Stereochemistry of Sugar Units in Glycosylamine Ligands of Octahedral Complexes derived from Tris(trimethylenediamine)-nickel(II) and Natural Aldohexoses†

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Some natural aldohexoses reacted with $[Ni(tn)_3]^{2+}$ (tn = trimethylenediamine) to yield octahedral nickel(II) complexes containing glycosylamine ligands. The complexes were characterized by elemental analyses, magnetic moments, electronic and CD spectra. The molecular structure of $[Ni(L\text{-Rha-tn})_2]Br_2\cdot 2H_2O\cdot MeOH$ [L-Rha-tn = 1-(3-aminopropylamino)-1,6-dideoxy-L-mannose] **1** has been determined by single-crystal X-ray techniques: orthorhombic, space group $P2_12_12_1$, $a = 12.373(1)$, $b = 21.614(2)$, $c = 11.272(1)$ Å, least-squares refinement led to a final R factor of 0.044 using 2657 reflections having $F_o > 3\sigma(F_o)$. From X-ray crystallographic studies of glycosylamine complexes, two typical co-ordination structures of the aldose unit have been found in **1** and $[Ni(D\text{-GlcN-en})_2]^{2+}$ [D-GlcN-en = 2-amino-1-(2-aminoethylamino)-1,2-dideoxy-D-glucose], which can be discriminated by the two geometrical isomeric forms arising from the two substituents on C^1 and C^2 of the pyranoside ring, namely *cis* and *trans*. The sugar unit of **1** has *cis* geometry containing equatorial and axial substituents on C^1 and C^2 of the pyranoside ring. In contrast, the sugar unit of the D-GlcN-en complex has *trans* geometry at these positions, which are both equatorial. Assuming the $^4C_1$ (chair) conformers to be the most stable and based on some stereochemical considerations of both the sugars and the chelate rings, the structures of the sugar units in the glycosylamine complexes from all natural aldohexoses can be classified into either of the above two types, the only difference being the relative absolute configuration at C^2 and C^5. This classification is well correlated with the CD spectral patterns obtained in methanolic solutions.

Currently there is great interest in the interaction of carbohydrates with transition metals. However, the co-ordination chemistry of carbohydrates presents some difficulties regarding the isolation of discrete compounds, and in the assignment of which hydroxy-groups are attached to the metal ion or in which anomer and in which conformer the sugar moiety is co-ordinated. Further, because of the steric complexity of sugars, there is no reliable technique, except for X-ray crystallography or NMR spectroscopy, to clarify the details of the structures of these complexes, even when the complex has been successfully isolated. Historically, there were two typical approaches to elucidate the general co-ordination behaviour of aldohexoses. Reeves[1] examined the optical rotatory power of some aqueous solutions of 'cupraammonia' ion and some modified aldosides to confirm the chelation of hydroxy-groups of sugar units to Cu^{2+}. Angyal[2] intensively investigated the affinity of sugars and several cyclic polyols for Ca^{2+} mainly by means of electrophoresis, and proposed the preferential stereochemical sequences of hydroxy-groups on five- or six-membered rings, with which sugars have a strong affinity towards metal ions. However, neither worker isolated discrete aldose–metal complexes. Moreover, many of the sugars described in their studies were not 'aldohexose' itself. Perhaps because of its structural flexibility the metal–sugar complex is not easily crystallized.

Recently, we have extensively studied the synthesis and characterization of transition-metal complexes containing glycosylamines formed by the reaction of sugars and amines[3–16] and discovered novel sugar-transformation reactions promoted by the co-operative effects of metal ions and polyamines.[17–22] Glycosylamines have proven to be good ligands especially for Ni^{II}. As sugar itself has no ability to produce distinct nickel(II) complexes, the formation of the glycosylamine is an effective method for the preparation and isolation of discrete, well assignable sugar–metal complexes of Ni^{II}. We have examined this reaction for some ketohexoses,[3,5,6] and the general co-ordination pattern of a ketose unit of these glycosylamines was well established.[6] For aldose complexes, however, the co-ordination structure of the sugar units has not been well established since only one crystal structure of $[Ni(D\text{-GlcN-en})_2]Br_2\cdot 4H_2O$[D-GlcN-en = 2-amino-1-(2-aminoethylamino)-1,2-dideoxy-D-glucose], has been determined.[7] However, in this complex the sugar is an amino sugar which has an NH_2 group on the C^2 atom instead of the hydroxy-group of D-Glc. The crystal structure showed that the sugar unit of a glycosylamine formed from an aldose and a diamine co-

