Molecular Rotations of Glucides in Relation to their Structures. IV. The Internal Conformation of C^6—O Bond in D*-Mannopyranose and* D*-Glucopyranose in their Aqueous Solutions*

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From the results of X-ray analysis on crystalline methyl-D-mannopyranoside, Cox and Goodwin proposed a presumption on the internal conformation of C^6—O bond in D-mannopyranose in crystalline state[1),*1]. Mc Donald and Beevers also determined the same conformation in crystalline D-glucopyranose by X-ray analysis about the crystal of this substance[2)]. But, for lack of any suitable method, the internal conformation in the molecules in aqueous solutions has been yet undetermind. In aqueous solution, OH group which combines with C^6 atom is considered to be free to rotate about the axis of C^5—C^6 bond and the position which has minimal potential and makes that OH group rest, will be decided principally by steric repulsions and secondarily by electrostatic

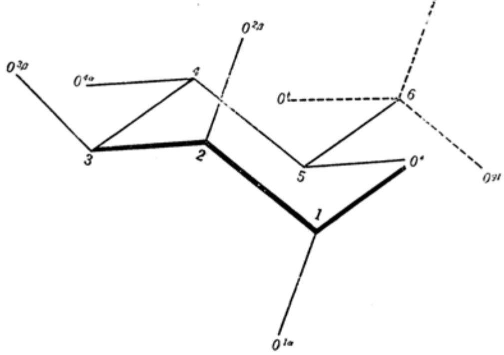

Fig. 1. Perspective drawing of the molecular model of α-D-mannopyranose
*g*I—*gauche* I ($\Phi=120°$), *g*II—*gauche* II ($\Phi=240°$), *t*—*trans* ($\Phi=0°$)

[1)] E. G. Cox and T. H. Goodwin, *J. Chem. Soc.*, **1932**, 1844.

[*1] Cox and Goodwin presumed that the aldopyranose-ring is flat, but their presumption was proved to be improper by McDonald and Beevers. (ref. (2)).

[2)] T. R. R. McDonald and C. A. Beevers, *Acta Cryst.*, **5**, 654 (1952).

TABLE I

Name	Unit Groups	$[M]_D^{20}$(W)	Lit.
α-D-mannose	$[(OH)^{1\alpha}, (OH)^{2\beta}, (OH)^{3\beta}, (OH)^{4\alpha}, (CH_2OH)^{5\beta}, \text{Ring}]$	53.8°	(a)
β-D-mannose	$[(OH)^{1\beta}, (OH)^{2\beta}, (OH)^{3\beta}, (OH)^{4\alpha}, (CH_2OH)^{5\beta}, \text{Ring}]$	−29.3°	(a)
α-D-rhamnose	$[(OH)^{1\alpha}, (OH)^{2\beta}, (OH)^{3\beta}, (OH)^{4\alpha}, (CH_3)^{5\beta}, \text{Ring}]$	14.0°	(b)
β-D-rhamnose	$[(OH)^{1\beta}, (OH)^{2\beta}, (OH)^{3\beta}, (OH)^{4\alpha}, (CH_3)^{5\beta}, \text{Ring}]$	−63.0°	(b)

forces and hydrogen bonding forces between the atoms in the molecule[3]. (Fig. 1).

According to the idea that the optical rotatory power should be a function of the angle which defines the internal conformation of CH_2Cl group in that molecule, Wood, Fickett and Kirkwood calculated the value of the optical rotatory power of 1,2-dichloropropane, and checked these values comparing them with the observed values. By this method, they could determine the absolute configuration of 1,2-dichloropropane[4]. The author wants to offer a new method of presuming the internal conformation of a bond. The principle of this method is the calculation in reversing order of Kirkwood's method, described above. By using this method, the author was able to presume the internal conformations of C^6—O bond in D-mannopyranose and D-glucopyranose in aqueous solutions.

Molecular Model and Data Used*2

Unit groups in hexose molecules under question and their corresponding molecular rotations, are shown in Table I. (Fig. 1).

In this paper, the hypothetically ideal model of Reeves' C 1 conformation*3 and Mc Donald and Beevers' model*4 which was determined by X-ray analysis of crystalline α-D-glucose, were used as the molecular model. The optical data for OH group and H atom, used in the previous paper[7], were also employed without any correction. The refractive indices of the aqueous solutions of glucides under question are presumed to be nearly equal (1.34)*5.

