Giant strain geared to transformable H-bonded network in compressed β-D-mannose†

Ewa Patyk, Anna Jenczak and Andrzej Katrusiak*

Networks of OH···O bonds in sugars and H2O ices are hardly affected by temperature, but transform under pressure. Such a transition at 1.95 GPa in β-D-mannose induces strong strain, non-destructive for the single crystal and easily visible in its shape deformation. This transition occurs at the lowest pressure of all sugars investigated at high pressure so far. The giant strain propagates perpendicular to the clearly visible zero-strain planes. The transition reconstructs the 3-dimensional pattern of OH···O hydrogen bonds, changes the conformation of molecules and preserves the space-group symmetry, like the analogous transitions of α-D-glucose and D-sucrose. However, new repulsing O···O contacts have been generated at high pressure in D-mannose only.

Introduction

Hydrogen bonds and their transformations are immanent parts of biological systems and life processes at the molecular level.¹,² Equally important are hydrogen bonds for geology and properties of rocks, as the minerals in Earth’s crust contain more water than all seas and oceans.³,⁴ The immense pressure in the deep-crust deposits strongly distorts the structure of minerals and most of all their softest interactions, including the hydrogen bonds.⁵,⁶ Therefore, an understanding of the pressure effects on the hydrogen bonds is important. This information about H-bond transformations is also essential for designing new functional materials,⁷ such as ferroelectrics and relaxors⁸–¹⁰ for electronic applications, as well as for obtaining new polymorphs of pharmaceutical active ingredients.¹¹–¹⁴ It was shown recently that pressure significantly modifies the 3-dimensional OH···O bond motifs of ν-sucrose and α-D-glucose.¹⁵,¹⁶ In this respect sugars resemble the structures of H2O ices, similarly governed by OH···O bonds building the frameworks, hardly affected by temperature, but efficiently destabilized by pressure.¹⁷–²⁰ However, in contrast to H2O ices, it is characteristic that high-pressure transitions of ν-sucrose, at 4.8 GPa, and α-D-glucose, at 5.4 GPa, preserve their space-group symmetry and lattice translations, an occurrence encountered at high pressure for quite a few compounds.²¹–²⁵ Presently, we found that a much lower pressure induces an exceptionally strong transformation between Phases I and II of β-D-mannose. Such major microscopic changes may lead to notable macroscopic effects.²⁶,²⁷ The giant strain in the transforming β-mannose crystal is clearly visible under the microscope (Fig. 1).

Fig. 1. Single crystal of β-β-mannose in Phase I (a); transformation (b and c) to the single crystal of Phase II (d), shown in 4 clips from Movie S1 (ESI† see also Movies S2–S4 showing the transformation of other samples). The size changes between Phases I and II along the crystal directions [x] and [y] are marked in red and green, respectively. The crystal axes and Miller indices of selected faces are indicated in plate (a). Angle φ, between the direction of zero strain and the x axis calculated according to eqn (1) in the text, is marked in plate (c). Small ruby chips for pressure calibration are scattered in the DAC chamber.
Metabolized β-D-mannose is incorporated into glycolipids and glycoproteins, so its role is mainly structural. Moreover, it exhibits antibacterial and antiviral properties, hence, it is used to treat and prevent recurrent urinary tract infections. Owing to its different codes of H-donor and H-acceptor functions, D-mannose can form intermolecular hydrogen bonds, convertible conformation and intermolecular interactions, adjusting to various environments. The structure of the β-anomer of D-mannose crystals, despite its diverse applications, has remained unknown until now.