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† *Supplementary data available:* see Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1993, Issue 1, pp. xxiii–xxviii.

ordinates to the nickel atom through the nitrogen atom on C^1 of the sugar and the nitrogen atom on C^2 and adopts its most stable $^4C_1$ chair conformer. From the structural resemblances of D-GlcN and D-Glc, the structure of the glycosylamine complexes derived from D-Glc is thought to be similar to that of those from D-GlcN.[7] However, it remains difficult to predict the preferential conformation of a pyranoside of D-Man (Man = mannose) and its co-ordinative analogues in their glycosylamine complexes because they have an axial hydroxy substituent on C^2 of the preferred $^4C_1$ conformer. Possible inversion of the pyranoid ring from $^4C_1$ to $^1C_4$ can also provide an equatorially oriented hydroxy-group on C^2. Thus, to clarify the general co-ordination behaviour for glycosylamines derived from aldohexoses, it is desirable to confirm the stereochemistry especially of the mannose derivative or its analogues.

In this paper we report the isolation and characterization of nickel(II) complexes of glycosylamines derived from the reaction of trimethylenediamine (tn) and natural aldohexoses [D-galactose (D-Gal), D-talose (D-Tal), L-fucose (L-Fuc) and L-rhamnose (L-Rha)] and an X-ray crystal structure determination of a newly isolated complex $[Ni(L\text{-}Rha\text{-}tn)_2]Br_2\cdot 2H_2O\cdot MeOH$ [L-Rha-tn = *N*-(L-rhamnosyl)propane-1,3-diamine]. The general co-ordination pattern of natural aldohexose units of the glycosylamine ligands is presented and correlated with their CD spectra. A preliminary account of this work has been published.[4]

Experimental

Preparation of Nickel(II) *Complexes of Glycosylamines.*—Tris(trimethylenediamine)nickel(II) dibromide dihydrate[23] (1.25 g, 2.5 mmol) was dissolved in methanol (20 cm^3). To the stirred solution was added an aldose (D-Gal, D-Tal, L-Rha, or L-Fuc) (0.9 g, 0.5 mmol). The solution was warmed to reflux for about 10 or 20 min until the colour changed from violet to blue. It was then cooled to about room temperature and loaded on a LH-20 gel permeation column (4 × 80 cm) and eluted with methanol. The coloured materials separated into a major blue and a minor yellow band. The blue fraction was collected and purified twice on the column. The final blue fractions thus obtained were concentrated. For D-Gal a small amount of propan-2-ol was added and the solution concentrated to precipitate a blue powder. The solution was placed in a refrigerator to cool. Each blue compound was recrystallized from the minimum amount of a hot methanol–propan-2-ol mixture. The crystals were collected and washed with cool ethanol followed by diethyl ether and dried *in vacuo*. When L-Rha was used good crystals (ordinarily 0.5 × 0.5 × 1 mm) were obtained suitable for an X-ray crystallographic study.

Reaction of $[Ni(tn)_3]^{2+}$ *and* D-Glc *Derivatives.*—The reactions of $[Ni(tn)_3]^{2+}$ and D-Glc analogues (3-*O*-methyl- and 6-deoxy-) were also examined under similar conditions. The resultant complex solution was purified by column chromatography and only examined by absorption and CD spectroscopy since the crystallization of these complexes was not facile.

Recovery of Sugars.—Each complex obtained was dissolved in the minimum amount of water, the solution made slightly acidic with 0.01 mol dm^{-3} H_2SO_4, and stirred for several hours. In order to remove the nickel(II) complexes the solution was passed through a column of Dowex-50W (Na^+) cation-exchange resin. It was confirmed that the solution contained monosaccharides by means of a TSK HLC-803D chromatographic system (Toyo Soda Kogyo Assoc.), which included a fluorimeter for monitoring sugars.[24]

Physical Measurements.—Electronic absorption spectra of finely ground solid samples were obtained with a Hitachi 340 spectrophotometer equipped with a reflectance attachment. Solution spectra of the complexes were obtained with a JASCO J-500C recording spectropolarimeter (circular dichroism) and a Hitachi 340 spectrophotometer (electronic absorption). Magnetic moments were determined by the Faraday method at room temperature with a Shimadzu model MB-100 magnetic balance. The molar susceptibility in each case was corrected for the diamagnetism of the ligand.[25] Microanalyses were performed by Shonan Bunseki Center Co.

