 20.9 (OAc), 20.8 (3 x OAc), 20.6 (OAc) ppm.

HRMS: found 453.1357 (M-Na$^+$). C$_{19}$H$_{26}$O$_{11}$Na$^+$ requires 453.1373.
3. References

[1] E. Kim, D. M. Gordon, W. Schmid, G. M. Whitesides, *J. Org. Chem.* **1993**, *58*, 5500–5507.

[2] T. Saloranta, C. Müller, D. Vogt, R. Leino, *Chem. - A Eur. J.* **2008**, *14*, 10539–10542.

[3] T. Saloranta, A. Peuronen, J. M. Dieterich, J. Ruokolainen, M. Lahtinen, R. Leino, *Cryst. Growth Des.* **2016**, *16*, 655–661.

[4] C. Einhorn, J.-L. Luche, *J. Organomet. Chem.* **1987**, *322*, 177–183.

[5] K. Rajesh, V. Suresh, J. Jon Paul Selvam, C. Rao, Y. Venkateswarlu, *Synthesis (Stuttg).* **2010**, *2010*, 1381–1385.

[6] T. Nishimura, N. Kakiuchi, T. Onoue, K. Ohe, S. Uemura, *J. Chem. Soc. Perkin Trans. 1* **2000**, *1*, 1915–1918.

[7] Belén Martín-Matute, Cristina Nevado, and Diego J. Cárdenas, A. M. Echavarren*, *J. Am. Chem. Soc.* **2003**, *125*, 5757.

[8] Monica A. Kacprzynski, Stephanie A. Kazane, and Tricia L. May, A. H. Hoveyda*, *Org. Lett.* **2007**, *9*, 3187–3190.

[9] J.-B. Langlois, A. Alexakis, *Angew. Chemie Int. Ed.* **2011**, *50*, 1877–1881.

[10] A. Sen, T. W. Lai, *Inorg. Chem.* **1984**, *23*, 3257–3258.

[11] D. Gauthier, A. T. Lindhardt, E. P. K. Olsen, J. Overgaard, T. Skrydstrup, *J. Am. Chem. Soc.* **2010**, *132*, 7998–8009.

[12] S. Kumar, *J. Org. Chem.* **1985**, *50*, 3070–3073.
NMR spectra
$^1$H NMR of 5:
$^{13}$C NMR of 5:
$^1$H NMR of 6:
$^{13}$C NMR of 6:

![Graph showing the $^{13}$C NMR spectrum of compound 6 with chemical shifts and peaks marked.](image_url)
$^1$H NMR of 7a and 7b:
$^{13}$C NMR of 7a and 7b:
$^{1}$H NMR of 12:
$^{13}$C NMR of 12:
$^1$H NMR of 13:
$^{13}$C NMR of 13:
$^1$H NMR of 17:
$^{13}$C NMR of 17:
$^1$H NMR of 18:
$^{13}$C NMR of 18:
$^1$H NMR of 19:
$\text{C NMR of 19}$: