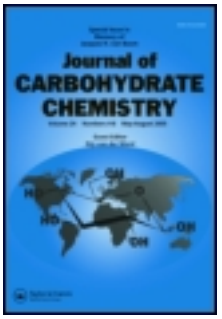

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Synthesis of Alkyl Fructosides Using Solid Acid Catalysts. Part I: Silica-Alumina Cracking Catalysts

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SYNTHESIS OF ALKYL FRUCTOSIDES USING SOLID ACID CATALYSTS. PART I: SILICA-ALUMINA CRACKING CATALYSTS

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ABSTRACT

Silica-alumina cracking catalysts and acid clays efficiently catalyze the 2-*O*-alkylation of D-fructose with long chain alcohols. Under the conditions applied virtually no degradation of fructose is observed. L-Sorbose and the aldopentoses also undergo silica-alumina-catalyzed alkylation. The rate of conversion is related to the solubility of the monosaccharide and the stability of the intermediate oxocarbenium ion. Best results in fructose alkylation are obtained by applying a recirculation method with butyl fructoside as soluble intermediate.

INTRODUCTION

The demand for detergent formulations which are completely based on renewable resources, such as triglycerides and carbohydrates, is growing.[1] Sucrose and starch-based surfactants can be easily synthesized from the natural feedstocks and they possess good surfactant properties combined with non-

toxicity and excellent biodegradability. Examples include the production of sucrose fatty acid esters (Suiker Unie/Dai Ichi), alkyl gluconamides (Procter and Gamble) and particularly alkyl polyglucosides (APG's), the latter being produced on a substantial scale by Henkel A.G. in the USA and recently also in Europe (Düsseldorf). Alkyl derivatives of fructose would present similar advantages whilst the increasing production of inulin, presently amounting to 40000 t/a in the Benelux, presumably will drive the price of fructose downwards. Hence, inulin and its monomer fructose may become economical starting materials, provided that an efficient alkylation method becomes available.

Long chain alkyl fructosides have been prepared from fructose using a number of protecting and deprotecting steps.[2] The direct acid catalyzed reaction of fructose with an alcohol, according to the Fischer method, is undoubtedly the most attractive method from an industrial point of view. Although acid catalyzed reactions of fructose with short chain alcohols (up to C8) have been described in the literature,[3] the direct conversion of fructose with fatty alcohols (> C8) has not been reported previously. Ambient conditions are not sufficient to effect reaction of fructose with higher alcohols whilst reaction at increased temperature tends to yield products of dehydration and degradation reactions, like 5-hydroxymethylfurfural (HMF) and levulinic acid. Alternative routes from sucrose using thermal[4] or acid catalyzed alcoholysis[5] result in low yields of fructosides for similar reasons. Enzyme-catalyzed alcoholysis of sucrose also gave moderate yields of lower alkyl fructosides and is ineffective for fatty alcohols.[6]

We have previously reported the direct synthesis of alkyl fructosides using mild homogeneous acid catalysts.[7] Whilst Fischer reaction of fructose and 1-octanol with sulfuric acid or other strong acids as the catalyst resulted in extensive degradation, oxalic acid effected selective alkylation. Because this result proved the feasibility of the Fischer alkylation of fructose with mild acid catalysts, we endeavoured to develop a heterogeneous catalyst which was stable under the reaction conditions. We here report that silica-alumina cracking catalysts and acid clays efficiently catalyze the alkylation of fructose as well as

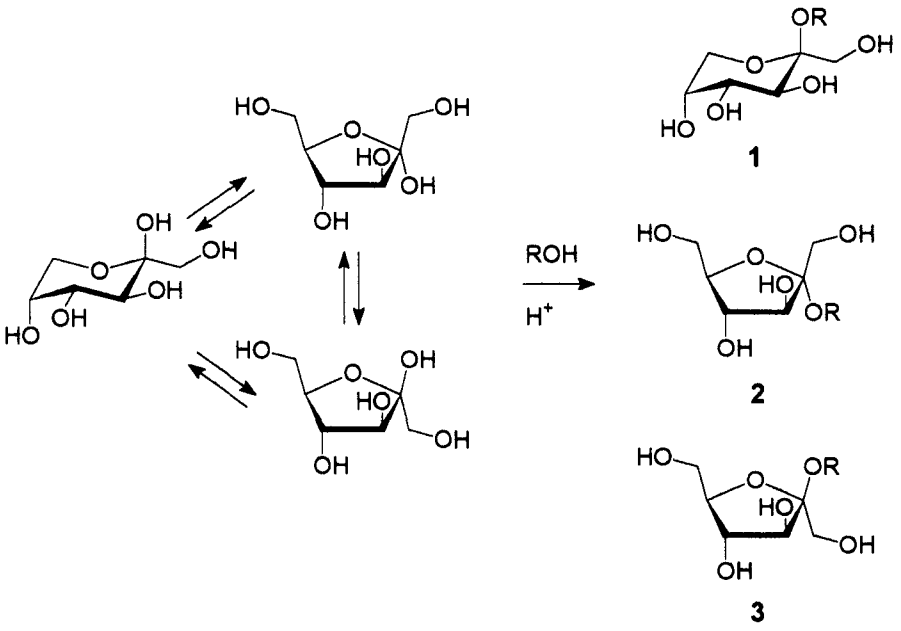


Figure 1. The reaction of D-fructose with fatty alcohols.

some other monosaccharides. The reactivity of the monosaccharides is related to the stability of the intermediate oxocarbenium ion.