Crystal Structure Determination.—*Crystal data for* $[Ni(L\text{-}Rha\text{-}tn)_2]Br_2\cdot 2H_2O\cdot MeOH$ **1**. $C_{19}H_{48}Br_2N_4O_{11}Ni$, $M = 727.11$, orthorhombic, space group $P2_12_12_1$, $a = 12.373(1)$, $b = 21.614(2)$, $c = 11.272(1)$ Å, $U = 3214.5(5)$ Å^3, $D_m = 1.62$ g cm^{-3}, $Z = 4$, $D_c = 1.60$ g cm^{-3}, Mo-Kα radiation, $\lambda = 0.7107$ Å, μ(Mo-Kα) = 39.71 cm^{-1}, $F(000) = 1504$.

A blue approximately cube-shaped crystal (0.33 mm), coated with epoxy cement since the crystals are sensitive to moisture, was mounted on a Rigakudenki AFC-5 four-circle diffractometer. The intensities of 3920 reflections ($2\theta_{max} = 55°$) were measured using graphite-monochromated Mo-Kα radiation. A total of 2657 independent reflections [$F_o > 3\sigma(F_o)$], corrected for absorption (Gaussian,[26] grid 6 × 6 × 6), were used in the refinement procedure. The structure was solved by the heavy-atom method and refined by block-diagonal least-squares techniques. Atomic scattering factors were taken from ref. 27. The weighting scheme $1/w = \sigma_{count}^2 + (0.015|F_o|)^2$ was employed, when $\Sigma w(|F_o| - |F_c|)^2$ was minimized in the least-squares procedure. Since the complex was derived from L-rhamnose the known absolute configurations of the asymmetric carbon atoms were used as internal reference asymmetric centres to determine the absolute configuration of the complex ion. Anomalous dispersion effects included in f' and f'' for Br, Ni, O, N and C were taken from ref. 28. Least-squares refinement, allowing all the non-hydrogen atoms to vibrate anisotropically, converged to R and R' values of 0.0555 and 0.0597, respectively, where $R = \Sigma||F_o| - |F_c||/\Sigma|F_o|$ and $R' = [\Sigma w(|F_o| - |F_c|)^2/\Sigma w|F_o|^2]^{\frac{1}{2}}$. When the f'' values were reversed in sign in order to test the final structure, convergence was reached with $R = 0.0691$ and $R' = 0.0764$, which are significantly larger than the above values. This result confirms the absolute configuration assumed and to which all atomic coordinates (Table 1) and diagrams (Figs. 2 and 3) correspond. Fourier difference syntheses revealed clear evidence of hydrogen atoms and, except for one of the hydroxy-groups and one of the hydrogen atoms of water and methanol molecules, were included in the subsequent cycles of least-squares refinement as isotropic contributions where the damping factor for hydrogen atoms was 0.1. Hydrogen atom scattering factors were taken from Stewart *et al.*[29] The final cycles of least-squares refinement gave $R = 0.0438$ and $R' = 0.0428$. A final Fourier difference synthesis showed no unusual features with $\Delta\rho_{max} = 0.49$e Å^{-3}. All calculations were performed on a FACOM system of the Information Processing Centre of Nara Women's University and a M680 at the Computer Centre of Tokyo University with the program system UNICS III.[30]

Additional material available from the Cambridge Crystallographic Data Centre comprises H-atom coordinates, thermal parameters and remaining bond lengths and angles.

Results and Discussion

Characterization of the Compounds.—In previous work[5b] we observed that a small difference in the length of the diamine chain (between tn and en) results in a remarkable change in the yields of nickel(II) complexes of the glycosylamine formed from D-Glc, D-Man, or D-Fru (D-fructose) and the diamine. Trimethylenediamine was found to be a suitable ligand for forming metal complexes of glycosylamines. In this study the other natural aldohexoses, even or the 6-deoxy-sugar, can also participate in this reaction to form similar blue glycosylamine complexes in a short time and in good yield (Table 1). All the complexes obtained except for that derived from D-Tal can be