Experimental

A single crystal of β-D-mannose (analytical grade; from VEB Berlin-Chemie) was installed in a modified Merrill-Bassett diamond-anvil cell (DAC). The gasket was made of 0.3 mm tungsten foil with a spark-eroded hole, 0.3–0.4 mm in diameter. The sample position in the DAC chamber was fixed with a few cellulose fibers or a small amount of glue. Ethanol solution saturated with D-mannose, fluorinert or an ethanol–water mixture was used as hydrostatic medium. Pressure inside the DAC was measured according to the ruby fluorescence method using an enhanced Photon Control Inc. spectrometer, affording an accuracy of 0.02 GPa. Diffraction data were collected at 0.48, 1.00, 1.60, 1.90, 2.02, 2.10 and 2.35 GPa (Fig. S1, ESI†) on a four-circle KUMA KM4-CCD X-ray diffractometer using graphite monochromated MoKα radiation, and at 2.85 GPa using a 4-cycle Xcalibur diffractometer equipped with the EOS CCD detector and an AgKα radiation source. The crystal and DAC centering were performed according to the methods described previously. Low-temperature data (150–295 K range; Fig. S2, ESI†) were measured using a 4-circle SuperNova diffractometer, CuKα radiation, and an Oxford Cryosystems attachment. For data collection, UB-matrix determination, absorption correction and data reduction, the program CrysAlisPro was used. The crystal structures were solved by direct methods using SHELXS and refined with the program SHELXL. Hydrogen atoms were located by molecular geometry with Uiso equal to 1.2Ueq for C-carriers and 1.5Ueq for O-carriers, and with the O–H and C–H bond lengths fixed at the distances of 0.82 Å for oxygen atoms, and 0.98 or 0.97 Å for tertiary and secondary carbon atoms, respectively. To allow the gradual transformation of the sample between the phases and the recording of the visual changes in the β-D-mannose crystal shape (Fig. 1, Movies S1–S4, ESI†), a membrane DXR-GM DAC from Diacell was applied for fine-tuning the pressure through the phase transition.

We found that β-D-mannose is compressed monotonically up to 1.95(2) GPa, when it undergoes a phase transition. It retains the symmetry of the orthorhombic space group P212121 and such phase transitions are described as isostuctural, isomorphistic, and sometimes as isosymmetric. Crystallographic data for β-D-mannose in ambient and high-pressure phases are compared in Table 1 (cf. Tables S1 and S2 in the ESI†). The giant strain between pressure limits of their stability regions and at 2.85 GPa, all at 295 K (cf. Tables S1 and S2 in the ESI†)

![Table 1: Selected structural data for β-D-mannose Phases I and II at the pressure limits of their stability regions and at 2.85 GPa, all at 295 K](https://example.com/table1.png)

The transition abruptly reduces the crystal volume by nearly 4% (Fig. 2). This transition strongly rearranges hydrogen bonds, and sometimes as isosymmetric. The crystallographic data for β-D-mannose in ambient and high-pressure phases are compared in Table 1 (cf. Tables S1 and S2 in the ESI†). The giant strain between pressure limits of their stability regions and at 2.85 GPa, all at 295 K (cf. Tables S1 and S2 in the ESI†)
of these networks exceeds the capabilities of graph descriptors used for the H-bonding patterns. Therefore, we have applied the rigorous ORTEP symmetry codes for precisely describing the H-bonds of one molecule in its nearest vicinity. The symmetry transformations described in superscripts by 4-digit ORTEP codes are explicitly listed in Table S3 (ESI†).

The extent of the transformations in the OH⋯O bonding network is quantitatively illustrated in Fig. 4, where the O⋯O and H⋯O distances of all H-bonds present either in Phase I or II are plotted. The transition considerably changes the distances of intermolecular O⋯O contacts, even by more than 2 Å for the H-bonds O1H⋯O63655 and O3H⋯O44655 formed in Phase II. The shortest of contacts O⋯O and H⋯O are only compressed from 2.70 Å to 2.56 Å and from 1.80 Å to 1.67 Å, respectively. High pressure slightly reduces the C⋯O distances, however the shortest of C⋯O contacts in Phase II are longer than those in Phase I (Fig. S4 in the ESI†). In this respect the shortest OH⋯O and CH⋯O bonds behave differently than in the pressure-transformed sucrose and glucose, where in Phase II the O⋯O distances are somewhat longer and CH⋯O bonds shorter than before the transition in Phase I. However, it is a common feature of the β-mannose, sucrose and glucose structures that the excess of H-acceptor sites (general for sugars) at high pressure is balanced by the formation of bifurcated OH⋯O bonds and new CH⋯O bonds.

The shortest of H⋯H contacts in Phase II is only about 0.3 Å shorter than that in Phase I, and this compression is stronger than that observed for the other types of contacts (Fig. S11, ESI†). All dimensions of intermolecular contacts (Fig. 4 and Fig. S4–S11, ESI†) are consistent with the strong molecular rearrangement and compression of the structure. The reduction of H⋯H distances is consistent with the collapse of the small voids in Phase I. The voids are contained between the molecules arranged in a herringbone pattern in Phase I, while above 1.95 GPa the molecules are nearly parallel along the plane (bc), as can be seen in the structures and their schemes in Fig. 5. To accommodate these molecular rotations, the crystal shrinks along a and expands along b. Moreover, the longest dimension of the molecule between atoms O2 and O6 becomes better aligned along b within the (bc) plane just above the transition, which is consistent with the more pronounced compression of the crystal along c and expansion along b.