RESULTS AND DISCUSSION

Catalyst selection and optimization. A number of conventional cracking catalysts of the silica-alumina type as well as an acid clay were active in the reaction of D-fructose with long chain alcohols. The three main products were β-D-fructopyranoside (**1**) and the α- and β-D-fructofuranosides **2** and **3** (see Figure 1).

The conversions which were obtained with these catalysts using 1-dodecanol as reactant and solvent are given in Table 1. With all four catalysts a useful conversion into dodecyl fructosides was obtained, without the strong degradation into coloured by-products which usually accompanies Fischer alkylation of fructose at higher temperature. The course of the reaction of

Table 1. Synthesis of dodecyl fructosides[a]

Catalyst	Reaction time (h)	Conversion to **1** - **3**[b] (%)
HA-HPV[c]	4.2	43
HA-SHPV[c]	5.0	45
LA-SHPV[c]	5.3	37
Tonsil[d]	3.5	45

a. Reaction conditions: D-fructose (3.0 g, 16.7 mmol), catalyst (activated at 430 °C for 24 h, 3.0 g), 1-dodecanol (49.6 g, 0.267 mol), 75 °C at 15 torr (2×10^3 Pa).
b. Determined by HPLC, maximum conversion observed.
c. Silica-alumina cracking catalysts ex AKZO-Nobel, see Experimental Part, Table 6, for specifications.
d. Acid clay standard FF ex Südchemie AG.

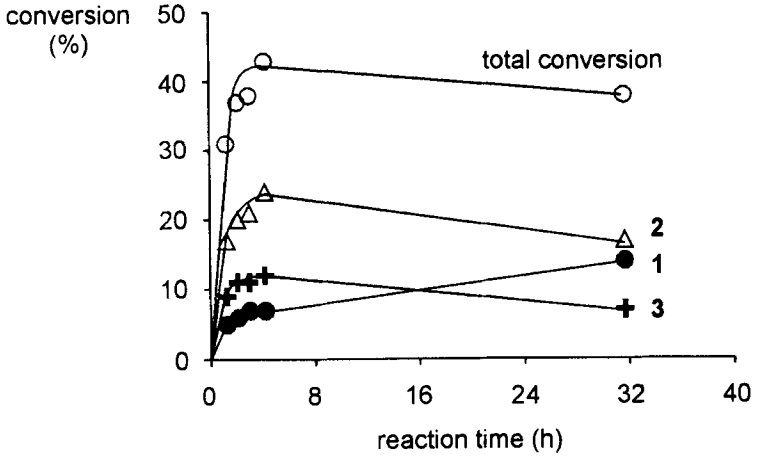


Figure 2. Course of the HA-HPV catalyzed reaction of fructose in 1-dodecanol. ●, 1; Δ, 2; +, 3; ○, total conversion. For reaction conditions see Table 1.

fructose in 1-dodecanol with silica-alumina HA-HPV (high alumina - high pore volume) activated at 430 °C is given in Figure 2, showing that the maximum conversion is achieved after 5 h followed by a slow isomerization.

From Figure 2 it becomes clear that the fructofuranosides (**2** and **3**) are the kinetically favoured products. At prolonged reaction times the

Table 2. Effect of the activation temperature[a] of HA-HPV on the reaction of fructose in 1-dodecanol

Temperature (°C)	Time[b] (h)	Conversion (% **1-3**)	Time (h)	Conversion (% **1-3**)
300	24.0	45	24.0	45
430	4.2	43	31.7	39
520	6.2	48	24.0	40
600	2.0	49	24.0	24
730	3.0	42	24.0	12
900	3.0	32	23.0	32

a. Reaction conditions: see Table 1; activation 24 h in air.
b. Reaction time for maximal conversion.

thermodynamically more stable β-D-fructopyranoside **1** increases and finally this compound becomes the major product. Compounds **1** , **2** and **3** are initially formed in a ratio of approximately 1:4:2. Hence, **1** is also formed directly from fructose and we conclude that the pyranose form of fructose (which in water at 31 °C accounts for 72% of the total[8]) does react in the present system but at a low rate. It is also apparent that the total amount of alkyl fructosides slightly decreases after long reaction times. This has to be attributed to slow consecutive reactions of these products and to deposition of oligomeric products on the catalyst. We will return to this point later on.