Table 1 Elemental analyses, magnetic data and yields of the complexes

Complex	Yield (%)[a]	Analysis (%)[b]			μ_{eff}
		C	H	N	
$[Ni(D\text{-}Gal\text{-}tn)_2]Br_2$	85	30.95 (30.50)	6.20 (5.85)	7.85 (8.10)	3.12
$[Ni(L\text{-}Fuc\text{-}tn)_2]Br_2$	70	31.90 (31.95)	6.30 (6.25)	8.45 (8.30)	3.38
$[Ni(D\text{-}Tal\text{-}tn)_2]Br_2\cdot 1.5H_2O$	40	29.85 (30.10)	5.90 (6.05)	8.30 (7.80)	2.98
$[Ni(L\text{-}Rha\text{-}tn)_2]Br_2\cdot 2H_2O\cdot MeOH$	60	32.80 (32.80)	6.20 (6.10)	8.50 (8.50)	3.18

[a] Of the crude isolated compounds. [b] Calculated values in parentheses.

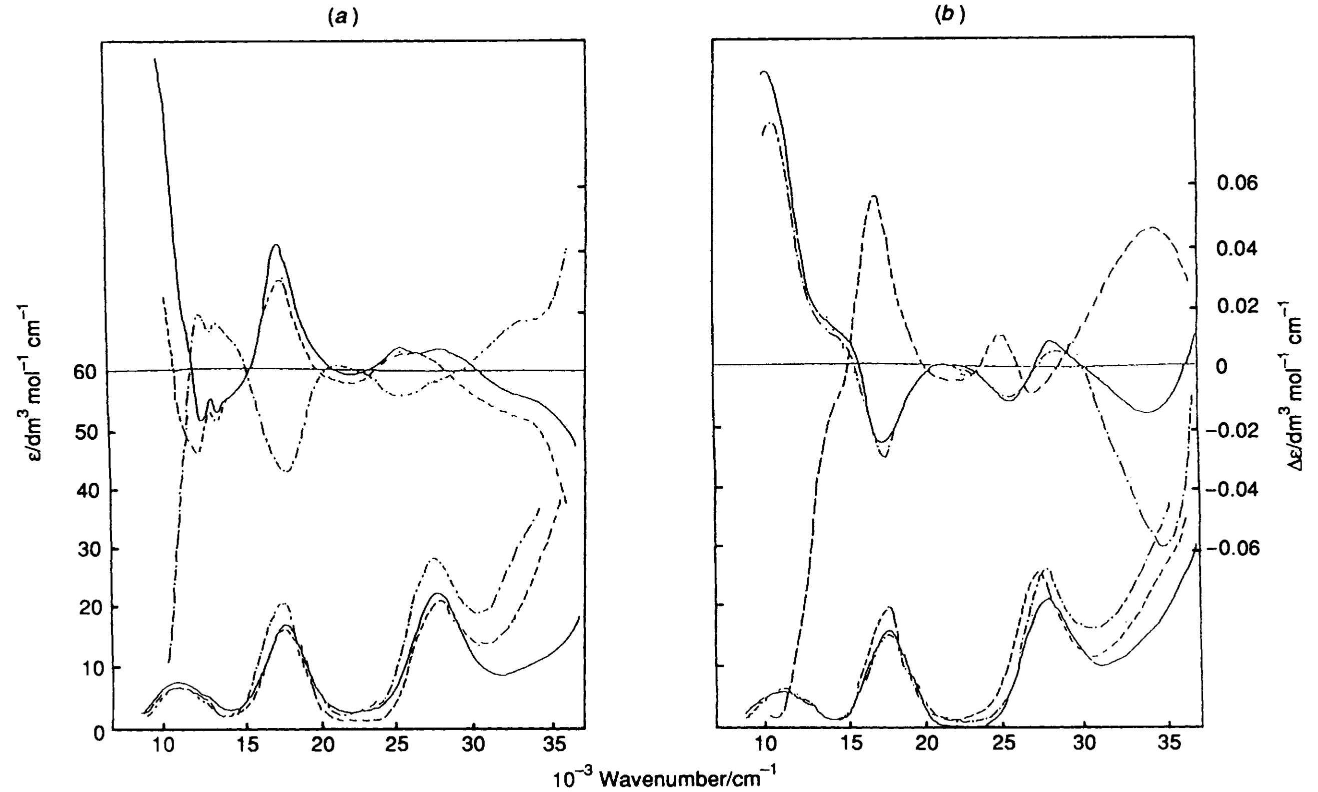

Fig. 1 Circular dichroism (upper) and absorption (lower) spectra of the nickel(II) complexes in methanol: (*a*) (——) $[Ni(D\text{-}Glc\text{-}tn)_2]^{2+}$,[5] (– – –) $[Ni(D\text{-}Gal\text{-}tn)_2]^{2+}$, (–·–·–) $[Ni(L\text{-}Fuc\text{-}tn)_2]^{2+}$; (*b*) (——) $[Ni(D\text{-}Man\text{-}tn)_2]^{2+}$,[5] (– – –) $[Ni(L\text{-}Rha\text{-}tn)_2]^{2+}$, (–·–·–) $[Ni(D\text{-}Tal\text{-}tn)_2]^{2+}$

recrystallized from methanol without any evidence of decomposition. The complex derived from D-Tal was recrystallized from a mixture of methanol and propan-2-ol. These complexes are sensitive to moisture. In slightly acidic solution all decompose into nickel(II) complexes of the diamine and the parent sugars. Similar decomposition also gradually occurred in neutral aqueous solution. Elemental analyses indicate that each complex contains two glycosylamines derived from the reaction of a sugar and tn [L-Rha-tn = 1-(3-aminopropylamino)-1,6-dideoxy-L-mannose, L-Fuc-tn = 1-(3-aminopropylamino)-1,6-dideoxy-L-galactose, D-Gal-tn = 1-(3-aminopropylamino)-1-deoxy-D-galactose and D-Tal-tn = 1-(3-aminopropylamino)-1-deoxy-D-talose].

