Table I. Assignments in the Proton-Decoupled Natural-Abundance Carbon-13 Spectra of Some Oligosaccharides[a]

Assignment[b]	Chemical shift[c] Stachyose[d]	Raffinose[e]	Sucrose[f]
F-2	88.9	88.9	89.1
IG-1	94.3		
TG-1	94.6[g]	94.2	
G-1	100.6	100.7	100.7
F-4	111.4	111.4	111.4
F-3	115.8	115.8	116.1
F-5	118.4	118.4	118.6
G-2,3,5	119.8	119.8	120.0
	121.4	121.3	120.4
	121.6	121.6	121.6
TG-5	121.7[g]	121.8[h]	
j	123.0[i]		
	123.1	123.1[i]	123.4
	123.3[i]	123.4	
IG-3,4	123.9		
	124.2		
TG-3	124.3[g]	124.1	
IG-6	126.2		
G-6	126.6	126.5	132.4
F-1,6	130.2	130.2	130.3
	130.8	130.8	131.1
TG-6	131.5[g]	131.5	

[a] Spectra were obtained at 15.08 MHz using the Fourier transform method. [b] F = fructose, IG = inner galactose, TG = terminal galactose, G = glucose. Numbering system is indicated in the structural formulas. Carbons written on the same line could not be assigned on a one-to-one basis. [c] In parts per million upfield from carbon disulfide. Measured with respect to internal dioxane, which was taken as 126.2 ppm. Estimated accuracy ± 0.1 ppm. [d] 0.5 *M* aqueous solution at 65°. [e] 0.6 *M* aqueous solution at 65°. [f] 1 *M* aqueous solution at 36°. [g] Specific assignment based on PRFT spectra. [h] Not a specific assignment. Interchange with a glucose carbon (2, 3, 5) assignment is possible. [i] Two-carbon resonance. [j] This region contains TG-2, TG-4, IG-2, IG-5, and G-4 in stachyose; TG-2, TG-4, and G-4 in raffinose; G-4 in sucrose.

erts. However, their assignments for C-3 and C-4 of the fructofuranose ring in sucrose were reversed, on the basis of the ^{13}C spectrum of melezitose (**4**).[20]

We believe that PRFT spectra will be an extremely useful addition to the existing methods used for assigning ^{13}C resonances, especially when internal motion contributes measurably to $1/T_1$ of some carbons. It should be emphasized that internal reorientation will have a measurable effect on $1/T_1$ only if the correlation times for internal motion are comparable to or shorter than the correlation times for overall reorientation of the molecule.[13]

Acknowledgment. This research was supported by the National Science Foundation (Grant No. GP-17966) and by the donors of the Petroleum Research Fund, administered by the American Chemical Society (Grant No. 4559-AC5).

(19) D. E. Dorman and J. D. Roberts, private communication. We thank the authors for making available a copy of their manuscript in advance of publication.

(20) The methine carbons of the fructofuranose ring in melezitose resonated at 109.6, 111.4, and 119.2 ppm upfield from CS_2, indicating a large downfield shift of the resonance at 116.1 ppm when going from sucrose (Table I) to melezitose. Since alkylation has a deshielding effect on a hydroxylated carbon,[18,19] the resonance at 116.1 ppm in sucrose must be carbon 3 of the fructofuranose ring.

Adam Allerhand,* David Doddrell

Contribution No. 1929, Department of Chemistry Indiana University, Bloomington, Indiana 47401

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Study of Anomeric Equilibria of Ketoses in Water by Natural-Abundance Carbon-13 Fourier Transform Nuclear Magnetic Resonance. D-Fructose and D-Turanose[1,2]

Sir:

Proton nuclear magnetic resonance has been used successfully to study anomeric equilibria of aldoses in aqueous solution[3-5] by observing the relatively isolated downfield resonance of the proton attached to carbon 1 of each anomer.[3,4] Proton nmr has not been used to study anomeric equilibria in reducing ketoses such as fructose and turanose (Figure 1), presumably because