Data on the effect of the activation temperature of the HA-HPV catalyst are given in Table 2. Earlier it was found[9] that the activation of silica aluminas was an important variable in their efficiency in acetalization of relatively low molecular weight compounds (cyclohexanone/ethanol). As regards the conversion of fructose to dodecyl fructosides, a slight increase in conversion is observed when the catalyst activation temperature is increased from 300 to 600 °C. The required reaction time for maximal conversion is much reduced however. A further increase in activation temperature leads to reduced conversion. Acti-

vation at 430 °C results in a nearly colourless reaction mixture, but the increase of activity of the catalyst upon activation at higher temperatures is accompanied by a decrease in selectivity, as judged by some colouring of the reaction mixture. The drop in conversion at prolonged reaction time also becomes more pronounced upon activation at elevated temperatures. No product decay was observed however upon activation at 900 °C. At this temperature sintering of silica-alumina is known to take place.[9]

Upon thermal activation of amorphous silica alumina cracking catalyst up to 400 °C Brønsted acid sites are formed by desorption of physically adsorbed water. Higher temperatures lead to dehydroxylation of the surface whereby the Brønsted sites are converted into Lewis sites. The optimum activation temperature for acetal synthesis using cracking catalyst was reported to be 700-750 °C,[9] at which temperatures only Lewis-acid sites are left. However, for alkyl fructoside synthesis, activation at 730 °C (Table 2) apparently yields a too aggressive catalyst, whereas the Brønsted acidity of catalysts activated at lower temperatures effects selective alkylation of fructose.

Conversion into alkyl fructosides using the present standard conditions never exceeded 55% as measured by HPLC. Apart from a small amount of oligomeric products in solution, most of the missing fructose was deposited on the catalyst, as became evident from its increase in mass. Washing the catalyst with hot methanol returned it to its original weight; the methanolic extract consisted mainly of fructose and oligomeric fructose anhydrides probably account for the remainder. Apparently a dissolution/deposition mechanism is operative. Precipitation of fructosidic material could partly be prevented by increasing the 1-dodecanol/fructose ratio from the standard value of 16 to 32; whereas a decrease to 8 resulted in a lower yield of **1** - **3** (see Figure 3).

Short chain alcohols. To investigate the scope of the silica-alumina-catalyzed fructose alkylation experiments were performed with a number of alcohols (Table 3). With short-chain alcohols up to 1-butanol excellent conversions were obtained. Apparently deposition of fructosidic material on the catalyst is not a problem in these relatively polar lower alcohols. Alkyl

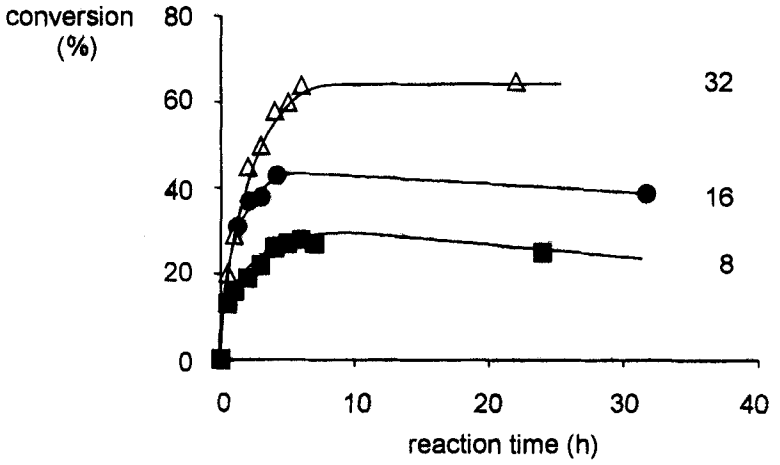


Figure 3. Effect of the 1-dodecanol/fructose molar ratio (■, 8; ●, 16; Δ, 32) on the conversion to **1** - **3** (HA-HPV catalyst, reaction conditions see Table 1).

Table 3. Effect of the alcohol chain length on the synthesis of alkyl fructosides[a]

Alcohol	Time (h)	Yield (% **1** - **3**)
Methanol	24.0[b]	100
Ethanol	4.5[b]	100
1-Butanol	1.8[c]	94
1-Octanol	4.0	60
1-Decanol	5.7	51

a. Reaction conditions: see Table 1 unless indicated otherwise. HA-HPV catalyst activated at 430 °C.
b. Reaction at reflux temperature using 50 mL of alcohol. Removal of water by reflux over zeolite KA.
c. Reaction at 75 °C using 50 mL of alcohol; reflux at reduced pressure over zeolite KA.