The magnetic data demonstrate that nickel ions in these compounds have two unpaired electrons, and the magnetic moments fall within the range 2.9–3.4 reported[31] for octahedral complexes of Ni^{II} (Table 1). The near infrared-visible absorption spectra for the nickel(II) complexes together with those of $[Ni(D\text{-}Glc\text{-}tn)_2]Br_2$ and $[Ni(D\text{-}Man\text{-}tn)_2]Cl_2\cdot 0.5H_2O$[5] obtained in methanol are illustrated in Fig. 1 and representative data are in Table 2. The absorption spectra are similar to each other and consist of three principal bands with comparable low intensity ($\varepsilon \approx 10$ dm³ mol⁻¹ cm⁻¹), which are characteristic of octahedral nickel(II) complexes.[32] The absorption maxima are in the range 10 200–11 000, 16 500–16 800 and 26 100–27 300 cm⁻¹ for all the complexes, the peaks in the first region showing no splitting. The three principal bands are assigned to the three spin-allowed octahedral nickel(II) transitions $^3A_{2g}(F) \longrightarrow {}^3T_{2g}(F)$, $^3A_{2g}(F) \longrightarrow {}^3T_{1g}(F)$ and $^3A_{2g}(F) \longrightarrow {}^3T_{1g}(P)$. Their locations and intensities are typical for octahedral *cis*-(O–O)-$[NiN_4O_2]$ complexes.[32] Although some differences in the wavenumbers of the peaks between the spectra in solution and the diffusion reflectance spectra in the solid state are observed, the patterns are similar. Accordingly these complexes seem to have similar co-ordination structures in the solid state and in solution. The elemental analyses, coupled with the magnetic susceptibility and spectral data, suggest that all the compounds are octahedral bis(tridentate ligand)nickel(II) complexes in which the ligand is a glycosylamine formed by condensation of a monosaccharide and tn.