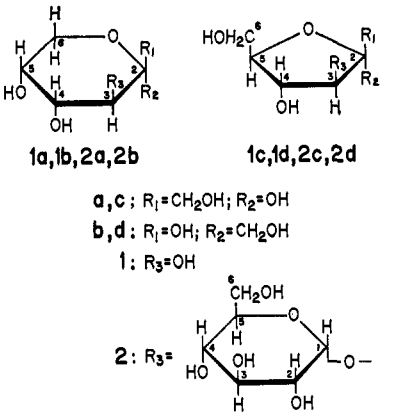

Figure 1. Structures of D-fructose (**1**) and D-turanose (**2**) anomers.

the anomeric carbon is nonprotonated, and thus there are no easily assignable resonances (Figure 2). Proton-decoupled natural-abundance ^{13}C spectra of saccharides are well resolved and much simpler to analyze than the corresponding proton spectra.[2,6-9] Recently, two anomeric forms of fructose have been observed by Dorman and Roberts[9] using continuous-wave carbon-13 nmr. We wish to demonstrate that the enhanced sensitivity of carbon-13 Fourier transform nmr[10] permits the observation of even minor components in anomeric mixtures of saccharides, with sufficient signal-to-noise ratio for quantitative studies. We present some results for D-fructose (**1a–d**) and 3-*O*-(α-D-glucopyranosyl)-D-fructose (turanose, **2a–d**). A spectrum obtained a few minutes after dissolving commercial β-D-fructose[11] in water (Figure 3A) indicated the presence of two components. The equilibrium spectrum (Figure 3B) contained resonances from four components (A, B, C, and D, given in order of decreasing concentration). On the basis of chemical

(1) Carbon-13 Fourier Transform Nuclear Magnetic Resonance, VII.

(2) Part VI: A. Allerhand and D. Doddrell, *J. Amer. Chem. Soc.*, **93**, 2777 (1971).

(3) M. Rudrum and D. F. Shaw, *J. Chem. Soc.*, 52 (1965).

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(7) A. S. Perlin and B. Casu, *Tetrahedron Lett.*, 2921 (1969).

(8) D. E. Dorman and J. D. Roberts, *J. Amer. Chem. Soc.*, **92**, 1355 (1970).

(9) D. E. Dorman and J. D. Roberts, private communication. We are grateful to the authors for a copy of their manuscript in advance of publication.

(10) A. Allerhand, D. W. Cochran, and D. Doddrell, *Proc. Nat. Acad. Sci. U. S.*, **67**, 1093 (1970).

(11) Obtained from Sigma Chemical Company, St. Louis, Mo.

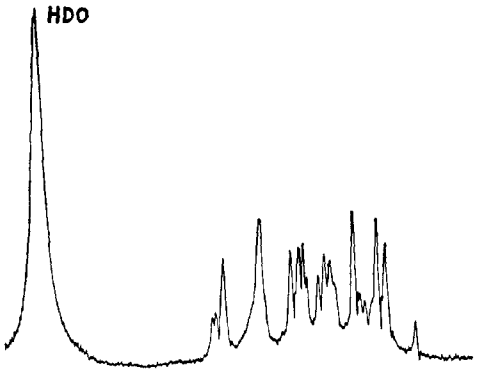

Figure 2. Proton nmr spectrum (100 MHz) of the equilibrium anomeric mixture in 0.5 *M* D-fructose in D_2O at about 30°. A spectral width of 1.46 ppm is shown.

shift information,[8,9] species A and D were identified as α-D-fructopyranose (**1a**) and β-D-fructopyranose (**1b**), but not on a one-to-one basis. Similarly, species B and C were identified as α-D-fructofuranose (**1c**) and β-D-fructofuranose (**1d**), but again not on a one-to-one basis. The predominant species in the "initial" spectrum (Figure 3A) was A, with only a small amount of B being present. This result, together with the fact that the crystalline material is known to be β-D-fructopyranose,[12] was used to identify species A as **1b**. Hence, species D must be **1a**. Specific identification of the two fructofuranose anomers was made by comparing the methine carbon chemical shifts of species B and C (in the range 110–119 ppm upfield from CS_2) with the corresponding chemical shifts in sucrose (β-D-fructofuranosyl α-D-glucopyranoside).[2,9] On this basis, species B had to be **1d**. It should be noted that twenty peaks were observed in the proton-decoupled ^{13}C spectrum of aqueous D-fructose at equilibrium, even though the resonance frequency was only 15.08 MHz. The nonprotonated carbon of **1a** was not observed, either because of a very low intensity or because of overlap with another nonprotonated resonance.