The considerable volume collapse at \( P_c \) allows the transition in β-mannose to be induced in gradually increasing portions of the sample crystal by a very slow increase in the volume reduction of the DAC chamber. In principle, if all the sample volume \( V_s \) collapses by \( \Delta V_s \) at \( P_c \), then the reduction of the volume of the DAC chamber by \( \Delta V_p \) from the start of the transition does not increase the pressure in the DAC until the entire sample has
transformed (Fig. 2a). This feature illustrates the possible applications of such materials for shock-absorbing or stress-compensating devices, but it also allows observations of the transition front propagating through the sample (Fig. 1).

It is remarkable that the giant strain in the β-D-mannose crystal does not break the sample. This infers that the transition front proceeds along the planes that minimize the local strain. It can be seen in Fig. 1 that the transition fronts only approximately progress along crystal planes (±1 ±1 0). For the crystal exhibiting negative linear compressibility, such as β-mannose, there are directions of zero strain and these directions can be calculated from the strain tensor between Phases I and II at \( P_c \). For the transition in β-mannose the strongest strain is generated within the \((ab)\) plane, due to the strongest positive and negative linear compression of the crystal along \( a \) and \( b \), respectively, (Fig. 1). Owing to the coexistence of positive and negative linear compression within the \((ab)\) plane, there are directions of zero strain along the planes parallel to \( c \) and inclined to axis \( a \) by angle \( \phi \)

\[
\phi = \pm \arctan \left[ \left(1 - a^2/b^2\right)/(b^2/a^2 - 1) \right]^{1/2},
\]

where indices in unit-cell dimensions \( a_1, b_1, a_2 \) and \( b_2 \) refer to Phases I and II, respectively. For the zero-strain transition fronts parallel to the \( c \) axis, the \( \phi \) angle calculated in this way is 43.83°, in accordance with the microscopic visual observations (cf. Fig. 1 and Movies S1–S4 in the ESI†).

Conclusions

The high-pressure effects in β-D-mannose strikingly resemble those in D-sucrose and α-D-glucose. In all these systems, crystals transform with no space-group symmetry change, when the OH···O bonding network reconstructs to a tighter version, with more bifurcated OH···O bonds and more CH···O bonds compensating for the insufficient number of hydroxyl donors. The transition in β-D-mannose, occurring at considerably lower pressure than those in D-sucrose and α-D-glucose, induces a giant anomalous strain, which is coupled to the molecular rearrangement. It appears that the sophisticated geometric code of H-donors and H-acceptors in sugars controls the monotonic and discontinuous strain in the compressed crystals. The experimental measurements of crystal compression are presently available for three sugars only, however it is already an intriguing result that each of these sugars undergoes only one isostructural phase transition in the high-pressure range, where several phase transitions occur for the H\(_2\)O ices, built of considerably simpler and more symmetric (C\(_{2v}\)) molecules. It shows that the small H\(_2\)O molecules cannot control the crystal symmetry and directions of crystal transformations in such a precise and unique way as the much more complex molecules of sugars. This conclusion
is partly supported by the relatively scarce occurrence of polymorphs in sugars, reported—aside from the high-pressure transformations in α-α-glucose, β-α-mannose, and γ-sucrose—for γ-ribose,39 β-α-galactose,52,53 α,α-trehalose54,55 and cellulose.56

Clearly, further studies are needed for the better understanding of external-stimuli effects and functional responses of H-bonded networks, which will ultimately allow their rational control and applications.

Acknowledgements

We are grateful to Ms Michalina Aniola and Wielkopolska Center of Advanced Technologies for the experimental support, as well as to Mr Michal Andrzejewski and Mr Michał Kazmierczak for their assistance in recording and editing movies included in the ESL."}