Table 2 Spectral data

Complex	Electronic 10^{-3} ν_{max}/cm^{-1} (ε/dm^3 mol^{-1} cm^{-1})	CD 10^{-3} ν_{max}/cm^{-1} ($\Delta\varepsilon/10^{-2}$ dm^3 mol^{-1} cm^{-1})	Reflectance 10^{-3} ν_{max}/cm^{-1}
[Ni(D-Glc-tn)$_2$]Br$_2$ *	10.5(7.7)		10.4
		12.0(−1.7)	
	12.0(sh)(5.0)	13.0(−1.5)	12.8(sh)
		14.6(−0.5)	
	17.1(17.8)	17.1(+4.4)	16.8
		25.0(+0.8)	
	27.8(42.3)	27.8(−0.1)	27.5
[Ni(D-Gal-tn)$_2$]Br$_2$	10.6(7.9)		10.6
		11.6(−2.9)	
	12.3(sh)(3.4)	12.3(−1.4)	12.7(sh)
		14.6(−0.6)	
	17.1(15.8)	17.1(+3.1)	17.4
		21.5(−0.4)	
		25.6(+0.7)	
	27.5(25.0)	28.0(+0.2)	28.1
		31.0(−1.4)	
[Ni(L-Fuc-tn)$_2$]Br$_2$	10.6(7.9)	10.4	
		12.0(+2.1)	
	12.2(sh)(3.2)	13.0(+1.9)	12.7(sh)
		14.8(+0.8)	
	17.1(20.2)	17.1(−3.4)	17.2
		24.9(−0.7)	
	27.4(30.0)	27.9(−0.3)	27.5
		32.5(+1.7)	
[Ni(D-Man-tn)$_2$]Cl$_2$·0.5H$_2$O *	10.5(6.7)	10.1(+10.0)	10.6
	12.4(sh)(3.4)	14.8(+1.3)	12.8(sh)
	17.2(15.8)	16.8(−2.5)	17.0
		21.6(+0.2)	
		25.2(−1.1)	
	27.4(21.6)	28.0(+1.5)	27.4
		33.8(−1.5)	
[Ni(D-Tal-tn)$_2$]Br$_2$·1.5H$_2$O	10.3(6.6)	10.1(+8.3)	10.4
	12.5(sh)(3.3)	14.3(+1.0)	12.7(sh)
	17.2(13.8)	16.8(−3.5)	17.2
		24.7(−1.0)	
	27.8(25.0)	26.7(+0.6)	27.6
		35.2(−6.1)	
[Ni(L-Rha-tn)$_2$]Br$_2$·2H$_2$O·MeOH	10.4(6.5)	10.4(−10.8)	10.4
	12.5(sh)(3.5)		12.7(sh)
	17.2(20.1)	16.8(+5.6)	16.9
		24.8(+1.1)	
	27.3(26.0)	27.0(−0.8)	27.5

* Data taken from ref. 5.

Structure of [Ni(L-Rha-tn)$_2$]Br$_2$·2H$_2$O·MeOH **1**.—Fig. 2 shows the crystal structure of the complex cation **1** where two glycosylamine molecules form an octahedral co-ordination around the nickel atom in the meridional mode and the complex has approximately C_2 symmetry. The cation has the *cis*-(O–O)-[NiN$_4$O$_2$] structure. The absolute configuration of the two co-ordinated chiral nitrogen atoms is *S*.[34] The absolute configuration of the two chelate rings is Λ. In this configuration the two sugar units are presumed to lie further apart than in the case of Δ. Each pyranoid ring of the sugar moiety has the β-$^1C_4$ chair conformation. The $^1C_4$ conformation is also adopted by L-rhamnose in the free state.[35] The sugar unit is co-ordinated to the nickel ion through the 2-hydroxy-group and the nitrogen atom on C^1. These donors are axial and equatorial respectively to the pyranoid ring. Each sugar residue forms a five-membered chelate ring with the nickel atom in the λ-*gauche* conformation. Each diamine residue forms a six-membered chelate ring with a chair conformation.

The atomic coordinates and selected intramolecular bond distances and angles are given in Tables 3–5. The Ni-N distances range from 2.08(1) [Ni-N(1)] to 2.11(1) Å [Ni-N(2)]. These values are normal for octahedral nickel(II) complexes. The Ni-O distances of 2.17(1) [Ni-O(1)] and 2.18(1) Å [Ni-O(5)] are similar to those of 2.2059(8) [Ni-O(2)] and 2.137(6) Å [Ni-O(3)] in [Ni(en)(L-Sor-en)]Cl$_2$·0.5MeOH **2** {L-Sor-en = 2-[(2-aminoethyl)amino]-2-deoxy-L-sorbose}.[3] The ring angles at the central atom for the diamine rings, namely N(1)–Ni–N(2) and N(3)–Ni–N(4), are *ca.* 90°. These values are significantly larger than those (85°) for the five-membered diamine rings in **2** and [Ni(en)(D-Fru-en)]Cl$_2$·MeOH **3**.[5] In **1** the average angle between the terminal co-ordinated atoms of the glycosylamine ligands at the nickel atom, *i.e.* N(1)–Ni–O(1) and N(3)–Ni–O(5), is 168.4°. Thus deviations from ideal octahedral geometry for the present complex are significantly smaller than those for the ethylenediamine complex [Ni(D-GlcN-en)$_2$]Br$_2$·4H$_2$O **4**. The corresponding value in **2** is 160.7°. In the same comparison, the C–N–C bond angles involving these co-ordinated secondary nitrogens are about 110° in **1** and nearly 120° in **4**. Thus these bond angles approach that of ideal tetrahedral geometry. The amelioration of such a distortion in **1** is presumably due to the strain-releasing effects of the six-compared with the five-membered ring as in **4**. This result is in good accordance with the fact that among the three dien (diethylenetriamine) type ligands, diethylenetriamine, 3-aminopropylethylenediamine and (3-aminopropyltrimethylenediamine), the second has the largest stability constants for complexation involving Ni^{2+}.[36]