Method Proposed

The geometry of D-mannopyranose, except that of C^6—O bond, has been determined in the previous paper[6]. At first, the author intended to calculate the optical rotatory power of D-mannopyranose as a function of the angle Φ which defines the internal conformation of C^6—O bond*6 according to Kirkwood's polarizability theory. But, in order to avoid the complexity of calculation, the author used the anomeric difference*7 instead of the molecular rotation itself, and compared the calculated values with the observed one to presume the internal conformation of C^6—O bond. In the molecule of α-D-mannopyranose, $\sum[\mu]_{\mathrm{D\,obs}}^{20}$, caused by the dynamical coupling effect of $(OH)^1$ is $(1\alpha)\barwedge(2\beta)$*2$+(1\alpha)\barwedge(3\beta)+(1\alpha)\barwedge(4\alpha)+(1\alpha)\barwedge(CH_2OH)^{5\beta}+(1\alpha)\barwedge R$, and the value in the molecule of β-D-mannopyranose is also calculated as

$$(1\beta)\barwedge(2\beta)+(1\beta)\barwedge(3\beta)+(1\beta)\barwedge(4\alpha)$$
$$+(1\beta)\barwedge(CH_2OH)^{5\beta}+(1\beta)\barwedge R$$ [5,7]

Therefore, $[\mu]_{\mathrm{D\,obs}}^{20}$ for the anomeric difference*7 of D-mannopyranose should be equal to the difference between the above two $\sum[\mu]_{\mathrm{D\,obs}}^{20}$ s. That is

$$\{(1\alpha)\barwedge(2\beta)-(1\beta)\barwedge(2\beta)\}+\{(1\alpha)\barwedge(3\beta)$$
$$-(1\beta)\barwedge(3\beta)\}+\{(1\alpha)\barwedge(4\alpha)-(1\beta)\barwedge(4\alpha)\}$$
$$+\{(1\alpha)\barwedge(CH_2OH)^{5\beta}-(1\beta)\barwedge(CH_2OH)^{5\beta}\}$$
$$+\{(1\alpha)\barwedge R-(1\beta)\barwedge R\}\equiv P$$

By the similar treatment, $[\mu]_{\mathrm{D\,obs}}^{20}$ for the

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3) S. Mizushima, Y. Morino and T. Shimanouchi, *J. Chem. Soc. Japan, Pure Chem. Sec.* **73**, 621 (1952); I. Miyagawa, ibid. **75**, 1169 (1954).

4) W. W. Wood, W. Fickett and J. G. Kirkwood, *J. Chem. Phys.*, **20**, 561 (1952).

*2 Abbreviated symbols, used in this paper, are the same as those in the preceding article (5).

5) S. Yamana, This Bulletin, **30**, 916 (1957).

a) C. N. Rüber and J. Minsaas, *Ber.*, **60**, 2402 (1927).

b) C. S. Hudson and E. L. Jackson, *J. Am. Chem. Soc.*, **59**, 1076 (1937).

*3 See the previous paper (6).

6) S. Yamana, This Bulletin, **30**, 207 (1957).

4 The shape of McDonald and Beevers' model is almost the same as that of the ideal model of Reeves' C 1 conformation, above mentioned. Mc Donald and Beevers decided the following values for the bond lengths and the valency angles in crystalline α-D-glucose molecule[2]; C^1—C^2 1.54 Å; C^2—C^3 1.56 Å; C^3—C^4 1.53 Å; C^4—C^5 1.54 Å; C^5—O 1.40 Å; O*—C^1 1.42 Å; C^1—O^1 1.32 Å; C^2—O^2 1.41 Å; C^3—O^3 1.44 Å; C^4—O^4 1.40 Å; C^5—C^6 1.53 Å; C^6—O^6 1.32 Å; O*—C^1—C^2 110°; C^1—C^2—C^3 104°; C^2—C^3—C^4 110°; C^3—C^4—C^5 108°; C^4—C^5—O* 109 1/2°; C^5—O*—C^1 111°; O*—C^1—O^1 112°; C^2—C^1—O^1 115°; C^1—C^2—O^2 109°; C^3—C^2—O^2 109°; C^2—C^3—O^3 102°; C^4—C^3—O^3 108°; C^3—C^4—O^4 110 1/2°; C^5—C^4—O^4 112°; C^4—C^5—C^6 112°; O*—C^5—C^6 110°; C^5—C^6—O^6 113°.