Measurement of integrated and peak intensities yielded the following equilibrium composition at 36°: 3 ± 1% **1a**, 57 ± 6% **1b**, 9 ± 1% **1c**, and 31 ± 3% **1d**. As far as we know, this is the first report of the detailed composition of D-fructose in aqueous solution. Our results indicate that the total amount of the furanose forms at equilibrium is about 40%, which is comparable to reported estimates[13] at 25°. In addition, our results confirm that the mutarotation of aqueous fructose is caused mainly by a pyranose–furanose interconversion[13,14] and not by an α–β anomerization. After the resonances of fructose were allocated to individual anomers, specific assignments (Table I) were made on the basis of previously assigned ^{13}C resonances of other saccharides.[2,8,9]

Three species were detected in the ^{13}C spectrum of the equilibrium anomeric mixture in aqueous D-turanose[11] (Figure 3C). Comparison with the chemical shifts of the fructose anomers identified these three species as 3-*O*-(α-D-glucopyranosyl)-β-D-fructopyranose (**2b**), 3-*O*-(α-D-glucopyranosyl)-α-D-fructofuranose (**2c**), and 3-*O*-(α-D-glucopyranosyl)-β-D-fructofuranose (**2d**).

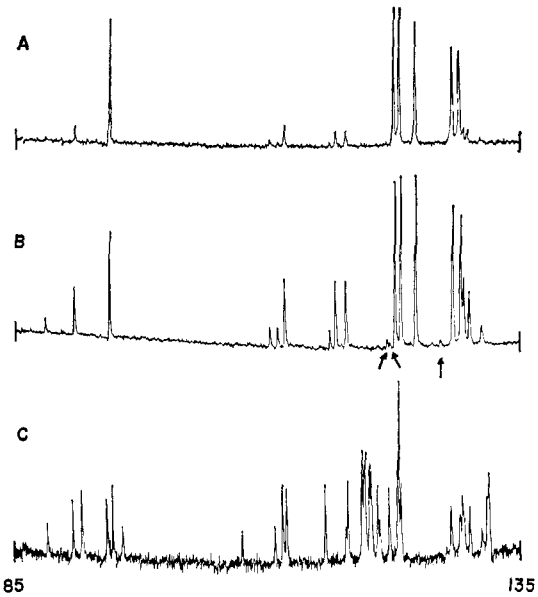

Figure 3. Proton-decoupled natural-abundance carbon-13 nmr spectra of **1** and **2** at 36°, obtained at 15.08 MHz by the Fourier transform method, with 4096 points in the time domain and 62.5-ppm sweep widths. Horizontal scale is in parts per million upfield from carbon disulfide: (A) spectrum of 3.7 *M* aqueous D-fructose at pH 5, recorded immediately after dissolving the crystalline material, using 128 scans with a recycle time of 2.72 sec (total time 5.8 min); (B) equilibrium spectrum of the above solution, obtained 22 hr later, using 512 scans with a recycle time of 2.72 sec (total time 23.2 min) (weak but reproducible resonances of **1a** are indicated by arrows); (C) equilibrium spectrum of 1 *M* aqueous D-turanose at pH 5, obtained using 285 scans with a recycle time of 2.72 sec (total time 12.9 min).