Table 4. HA-HPV-catalyzed reaction of various monosaccharides and 1-dodecanol[a]

Saccharide	Solubility[b] (M)	Initial rate[c] (% **1** - **3**)	Reaction time[d] (h)	Conversion (% **1** - **3**)
Ketohexoses				
D-Fructose	0.033	43	4.2	43
L-Sorbose	0.017	14	17	23
Aldopentoses				
D-Ribose	0.247	32	27	60
D-Arabinose	0.026	22	29	63
D-Xylose	0.031	17	46	54
Aldohexoses				
D-Mannose	0.020	3	50	14
D-Galactose	0.004	0.8	50	11
D-Glucose	0.012	< 0.1	50	< 1

a. Reaction conditions see Table 1.
b. In 1-decanol at 72 °C as measured by GC.
c. Conversion to **1** - **3** as measured by GC after 4 h.
d. Reaction time for maximal conversion to **1** - **3**.

fructofuranosides were mainly formed which were partly converted into the β-pyranosides after long reaction times. Reaction in 1-octanol and 1-decanol showed lower conversion to alkyl monofructosides due to deposition of material on the catalyst.

Recirculation procedure. A recirculation procedure solved the problem of deposition of material on the catalyst. Butyl fructosides were prepared from fructose and 1-butanol as above, 1-dodecanol was added and butanol was evaporated by vacuum distillation at 75 °C. After 4 h at 75 °C a maximum conversion of 64 % to dodecyl fructosides was reached. The cracking catalyst containing deposition products was filtered off and was treated with 1-butanol (50 mL) at 75 °C. A reaction mixture containing mainly butyl fructosides and

a nearly clean catalyst resulted. This is a strong indication that the deposit on the catalyst surface consists of fructose oligomers (anhydrides). Repeating this procedure resulted in a nearly quantitative conversion of fructose into dodecyl fructosides. The catalyst can be reactivated; we found that the activity was maintained through at least four cycles of use and reactivation.

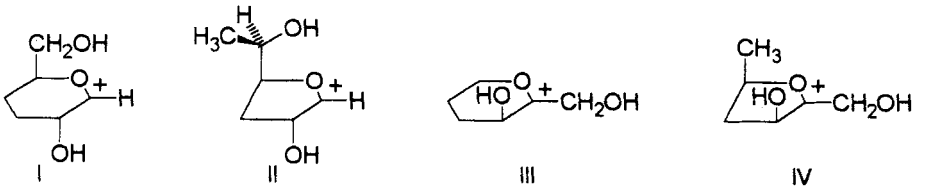
Other monosaccharides. The successful alkylation of fructose encouraged us to attempt the application of solid acid catalyst for the Fischer alkylation of other common monosaccharides. In a number of cases this proved to be possible (see Table 4).

Isolation of the products. We found that long (>C6) chain alkyl β-D-fructopyranosides (**1**) generally could be crystallized selectively from the reaction mixture by the addition of diethyl ether. For example, addition of 4 volumes of diethyl ether to the dodecyl fructoside reaction mixture provided 12% of dodecyl β-D-fructopyranoside, i.e., 72% of the pyranoside present. The octyl, decyl and dodecyl β-D-fructopyranosides were crystallized in this way and could be characterized. These new compounds proved to possess very interesting liquid crystalline properties which will be the subject of a subsequent paper.[10]

Carbohydrate structure and reactivity. The process of alkylation of a saccharide at the anomeric position is conveniently segmented into dissolution, activation and oxyalkylation. Each of the steps involved may become rate-limiting.

The saturation solubility of the saccharide in the reaction medium will have a direct influence on the reaction rate. The *rate* of dissolution from the solid state is difficult to quantify or control, but it will be enhanced by a small particle size.

Protonation of the ring oxygen atom at or near the catalyst surface will result in mutarotation of the crystalline isomer to the equilibrium composition; this process is generally assumed to be fast.[11] Protonation at the anomeric oxygen atom followed by dehydration gives rise to carbenium ion intermediates with the formal charge at the anomeric carbon atom. Secondary carbenium ion intermediates are formed from aldoses, whereas ketoses give rise to the more



(glucopyranoside) (glucofuranoside) (fructopyranoside) (fructofuranoside)

Figure 4. Model structures used in the calculations.

stable tertiary carbenium ions. Hence, ketoses will generally react faster than aldoses.