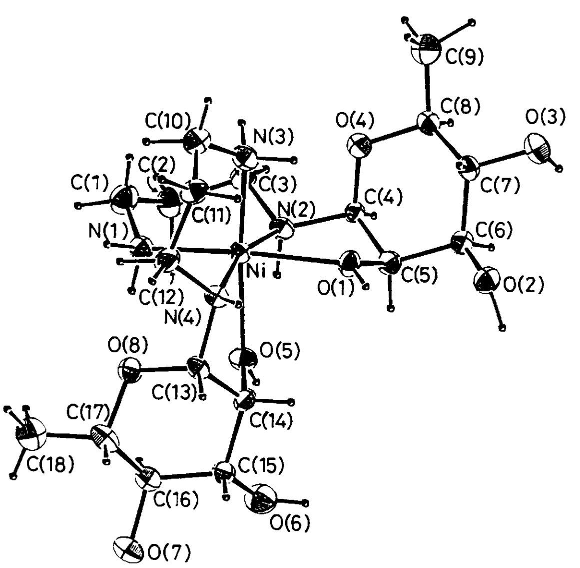

Fig. 2 An ORTEP[33] drawing of $[Ni(L\text{-}Rha\text{-}tn)_2]^{2+}$ with the atomic numbering scheme

Table 3 Fractional coordinates ($\times 10^4$) with standard deviations in parentheses.

Atom	*x*	*y*	*z*
Ni	23(1)	1137.6(4)	2091(1)
O(1)	890(4)	368(2)	1303(4)
O(2)	1809(4)	−631(2)	194(4)
O(3)	2489(4)	−113(2)	−2052(5)
O(4)	630(4)	1049(2)	−830(4)
O(5)	−978(4)	426(2)	2910(4)
O(6)	−1886(4)	−584(2)	4067(5)
O(7)	−2526(5)	−38(3)	6300(4)
O(8)	−647(3)	1106(2)	5008(4)
O(9)	1205(6)	3175(4)	−3728(7)
O(10)	1073(5)	4329(3)	−2618(5)
O(11)	494(5)	3409(3)	1047(7)
N(1)	−1072(5)	1803(3)	2675(5)
N(2)	−822(4)	1011(3)	485(5)
N(3)	1242(5)	1730(3)	1495(5)
N(4)	813(4)	1025(3)	3719(4)
C(1)	−1570(7)	2220(3)	1801(7)
C(2)	−2081(6)	1888(4)	763(7)
C(3)	−1291(6)	1578(3)	−90(6)
C(4)	−176(6)	646(3)	−359(6)
C(5)	354(6)	100(3)	291(6)
C(6)	1158(6)	−235(3)	−495(6)
C(7)	1902(5)	211(3)	−1163(6)
C(8)	1283(6)	744(3)	−1711(6)
C(9)	2041(7)	1232(4)	−2201(8)
C(10)	1740(6)	2164(3)	2348(7)
C(11)	2162(6)	1863(3)	3463(6)
C(12)	1301(6)	1591(3)	4271(6)
C(13)	136(6)	685(3)	4561(6)
C(14)	−433(5)	−162(3)	3912(7)
C(15)	−1233(6)	−169(3)	4718(6)
C(16)	−1979(6)	284(3)	5365(6)
C(17)	−1333(6)	828(3)	5895(6)
C(18)	−2022(7)	1331(4)	6400(7)
C(19)	486(11)	2796(5)	−3048(12)
Br(1)	3855(1)	997.4(4)	1048(1)
Br(2)	255(1)	−1726(1)	1074(1)