Notes and references

1 G. A. Jeffrey and W. Saenger, Hydrogen Bonding in Biological Structures, Springer, Berlin, Heidelberg, 1994, ch. 1, pp. 3–14, ch. 19, pp. 351–393.
2 G. R. Desiraju and T. Steiner, The Weak Hydrogen Bond: In Structural Chemistry and Biology, Oxford University Press, Oxford, 2001, ch. 5, pp. 343–440.
3 B. Schmandt, S. D. Jacobsen, T. W. Becker, Z. Liu and K. G. Duck, Science, 2014, 344, 1265.
4 D. G. Pearson, F. E. Brencher, F. Nestola, J. Neenell, L. Nasdala, M. T. Hutchinson, S. M. Ve, K. Mather, G. Silversmit, S. Schmitz, B. Vekemans and L. Vinze, Nature, 2014, 507, 221.
5 N. Noguchi, T. Moriwaki, Y. Ikemoto and K. Shinoda, Am. Mineral., 2012, 97, 134.
6 P. F. Zanazzi, M. Montagnoli, S. Nazzareni and P. Comodi, Am. Mineral., 2007, 92, 655.
7 G. Resnati, E. Boldyreva, P. Bombicz and M. Kawano, IUCrJ, 2015, 2, 675.
8 L. Kong, L. Wang, S. Zhang, O. Tschauner, Y. Zhao, W. Yang, H. Liu and H.-K. Mao, Appl. Phys. Lett., 2012, 101, 062904.
9 T. Aoyama, K. Yamauchi, A. Iyama, S. Picozzi, K. Shimizu and T. Kimura, Nat. Commun., 2014, 5, 4927.
10 M. Szafranski, CrystEngComm, 2014, 16, 6250.
11 F. P. A. Fabbiani, G. Buth, D. C. Levendis and A. J. Cruz-Cabeza, Chem. Commun., 2014, 50, 1817.
12 F. P. A. Fabbiani, D. R. Allan, W. I. F. David, A. J. Davidson, A. R. Lennie, S. Parsons, C. R. Pulham and J. E. Warren, Cryst. Growth Des., 2007, 7, 1115.
13 M. A. Neumann, J. van de Streek, F. P. A. Fabbiani, P. Hidber and O. Grassmann, Nat. Commun., 2015, 6, 7793.
14 E. V. Boldyreva, T. P. Shahktsheiner, H. Ahsbhs, H. Sowa and H. Uchtmann, J. Therm. Anal. Calorim., 2002, 68, 437.
15 E. Patyk, J. Skumiel, M. Podsiadlo and A. Katrusiak, Angew. Chem., Int. Ed., 2012, 51, 2146.
16 E. Patyk and A. Katrusiak, Chem. Sci., 2015, 6, 1991.
17 G. G. Salzmann, P. G. Radaelli, B. Slater and J. L. Finney, Phys. Chem. Chem. Phys., 2011, 13, 18468.
18 B. Kamb and B. L. Davis, Proc. Natl. Acad. Sci. U. S. A., 1964, 52, 1433.
19 J. D. Londono, W. F. Kuhs and J. L. Finney, J. Chem. Phys., 1993, 98, 4878.
20 R. J. Hemley, A. P. Jephcoat, H. K. Mao, C. S. Zha, L. W. Finger and D. E. Cox, Nature, 1987, 330, 737.
21 A. Jayaraman, Phys. Rev., 1965, 137, A179; K. Gesi, Phase Transitions, 1992, 40, 187; A. G. Christy, Acta Crystallogr., Sect. B: Struct. Sci., 1995, 51, 753.
22 W. Cai and A. Katrusiak, Nat. Commun., 2014, 5, 4337.
23 D. Paliwoda, K. Kowalska, M. Hanfland and A. Katrusiak, J. Phys. Chem. Lett., 2013, 4, 4032.
24 J. Zhao, L. Wang, D. Dong, Z. Liu, H. Liu, G. Chen, D. Wu, J. Luo, N. Wang, Y. Yu, C. Jin and Q. Guo, J. Am. Chem. Soc., 2008, 130, 13828.
25 S. V. Goryainov, E. V. Boldyreva, M. B. Smirnov, H. Ahsbhs, V. V. Chernyshev and H.-P. Weber, Dokl. Phys. Chem., 2003, 390, 154.
26 Z. Skoko, S. Zamir, P. Naumov and J. Bernstein, J. Am. Chem. Soc., 2010, 132, 14191.
27 M. Lusi and J. Bernstein, Chem. Commun., 2013, 49, 9293.
28 R. H. Herman, Am. J. Clin. Nutr., 1971, 24, 488.
29 B. Kranjec, D. Papeš and S. Altarac, World J. Urol., 2014, 32, 79.