Pyranosidic and furanosidic oxocarbenium ion species will be present as high-energy intermediates towards pyranoside and furanoside products, respectively. Because mutarotation is fast, their abundance will be determined by their relative energy. The rate of reaction and the initial composition of the product will reflect the stability of these oxocarbenium ions rather than the anomeric composition of the carbohydrate.[11]

More insight in these effects might be obtained from the relative stabilities of the correspondig five- and six-membered ring carbenium ions. Simplified models of these ions (see Figure 4) were calculated using semi-empirical quantum mechanical methods. The fructoside-type carbenium ions III and IV are 15 - 25 $kJ.mol^{-1}$ lower in Gibbs energy than their glucose-type counterparts I and II (see Table 5). Also the furanoside carbenium ions II and IV are more stable than the corresponding pyranoside ions I and III, but the difference is much more pronounced in the case of the fructoside models III and IV. The calculated $O\text{-}C^+$ bond distances are in the range 1.26 - 1.28 Å, which indicates an appreciable double bond character.

The stability of furanoside carbenium ions relative to their pyranoside counterparts explains why Fischer alkylation generally favours furanosidic products kinetically,[11] as is also apparent in the present case.

Oxyalkylation of the oxocarbenium ion intermediate - which is assumed to be adsorbed onto the catalyst surface - by alcohol results in the desired reaction

Table 5. Calculated heat of formation, entropy and Gibbs energy of the model carbenium ions I - IV[a]

Compound $C_6H_{11}O_3^+$	Number of minima	300 K H_f kJ.mol^{-1}	350 K H_f kJ.mol^{-1}	350 K S J.mol^{-1}.K^{-1}	350 K G kJ.mol^{-1}
I	7	232.9	242.6	437.3	89.3
II	8	231.5	240.3	434.0	88.4
III	17	223.1	231.9	448.9	74.8
IV	11	214.5	223.5	457.4	63.4

a. Calculations were performed using the MOPAC 6.0 program, see Experimental.

product. Protonation and ring opening similar to the mutarotation of the parent carbohydrate causes the observed drift of the product composition towards the more stable isomer, this will generally be a pyranosidic one. Reaction of the cationic intermediate with a second monosaccharide (or derivative) will lead to anhydro (oligo) saccharides; the poor solubility of these latter products will effect their deposition on the catalyst resulting in its deactiviation. This process is enhanced by the reversibility of the oxyalkylation step and it is partly suppressed by a large excess of alcohol (cf. Figure 3).

The aldopentoses ribose, arabinose and xylose all three reacted readily under the usual reaction conditions, whereas the aldohexoses mannose, galactose and glucose were relatively unreactive. Sorbose, the other ketohexose tested for activity, showed a moderate conversion. The lower reactivity of sorbose compared with fructose is in line with its solubility, which is 50 % of that of fructose. When comparing the ketohexoses with the aldohexoses, a much lower reactivity is found for the latter as would be expected considering the stability of the corresponding model carbenium ions.

When comparing the results obtained with aldohexoses and -pentoses it appears that the latter compounds perform much better than expected, even considering their solubility, whilst the structure of their respective pyranoside

cationic intermediates is quite similar. It would seem that the aldopentoses are less sensitive to oligomerization reactions because they have one hydroxyl function less than the hexoses. For the same reason, products from aldopentoses will more readily desorb from the catalyst which also minimizes oligomerization.

CONCLUSIONS

Silica-alumina cracking catalysts are efficient catalysts for the alkylation of D-fructose at the anomeric position. With short chain alcohols quantitative conversions to alkyl fructosides are obtained. With fatty alcohols deposition of fructose and fructose anhydrides on the catalyst surface constitutes a problem. When applying 1-butanol in a first stage, recirculation of deposited material and catalyst is possible leading to a high yield method. Pure alkyl β-D-fructopyranosides can be separated from the reaction mixture by crystallisation.

Using the same method, the aldopentoses ribose, arabinose and xylose are efficiently converted into their glycosides. The differences in reactivity between keto- and aldohexoses can be traced back to the stability of the respective intermediate oxocarbenium ions.

EXPERIMENTAL

Catalysts and Chemicals. The silica-alumina cracking catalysts were donated by Akzo Nobel. The specifications are given in Table 6.

D-Fructose, D-mannose and D-xylose were purchased from Merck. D-Galactose, D-ribose, D-arabinose and L-sorbose were procured from Janssen and D-glucose from J.T. Baker Chemicals. Methanol, ethanol and 1-decanol were purchased from Janssen, 1-butanol and 1-octanol from J.T. Baker Chemicals and 1-dodecanol from Merck. Tonsil; standard FF (1989), was donated by Südchemie AG.

Table 6. Catalyst Specifications

Catalyst	Al_2O_3 (wt %)	SiO_2 (wt %)	Na_2O (wt %)	SO_4 (wt %)	Fe (wt %)	Surface area (m^2/g)	Pore volume (mL/g)
HA-HPV[a]	25.0	balance	0.01	1.0	0.03	540	0.87
HA-SHPV[b]	24.2	balance	0.045	0.68	0.04	473	1.31
LA-SHPV[c]	12.0	balance	0.08	1.0	0.02	539	1.34

a. HA-HPV; high alumina, high pore volume.
b. HA-SHPV; high alumina, super high pore volume.
c. LA-SHPV; low alumina super high pore volume.