Table I. Assignments in the Proton-Decoupled Natural-Abundance Carbon-13 Spectra of D-Fructose and D-Turanose[a]

Assignment[b]	Chemical shift[c] Fructose[d]	Chemical shift[c] Turanose[e]
c-2	88.3	88.5
d-2	91.2	91.1
b-2	94.7	95.0
c-3	110.6	107.9
c-4	111.4	111.2
d-4	112.1	111.9
d-3	117.1	112.4
c-5	116.6	118.2
d-5	118.1	118.4
a-3	122.2	*f*
a-4	122.6	*f*
b-3	123.0	116.1
b-4	123.6	*f*
b-5	125.0	*f*
a-1,6[g]	127.6	*f*
b-1	128.7	128.6
b-6	129.4	129.5
d-1	129.7	129.8
d-6	130.3	130.4
c-1,6[g]	131.5	131.7

[a] Spectra were obtained at 15.08 MHz and 36° using the Fourier transform method. Chemical shift values connected by braces indicate resonances that could not be assigned on a one-to-one basis. [b] Letters designate the anomers, as in Figure 1. Numbers refer to carbon sites on the fructose ring. The glucopyranose carbons of turanose were not assigned. [c] In parts per million upfield from carbon disulfide. Measured with respect to internal dioxane, which was taken as 126.2 ppm. Estimated accuracy ±0.1 ppm. [d] 3.7 *M* aqueous solution at pH 5. [e] 1 *M* aqueous solution at pH 5. [f] Not detected. [g] Carbon 1 and/or carbon 6.

(12) L. M. J. Verstraeten, *Advan. Carbohyd. Chem.*, 22, 229 (1967).
(13) F. Gronlund and B. Andersen, *Acta Chem. Scand.*, 20, 2663 (1966).
(14) H. S. Isbell and W. W. Pigman, *J. Res. Nat. Bur. Stand.*, 20, 773 (1938).

No signals arising from the α-fructopyranose anomer (**2a**) were detected. Peak intensities yielded the following composition: 39 ± 4% **2b**, 20 ± 2% **2c**, 41 ± 4% **2d**, and less than 4% **2a**. We were not able to accumulate a spectrum quickly enough to observe a composition far removed from equilibrium. Specific assignments of the fructose resonances were made on the basis of the D-fructose chemical shifts (Table I). The fructose nonprotonated resonances of all the anomers fall in the same spectral region as the methine carbon at position 1 of the glucopyranose ring. The methine resonances were distinguished from the nonprotonated ones by means of partially relaxed Fourier transform spectra.[2] It is interesting that a separate glucopyranose C-1 resonance was observed for each anomer.[15] There was also evidence for chemical shift differences between the anomers at other glucopyranose positions. Thirty-one resonances were identified in the spectrum of aqueous D-turanose!

Carbon-13 Fourier transform nmr has a very promising future in detailed studies of anomeric processes in saccharide solutions.

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(15) Chemical shifts of 92.0, 94.5, and 96.0 ppm upfield from carbon disulfide.

David Doddrell, Adam Allerhand*
Contribution No. 1931, Department of Chemistry
Indiana University, Bloomington, Indiana 47401
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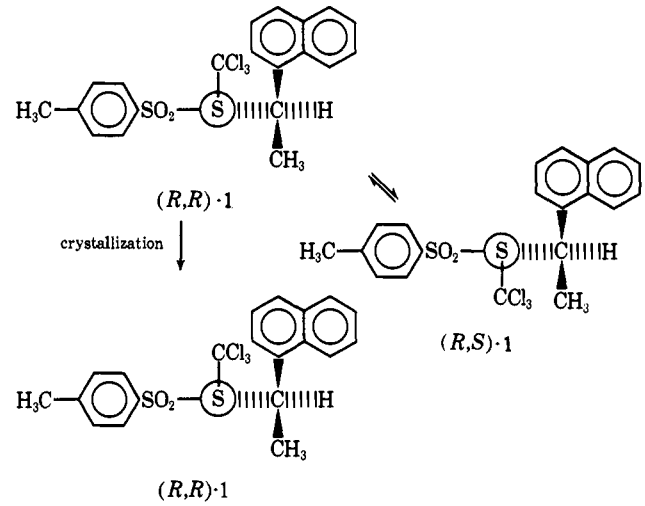
The Sulfenamide Chiral Axis. Nuclear Magnetic Resonance, Optical Rotatory Dispersion, and Circular Dichroism Spectra[1a,b]

Sir:

Nmr experiments have demonstrated that the sulfenamide grouping, $R_1SNR_2R_3$, is dissymmetric, and that the axial chirality of this moiety derives from restricted rotation about the N–S bond rather than slow inversion of the nitrogen pyramid.[2,3] Optical activity in compounds containing this chiral unit has not yet been reported. This communication describes the nmr, ORD, and CD spectra of a sulfenamide, the absolute configuration of which has been determined using single-crystal X-ray diffraction.[4] Correlation of the configuration in the solid state with that in solution was made using nmr spectroscopy.