30 D. Porru, A. Parmigiani, C. Tinelli, D. Barletta, D. Choussos, C. Di Franco, V. Bobbi, S. Bassi, O. Miller, B. Gardella, R. E. Nappi, A. Spillino and B. Rovereto, J. Clin. Urol., 2014, 7, 208.
31 S. Vanwetswinkel, A. N. Volkov, Y. G. J. Sterckx, A. Garcia-Pino, L. Buts, W. F. Franken, J. Bouckaert, R. Roy, L. Wynn and N. A. J. Van Nuland, J. Med. Chem., 2014, 57, 1416.
32 E. I. Mondo, Sugars That Heal: The New Healing Science of Glyconutrients, Random House Publishing Group, New York, 2008, ch. 2, pp. 20–37.
33 K. H. Nam, M. W. Sung and K. Y. Hwang, Biochem. Biophys. Res. Commun., 2010, 391, 1131.
34 T. Tomášíc, S. Rabbani, M. Gobec, I. M. Raščan, Č. Podlipnik, B. Ernst and M. Anderluh, MedChemComm, 2014, 5, 1247.
35 J. F. Nagle, M. Mille and H. J. Morowitz, J. Chem. Phys., 1980, 72, 3959.
36 L. Merrill and W. A. Bassett, Rev. Sci. Instrum., 1974, 45, 290–294.
37 H. K. Mao, J. Xu and P. M. Bell, J. Geophys. Res.: Solid Earth, 1986, 91, 4673.
38 A. Budzianowski and A. Katrusiak, in High-Pressure Crystallography, ed. A. Katrusiak and P. McMillan, Springer, Netherlands, 2004, pp. 101–112.
39 Oxford Diffraction, Oxford Diffraction Ltd., Xcalibur CCD system, CrystAlis Software system, Version 1.171, 2004.
40 G. M. Sheldrick, Acta Crystallogr., Sect. A: Found. Crystallogr., 2008, 64, 112.
41 G. M. Sheldrick, Acta Crystallogr., Sect. C: Struct. Chem., 2015, 71, 3.
42 F. H. Allen and I. J. Bruno, Acta Crystallogr., Sect. B: Struct. Sci., 2010, 66, 380.
43 A. Bondi, J. Phys. Chem., 1964, 68, 441.
44 E. Arunan, G. R. Desiraju, R. A. Klein, J. Sadlej, S. Scheiner, I. Alkorta, D. C. Clary, R. H. Crabtree, J. J. Dannenberg, P. Hobza, H. G. Kjaergaard, A. C. Legon, B. Mennucci and D. J. Nesbitt, Pure Appl. Chem., 2011, 83, 1637.
45 G. A. Jeffrey and S. Takagi, Acc. Chem. Res., 1978, 11, 264.
46 M. C. Etter, J. C. MacDonald and J. Bernstein, Acta Crystallogr., Sect. B: Struct. Sci., 1990, 46, 256.
47 C. K. Johnson, ORTEPII. Report ORNL-5138, TN: Oak Ridge National Laboratory, Memphis, 1976.
48 C. F. Macrae, I. J. Bruno, J. A. Chisholm, P. R. Edgington, P. McCabe, L. Rodriguez-Monge, R. Taylor, J. van de Streek and P. A. Wood, J. Appl. Crystallogr., 2008, 41, 466.
49 D. Šišak, L. B. McCusker, G. Zandomeneghi, B. H. Meier, D. Bläser, R. Boese, W. B. Schweizer, R. Gilmour and J. D. Dunitz, Angew. Chem., Int. Ed., 2010, 49, 4503.
50 L. M. J. Kroon-Batenburg, P. van der Sluis and J. A. Kanters, Acta Crystallogr., Sect. C: Cryst. Struct. Commun., 1984, 40, 1863.
51 P. A. Bonnet, J. van de Streek, A. V. Trask, W. D. S. Motherwell and W. Jones, CrystEngComm, 2004, 6, 535.
52 C. Platteau, J. Lefebvre, F. Affouard and P. Derollez, Acta Crystallogr., Sect. B: Struct. Sci., 2004, 60, 453.
53 C. Platteau, J. Lefebvre, F. Affouard, J.-F. Willart, P. Derollez and F. Mallet, Acta Crystallogr., Sect. B: Struct. Sci., 2005, 61, 185.
54 G. A. Jeffrey and R. Nanni, Carbohydr. Res., 1985, 137, 21.
55 H. Nagase, N. Ogawa, T. Endo, M. Shiro, H. Ueda and M. Sakurai, J. Phys. Chem. B, 2008, 112, 9105.
56 A. Isogai, M. Usuda, T. Kato, T. Uryu and R. H. Atalla, Macromolecules, 1989, 22, 3168.