Semi-empirical Quantum Chemical Calculations were done using the MOPAC 6.0 program[12] with the PM3 Hamiltonian.[13] All combinations of staggered geometries of the side chains were used as initial geometries. The furanose rings are almost flat. Five ring atoms of the pyranose rings lie almost in the same plane, carbon atom 4 is above or below this plane. Both series of initial conformations were searched in these cases. The number of energy minima found for each carbenium ion is given in Table 5. All minima were optimized to a gradient norm of 0.01 or less and are characterized by six eigen values of the final force constants matrix with a corresponding vibration wave number of less than $|10|$ cm^{-1} and no negative eigen values beyond this value. Heats of formation are relative to the elements in the standard state at 298.15 K. No vibrations were excluded in the calculations of the entropies and the corrections of the heats of formation to 350 K. Archive files of the geometries can be obtained upon request.

Analysis. HPLC analysis was carried out on a system equipped with a Waters M45 pump, a Millipore-Waters 8 × 100 mm 4 μ Nova-Pak C18 cartridge contained in a Millipore-Waters 8×10 Radial Compression unit, a Shodex RI SE-61 refractive index detector and Shimadzu SPD-6A UV-detector (220 nm). In the case of methyl and ethyl fructosides water at 1.0 mL/min was used as the eluent. For octyl, decyl and dodecyl fructosides methanol-water mixtures (70:30,

80:20 and 90:10 v/v, respectively) at 1.0 mL/min were used as eluent. Peaks were integrated using a Spectra-Physics SP 4270 integrator.

Preparative scale HPLC was performed using a Millipore-Waters Prep LC 500 instrument equipped with two 50 x 300 mm reverse-phase cartridges (Millipore-Waters PrepPak LC 500-C18). The flow of the mobile phase was 25-100 mL/min.

GC analysis was performed on a Hewlett-Packard 5890 Series II gas chromatograph equipped with a 7673 auto injector and a Chrompack 25 m × 0.32 mm CP-Sil 5 CB, 0.12 μ column. Peaks were detected using FID and were integrated on a HP 3396A integrator. Samples were derivatized by reaction with a stock solution consisting of pyridine (104 mL), *N*,*N*-bis(trimethylsilyl)-trifluoroacetamide (26 mL), and trimethylsilyl chloride (13 mL).

NMR spectra were recorded using a 400 MHz Varian-VXR 400S spectrometer.

Reaction of Fructose with 1-Dodecanol. D-Fructose (3 g, 16.7 mmol) and 1-dodecanol (49.6 g, 266.7 mmol) were brought into a round bottom flask. The mixture was heated in 15 min to a temperature of 70 °C at a pressure of 15 mmHg. Subsequently silica-alumina cracking catalyst (Ketjencat HA-HPV, 3 g, activated by heating at 430 °C for 24 h) was introduced and the mixture was again brought to 70 °C at 15 mm Hg. Periodically samples were taken which were analyzed by HPLC and GC. After 24 h the reaction was stopped and the reaction mixture was filtered over a glas filter and the residue washed with diethyl ether. The filtrate was diluted with 200 mL diethyl ether and cooled to -8 °C upon which the dodecyl β-D-fructopyranoside precipitated. The crude pyranoside was filtered and recrystallized from ethyl acetate (yield 0.72 g, 12%; this corresponds to 72% of the pyranoside present in the reaction mixture), $[\alpha]_D$ -82.5° (*c* 1.0, ethanol). ^{13}C NMR ($CDCl_3$) δ 14.04 (CH_3), 22.62 (CH_2), 26.27 (CH_2), 29.28 (CH_2), 29.49 (CH_2), 29.58 (4×CH_2), 30.03 (CH_2), 31.87 (CH_2), 61.04 (Cα), 63.45 (C-1), 63.78 (C-6), 69.44 (C-5), 70.75, 71.30 (C-3, C-4), 99.77 (C-2).

Anal. Calcd for $C_{18}H_{36}O_6$ (348.47): C, 62.04; H, 10.41; O, 27.55. Found: C, 62.00; H, 10.48; O, 27.5.

Isolation of Dodecyl Fructofuranosides. Following the above reaction procedure, after 24 h 49.2 g of the reaction mixture was diluted with 500 mL of dichloromethane. This solution was brought onto a silica gel column and subsequently dichloromethane was continuously passed through the column, the dichloromethane was refluxed and fed back to the top of the column. After 30 h, when it appeared that no more alcohol eluted, the column was flushed with methanol and a solution of dodecyl fructosides in methanol was obtained. The methanol was evaporated and a mixture of dodecyl fructosides (2.62 g, 45%) was obtained; composition 46% dodecyl α-D-fructofuranoside, 20% dodecyl β-D-fructofuranoside, 34% dodecyl β-D-fructopyranoside. (Depending on the reaction temperature and the activation temperature of the catalyst this composition shifted to 35% α-furanoside, 15% β-furanoside, 50% β-pyranoside at prolonged reaction times). The furanosides present were isolated by preparative HPLC using methanol-water (80:20, v/v) as eluent, and characterized by ^{13}C NMR.