7) S. Yamana, This Bulletin, **30**, 203 (1957).

*5 ref. *8 in the previous paper (6).

6 The author defined an angle Φ specifying the internal conformation as follows; (i) Φ is zero at the situation which the O atom in C^6—O bond and the ring-O-atom (represented by O) are in *trans* position each other. (ii) Its positive direction of rotation from zero increases the distance between C^4-atom and the O atom in C^6—O bond.

*7 This is the difference in optical rotation of α and β aldoses. (ref. (6)).

anomeric difference of D-rhamnopyranose[*8] is obtained as

$$\{(1\alpha)\bar{\Lambda}(2\beta)-(1\beta)\bar{\Lambda}(2\beta)\}+\{(1\alpha)\bar{\Lambda}(3\beta)-(1\beta)\bar{\Lambda}(3\beta)\}+\{(1\alpha)\bar{\Lambda}(4\alpha)-(1\beta)\bar{\Lambda}(4\alpha)\}+\{(1\alpha)\bar{\Lambda}(CH_3)^{5\beta}-(1\beta)\bar{\Lambda}(CH_3)^{5\beta}\}+\{(1\alpha)\bar{\Lambda}R-(1\beta)\bar{\Lambda}R\}\equiv Q$$

Both of the above obtained two $[\mu]^{20}_{\mathrm{Dobs}}$s (P and Q) contain the terms concerning the aldopyranose-ring R. It is impossible to calculate these terms at present. Then, in order to avoid this difficulty, Q was subtracted from P and the terms concerning R disappear as below:

Difference between the anomeric difference of D-mannopyranose (P) and that of D-rhamnopyranose (Q) is as follows,

$$P \text{ minus } Q=[(1\alpha)\bar{\Lambda}(CH_2OH)^{5\beta}-(1\beta)\bar{\Lambda}(CH_2OH)^{5\beta}]-[(1\alpha)\bar{\Lambda}(CH_3)^{5\beta}-(1\beta)\bar{\Lambda}(CH_3)^{5\beta}]$$

The terms of this difference can be simplified by the following procedure. $(CH_2OH)^{5\beta}$ may be considered to occur by replacing an H atom in $(CH_3)^{5\beta}$ by an OH group. Becauses of its small polarizability, $[\mu]^{20}_{\mathrm{Dobs}}$, caused by the dynamical coupling effect of H atom, may be neglected[8], [*9]. Then (P minus Q) becomes as below[*10];

$$[(1\alpha)\bar{\Lambda}\{(CH_2)^{5\beta}+(OH)^6\}-(1\beta)\bar{\Lambda}\{(CH_2)^{5\beta}+(OH)^6\}]-[(1\alpha)\bar{\Lambda}\{(CH_2)^{5\beta}+(H)^6\}-(1\beta)\bar{\Lambda}\{(CH_2)^{5\beta}+(H)^6\}]=(1\alpha)\bar{\Lambda}(OH)^6-(1\beta)\bar{\Lambda}(OH)^6$$

Referring to the previous papers[5–7], the value for $\{(1\alpha)\bar{\Lambda}(OH)^6-(1\beta)\bar{\Lambda}(OH)^6\}$ was calculated as a function of Φ[*11]. The results of calculation are given in Table II.

$(53.8+29.3)-(14.0+63.0)=6.1$[*12] is gained as the corresponding observed value. This value coincides with the calculated values in Table II when Φ is 0° and 240°[*13]. Therefore, the internal conformation of C^6—O bond should correspond to one or both of these two angles. According to Mizushima, Morino and Shimanouchi's empirical rule[*14], the molecule of $XH_2C—CH_2Y$ type can exist in several forms of rotational isomer in liquid or gaseous state. Then, there may exist an equilibrium between these two types of internal conformations of C^6—O bond in aqueous solutions. These two types happen in the two of the three structures of potentially minimal 1,2-dichloropropane[9] (*trans* form and *gauche* II form). (Fig. 2)[*15]

TABLE II

$\Sigma[\mu]^{20}_{\mathrm{Dobs}}$ FOR THE DIFFERENCE BETWEEN THE ANOMERIC DIFFERENCE OF D-MANNOPYRANOSE (P) AND THAT OF D-RHAMNOPYRANOSE (Q), AS A FUNCTION OF Φ