Since the sulfenyl S–N bond is conformationally labile, with a free energy of activation for racemization of only 12–19 kcal/mol,[2,3] resolution of a racemic modification was not practical. However, asymmetry could be induced into the sulfenamide chiral axis from an asymmetric carbon atom in an equilibrium asymmetric induction[5] which occurs when both chiral units are present in the same molecule.

Accordingly, we chose for this study a compound which possesses an asymmetric carbon atom in addition to the sulfenamide unit, *N*-(1-α-naphthylethyl)-*N*-benzenesulfonyltrichloromethanesulfenamide (**1**). As two chiral units are present, diastereomerism is possible. Since **1** was prepared from the benzenesulfonamide of



optically pure (*R*)-(+)-1-(1-naphthyl)ethylamine,[6] the configuration at the asymmetric carbon atom is determined and must be (*R*). The two diastereomers thus have the (*R*,*R*) and (*R*,*S*) absolute configurations,[7] *i.e.*, they are epimeric at the chiral axis. The configurations of the two isomers are represented in Newman–Fischer projection formulas (*R*,*R*)-**1** and (*R*,*S*)-**1**.

This diastereomerism is reflected in the room temperature nmr spectrum of **1** in methylene chloride, especially in the region of the C-methyl resonances, which appear as two unequal doublets centered at δ 1.72 (J = 7 Hz) and 2.06 (J = 7 Hz) corresponding to a ratio of diastereomers of 1.85:1.0 (Figure 1). A similar situation obtains in acetonitrile-d_3 solution; the two doublets resonate at δ 1.54 and 2.01, and the equilibrium constant is 2.0:1.0. Thus equilibrium asymmetric induction results in a ratio of torsional epimers which differs from unity.

The configuration of the major (upfield) isomer was shown to be (*R*,*R*) in the following manner. Crystallization of **1** is accompanied by second-order asymmetric transformation and the solid material is composed of a single diastereomer[8] which has been shown by single-crystal X-ray diffraction analysis to have the absolute (*R*,*R*) configuration.[4] Interconversion of the diastereomers is rapid on the nmr time scale, since the torsional barrier of the N–S bond has a magnitude of only *ca.* 18.0 kcal/mol ($\Delta\nu$ = 20.5 Hz, T_c = 78°). On

(1) (a) XII. Stereochemistry at Trivalent Nitrogen. Part XI: M. Raban and F. B. Jones, Jr., *J. Amer. Chem. Soc.*, **93**, 2692 (1971). (b) Abstracted from the M.S. Thesis of S. K. Lauderback, Wayne State University, 1970.

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(5) M. Carmack and L. A. Neubert, *ibid.*, **89**, 7134 (1967).

(6) M. G. Drew, *Acta Crystallogr., Sect. B*, **25**, 1320 (1969); J. Jacobus, M. Raban, and K. Mislow, *J. Org. Chem.*, **33**, 1142 (1968).

(7) We have arbitrarily chosen the first designation as referring to the asymmetric carbon atom and the second to the sulfenyl chiral axis. In applying the Cahn–Ingold–Prelog convention for chiral axes to the sulfenamide bond it is necessary to use the ligancy complementation rule to generate an additional "phantom" ligand of zero atomic weight attached to sulfur on the side opposite to the trichloromethyl group. The order of priority of the ligands is CCl_3 > phantom > $C_6H_5SO_2$ > $C_{12}H_{11}$.

(8) M. Raban, G. W. J. Kenney, Jr., J. M. Moldowan, and F. B. Jones, Jr., *J. Amer. Chem. Soc.*, **90**, 2985 (1968).