Dodecyl α-D-Fructofuranoside. ^{13}C NMR ($CDCl_3$) δ 14.13 (CH_3), 22.71 (CH_2), 26.16 (CH_2), 29.39 (CH_2), 29.50 (CH_2), 29.68 (4×CH_2), 30.14 (CH_2), 31.94 (CH_2), 60.49 (Cα), 60.79, 61.77 (C-1, C-6), 76.79, 81.44, 83.34 (C-3, C-4, C-5), 107.88 (C-2).

Dodecyl β-D-Fructofuranoside. ^{13}C NMR (D_2O) δ 14.74 (CH_3), 23.54 (CH_2), 27.06 (CH_2), 29.92 (CH_2), 30.11 (CH_2), 30.30 (CH_2), 30.50 (CH_2), 30.70 (2×CH_2), 30.89 (CH_2), 32.87 (CH_2), 61.31 (Cα), 62.42, 64.57 (C-1, C-6), 76.93, 77.65, 82.52 (C-3, C-4, C-5), 104.87 (C-2).

Methyl and Ethyl Fructosides. D-Fructose (3 g, 16.7 mmol) and alcohol (50 mL) were brought into a round-bottomed flask which was connected to a Soxhlet apparatus. The mixture was brought to a reflux. After 5 min silica-alumina cracking catalyst (Ketjencat HA-HPV, 3 g, activated for 24 h at 430 °C) was added. The water formed during the reaction was absorbed by zeolite KA (pore size 3 Å) which was contained in the Soxhlet apparatus. After 24 h for the reaction with methanol, and 4.5 h for the reaction with ethanol, respectively, the reaction was stopped, the reaction mixture was filtered and the catalyst washed with methanol. The alcohol was removed by evaporation *in vacuo* and

the residue was dried at 50 °C *in vacuo*. Methyl fructosides (3.2 g, 100%) consisting mainly of the two furanosides and ethyl fructosides (3.5 g, 100%) were obtained in this way. ^{13}C NMR data of the methyl fructoside mixture were in agreement with those reported in the literature,[14] ^{13}C NMR data of the ethyl fructoside mixture are, except for the alkyl part, virtually identical with those of the butyl fructoside mixture (see below).

Butyl Fructosides. D-Fructose (3 g, 16.7 mmol) and 1-butanol (50 mL) were brought into a round-bottomed flask which was connected to a Soxhlet apparatus, in such a way that the reaction could be carried out under vacuum. The mixture was brought to 75 °C at such a pressure that a constant reflux of 1-butanol was obtained. After 5 min silica-alumina cracking catalyst (Ketjencat HA-HPV, 3 g, activated for 24 h at 430 °C) was added. The water formed during the reaction was absorbed by zeolite KA which was contained in the Soxhlet apparatus. After 1.8 h the reaction was stopped, the reaction mixture was filtered and washed with diethyl ether. Concentration of the filtrate *in vacuo* and subsequent drying at 50 °C *in vacuo* afforded the butyl fructosides (3.7 g, 95%). ^{13}C NMR (DMSO-d_6) δ 13.68, 13.79 (3×CH_3), 18.82, 18.97, 31.77, 31.91 (30× CH_2), 59.38, 59.81, 60.19 (3×Cα), 60.19, 60.35, 61.08, 62.91 (C-1, C-6 α-D-fructofuranoside (α-fur), C-1, C-6 β-D-fructofuranoside (β-fur)), 62.02 (C-1 β-D-fructopyranoside (β-pyr)), 63.76 (C-6 β-pyr), 68.95 (C-5 β-pyr), 69.12, 69.34 (C-3, C-4 β-pyr), 75.37, 81.82, (C-3, C-4, C-5 β-fur), 76.56, 81.27, 82.15 (C-3, C-4, C-5 α-fur), 100.06 (C-2 β-pyr), 103.84 (C-2 β-fur), 107.05 (C-2 α-fur).

To the recovered catalyst methanol (150 mL) was added at 60 °C. The solution was filtered and the filtrate was subjected to film-evaporation and vacuum drying at 50 °C. The residue (0.2 g) consisted of unconverted fructose, butyl fructosides and polymerization products deposited onto the catalyst during the reaction.