Φ	Ideal Model	McDonald and Beevers' Model
0	7.2	7.3
20	2.8	2.8
40	− 3.0	− 3.1
60	−10.4	−10.1
80	−15.6	−16.8
100	−18.9	−21.2
120	−18.2	−21.5
140	−13.8	−17.5
160	− 8.1	−11.0
180	− 2.6	− 4.3
200	1.7	1.3
220	4.7	5.4
240	7.2	8.3
260	9.2	10.3
280	10.8	11.8
300	11.6	12.3
320	11.4	11.9
340	9.9	10.3

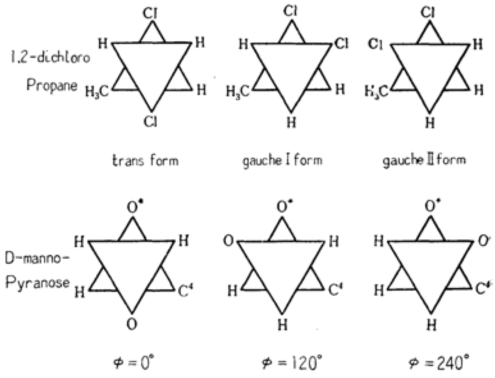

Fig. 2. Internal conformation along the C^6—C^5 axis.

[8*] D-rhamnopyranose has been confirmed to have Reeves' C 1 conformation by the experiments of cuprammonium-glycoside complexes. (R. E. Reeves, *J. Am Chem. Soc.*, **72**, 1499 (1950).

8) J. G. Kirkwood, *J. Chem. Phys.*, **5**, 479 (1937).

[*9] Consequently. $(1\alpha)\bar{\Lambda}(H)^6=1\beta\bar{\Lambda}(H)^6=0$

[*10] $(OH)^6$ and $(H)^6$ mean OH group and H atom which combine with the C atoms in $(CH_2OH)^{5\beta}$ and $(CH_3)^{5\beta}$, respectively.

[*11] When using McDonald and Beevers' model, κ is $241.2/19.68(n^2+2)$. Then, in order to obtain $[\mu]^{20}_{\mathrm{Dobs}}$ from $[\mu]^{20}_{\mathrm{Dcalcd}}(3/n^2+2)$, the latter must be multiplied by $80.4/19.68=4.085$.

[*12] Ref. Table 1 in this paper.

[*13] When using the value of C—O bond length of 1.48 Å (M. Kimura, *J. Chem. Soc. Japan, Pure Chem. Sec.* **71**, 18 (1950)), κ is $13.2/n^2+2$ and both of the calculated values of the difference between two anomeric differences, corresponding to $\Phi=0°$ and 240°, become 7.5.

[*14] Ref. "Discussion on the Results" in this article.

9) I. Miyagawa, *J. Chem. Soc. Japan, Pure Chem. Sec.* **75**, 1165 (1954).

[*15] But the O atom in D-mannopyranose molecule corresponds to the Cl atom in 1,2-dichloropropane molecule.

The above obtained two types of internal conformation of C^6—O bond in D-mannopyranose in aqueous solution are presumed to happen also in D-glucopyranose. The reason for this is as follows ; If the orientation of (OH)^2[*16] of D-mannopyranose changes from β to α, D-glucopyranose-molecule can be obtained. But the distance between the O atom in (OH)^2 and that in C^6—O bond is too large[*17] to give rise to any influence of the orientation-change of (OH)^2 on the internal conformation of C^6—O bond[*18].

Discussion on the Results

According to Mc Donald and Beevers' experiment[2)], the internal conformation of C^6—O bond in α-D-glucopyranose, in crystalline state, is almost consistent with the conformation corresponding to *gauche* 1 form[*19]. Then, it may be concluded that, when α-D-glucopyranose is dissolved in water, the internal conformation of C^6—O bond changes from *gauche* 1 to *trans* and *gauche* II types. On the other hand, Mizushima, Morino and Shimanouchi[3)] found an empirical rule that the molecule of $XH_2C—CH_2Y$ type, may be able to exist in several forms of rotational isomer in liquid or gaseous state, and one of these forms is identical with the form in the solid state. The author's conclusion[*20] on the conformation of C^6—O bond in α-D-glucose somewhat seems to deviate from this empirical rule. This disharmony may be explained as follows. As Mc Donald and Beevers observed[2)] that O^6- atom of a molecule of crystalline α-D-glucopyranose is combined, by hydrogen bonding forces, with both O^2- and O^3- atoms of the neighboring molecule[*21], the internal conformation of C^6—O bond in crystalline α-D-glucopyranose is greatly influenced by the atoms of the other molecules in the crystal. These forces contribute to make O^6- atom rest at such a position that C^6—O bond takes *gauche* I conformation. But when α-D-glucose is dissolved in water, each molecule is separated from other molecules and the influences of the neighboring molecule decrease. Therefore, the internal conformation of C^6—O bond in that molecule is influenced principally by the atoms in its own molecule. Moreover, as the distance between $O^{4\alpha}$ and O^6 is almost equal to that between O^6- and C^4- or O*- atoms (ref. Table III), the influence of $O^{4\alpha}$ on O^6 may be unable to neglect. (Fig. 1)

TABLE III
THE DISTANCES BETWEEN O^6- ATOM AND ITS NEIGHBORING ATOMS IN McDONALD AND BEEVERS' MODEL AND THE IDEAL MODEL[*22]

	trans	*gauche* I	*gauche* II
O^6 and $O^{4\alpha}$	2.69Å (2.51)	4.18Å (4.19)	3.45Å (3.42)
O^6 and C^4	2.96Å (2.89)	3.73Å (3.76)	2.96Å (2.89)
O^6 and O*	3.57Å (3.76)	2.81Å (2.89)	2.81Å (2.89)

In Table III, the distance between O^6 and $O^{4\alpha}$ in *trans* form is the shortest (this is 2.69 Å) and is just equal to the length of a hydrogen bond[*23]. Therefore, O^6- atom which is only one movable atom in Table III, may be attracted by $O^{4\alpha}$- atom most strongly and is forced to rest at the *trans* position[*24] by making a hydrogen bond between (OH)^6 and (OH)$^{4\alpha}$ group. In order to find a reason for non-existence of *gauche* I form in aqueous solutions against its expectation of appearance by the empirical rule, the affinity of O^6- atom to *gauche* I and *gauche* II positions should be compared. By using Table III, it is noticed that the distances between O^6 and any one of these neighboring atoms ($O^{4\alpha}$, C^4 and O*) in *gauche* I form is always larger than (or at least equal to) that in *gauche* II form, respectively. Then the total of the attractive forces of the neighboring atoms on O^6-atom in *gauche* II form should be greater than that in *gauche* I form. This fact causes the affinity of O^6- atom to *gauche* II rather than to *gauche* I position. These may be the reason for non-existence of *gauche* I form of rotational isomer of D-glucopyranose and D-mannopyranose in aqueous solutions.

[*16] (OH)^2 means OH group which combines with the C^2- atom of the aldopyranose-ring.

[*17] The distances between the O atom in (OH)^2 and that in C^6—O bond are as below;

	longest	shortest
(OH)$^{2\alpha}$	6.49 Å (at Φ=40°)	6.03 Å (at Φ=220°)
(OH)$^{2\beta}$	5.82 Å (at Φ=60°)	4.56 Å (at Φ=240°)

[*18] It must be remembered here, that the coefficient 4.123 (in the previous paper (5)) and 4.085 (in *11 of this article), used in calculating $[\mu]^{20}_{\mathrm{Dobs}}$ from $[\mu]^{20}_{\mathrm{Dcalcd}}$ $(3/n^2+2)$ were obtained under this hypothesis.

[*19] The observed internal conformation of C^6—O bond corresponds to $\Phi=111^1/_2°$ in Mc Donald and Beevers' model.

[*20] The possible internal conformation of C^6—O bond are *trans* and *gauche* II in aqueous solution but *gauche* 1 only, in crystalline state.

[*21] O^2—O^6 2.74 Å; O^3—O^6 2.70 Å

[*22] The values in the ideal model are given in parentheses.

[*23] cf. *21 in this paper.

[*24] This is the position of O^6- atom which corresponds to *trans*-type conformation of C^6—O bond.

Summary

The internal conformation of C^6—O bond in the molecules of D-mannopyranose and D-glucopyranose in aqueous solutions were presumed by a new method, and was concluded to take *trans* (mostly) and *gauche* II (only sometimes) forms.

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