Recirculation Procedure. Following the above procedure a reaction mixture containing butyl fructosides, 1-butanol and HA-HPV was obtained. 1-Dodecanol (49.6 g) was added and 1-butanol was distilled off under reduced pressure at 75 °C. After 4.5 h a conversion of 64% to dodecyl fructosides was

reached. The reaction was stopped and the reaction mixture was filtered over a glass filter and the residue washed with diethyl ether. 1-Butanol (50 mL) was added to the residue and the mixture was reacted at 75 °C . Analysis by GC showed that mainly butyl fructosides were formed. Work up as above yielded a mixture of mainly butyl fructosides (30%).

Octyl and Decyl Fructosides. D-Fructose (3.0 g, 16.7 mmol) was reacted with, respectively, 1-octanol (34.7 g, 266.7 mmol) or 1-decanol (42.1 g, 266.7 mmol) following the same procedure as for the reaction with 1-dodecanol. After, respectively, 4 h and 5.7 h conversions of 60% (1-octanol) and 51% (1-decanol) were reached. After filtration of the catalyst 400 mL (1-octanol) or 300 mL (1-decanol) of diethyl ether was added and the filtrate was cooled to -8 °C; subsequently crude octyl and decyl fructopyranosides precipitated which were contaminated with some oligomeric products. Recrystallisation from water afforded pure octyl β-D-fructopyranoside, $[\alpha]_D$ -113.0° (*c* 1.0, ethanol), and decyl β-D-fructopyranoside, $[\alpha]_D$ -102.5° (*c* 1.0, ethanol), respectively. The ^{13}C NMR spectra, with exception of the number of methylene groups, were virtually identical to the spectrum of dodecyl β-D-fructopyranoside.

Anal. Calcd for $C_{14}H_{28}O_6$ (292.36): C, 57.51; H, 9.65; O, 32.83. Found: C, 57.17; H, 9.56; O, 32.0.

Anal. Calcd for $C_{16}H_{32}O_6$ (320.42): C, 59.98; H, 10.07; O, 29.95. Found: C, 59.88; H, 9.85; O, 30.28.

Reaction of Other Monosaccharides with 1-Dodecanol. The same procedure was followed as for the reaction of D-fructose with 1-dodecanol; 3.0 grams of monosaccharide (16.7 mmol for L-sorbose, D-glucose, D-galactose; 20 mmol for D-ribose, D-arabinose, D-xylose) were reacted with 1-dodecanol (49.6 g, 267 mmol) in the presence of 3 g HA-HPV catalyst. Reactions were monitored by GC. After 24 h the reaction was stopped and the reaction mixture was filtered over a glass filter. In the cases of sorbose and the C5 monosaccharides, 200 mL of diethyl ether was added to the filtrate. In the cases of sorbose, ribose and arabinose precipitation of product followed. No further optimization was attempted. The isolated products were characterized by ^1H and ^{13}C NMR.

Dodecyl α-L-Sorbopyranoside. $[\alpha]_D$ -52.4° (*c* 1.0, ethanol).^{13}C NMR ($CDCl_3$) δ 14.07 (CH_3), 22.53 (CH_2), 26.09 (CH_2), 29.18 (CH_2), 29.40 (CH_2), 29.47 (4×CH_2), 29.90 (CH_2), 31.75 (CH_2), 60.44 (Cα), 62.83 (C-1), 62.93 (C-6), 70.07 (C-5), 73.70 (C-3), 74.58 (C-4), 99.21 (C-2).

Anal. Calcd for $C_{18}H_{36}O_6$ (348.47): C, 62.04; H, 10.41; O, 27.55. Found: C, 61.55; H, 10.49; O, 27.9.

Dodecyl β-D-Ribofuranoside. $[\alpha]_D$ -38.2° (*c* 1.0, ethanol). ^{13}C NMR (CD_3OD) δ 14.46 (CH_3), 23.76 (CH_2), 27.32 (CH_2), 30.50 (CH_2), 30.59 (CH_2), 30.76 (4×CH_2), 30.81 (CH_2), 33.10 (CH_2), 65.26 (C5), 68.93 (Cα), 72.91 (C-3), 76.35 (C-2), 84.80 (C-4), 108.79 (C-1).

Anal. Calcd for $C_{17}H_{34}O_5$ (318.44): C, 64.12; H, 10.76; O, 25.12. Found: C, 63.67; H, 10.73; O, 25.3.

Dodecyl β-D-Arabinopyranoside. $[\alpha]_D$ -126.8° (*c* 1.0, ethanol). ^{13}C NMR ($CDCl_3$) δ 14.08 (CH_3), 22.58 (CH_2), 26.09 (CH_2), 29.24 (CH_2), 29.36 (CH_2), 29.51 (3×CH_2), 31.81 (CH_2), 62.59 (C-5), 68.19 (Cα), 69.00 (C-2), 69.63 (C-3), 70.23 (C-4), 98.90 (C-1).

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