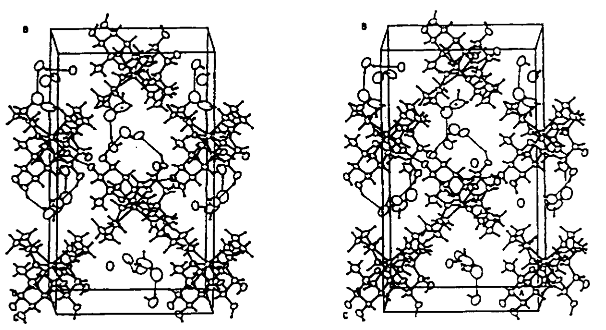

Fig. 3 A stereoview of the unit-cell contents viewed along the *c* axis. Thin lines show hydrogen bonds

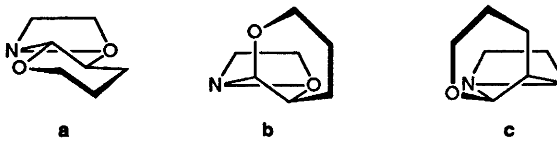

Fig. 4 Three possible co-ordination skeletons for a sugar unit in glycosylamine: **a** *trans*, **b** *cis*-O_{ax} and **c** *cis*-C_{ax}

These structural features support the view that six-membered diamine chelates are an aid in the preparation of metal complexes with glycosylamines. We have observed that sugars react with $[Ni(tn)_3]^{2+}$ to give good yields of the glycosylamine complexes in a short time in this and previous work.[5b]. The inner bond lengths of the sugar moiety are almost the same as those in the single crystal of L-Rha.[35] This observation provides a general ground for the following section.

The bond distances involving the hydrogen atoms in the complex cation range from 0.85 to 1.21 (average 0.99 Å) for C–H, from 0.74 to 1.01 (average 0.88 Å) for O–H and from 0.89 to 1.10 Å (average 0.99 Å) for N–H. Corresponding bond angles range from 98 to 121 (average 110°) for X–C–H (X = C, N or O), from 82 to 139 (average 101°) for C–N–H and from 113 to 129° (average 123°) for C–O–H. Some intermolecular hydrogen bonds of the type O–H ··· O and O–H ··· Br were observed (Fig. 3).

Consideration of the Complex Structures.—To confirm the co-ordinating atoms of the glycosylamine ligands, we have examined the reactions of $[Ni(tn)_3]^{2+}$ and some Glc analogues. When we used 6-deoxy-D-glucose and 3-*O*-methyl-D-glucose the CD spectra of these complex solutions had nearly the same shape as those of the glycosylamine complex derived from D-Glc. However, in the case of 2-deoxy-D-glucose, the CD spectrum of the reaction solution was very different from that of D-Glc. This result clearly indicates co-ordination of the C^2 hydroxy group of the aldose unit.

In the natural aldohexoses the $^4C_1$ chair conformer is more stable than $^1C_4$. One conformational analysis of aldohexose showed the relative stability of $^4C_1$ compared to $^1C_4$ is at least 2.35 kcal mol^{-1} (*ca.* 9.83 kJ mol^{-1}) in the most reducing case of α-D-Tal.[37] So even in co-ordination to a metal ion, the sugar moiety will retain a certain preference for the $^4C_1$ conformation.

On the basis of the above two assumptions concerning the bonding mode and conformational preference of the sugar unit, there appear to be three distinct co-ordination structures for each aldohexoside (Fig. 4). In this figure the absolute configuration on C^2 is chosen as *S* and all other substituents on the pyranoid ring are omitted. For example, in the case of D-Man, the three structures **a**, **b** and **c** correspond to α-$^1C_4$, β-$^4C_1$, and β-$^1C_4$ respectively. The residual α-$^4C_1$ conformer cannot form a chelate ring because its dihedral angle involving the two donor groups on C^1 and C^2 is 180°. The steric stability of these chelate rings may decrease from **a** to **c**, for the former will have fewer ligand–ligand interactions. Structure **a** is the only one containing a *trans* configuration about the C^1–C^2 bond of the pyranoid ring and has the least ligand–ligand interaction among the three. Structures **b** and **c** both involve a *cis* configuration about the C^1–C^2 bond. The difference between these two forms can be discriminated by the axial substituents of the chelate ring: **b** has the axial oxygen on C^1 and **c** has the axial carbon atom

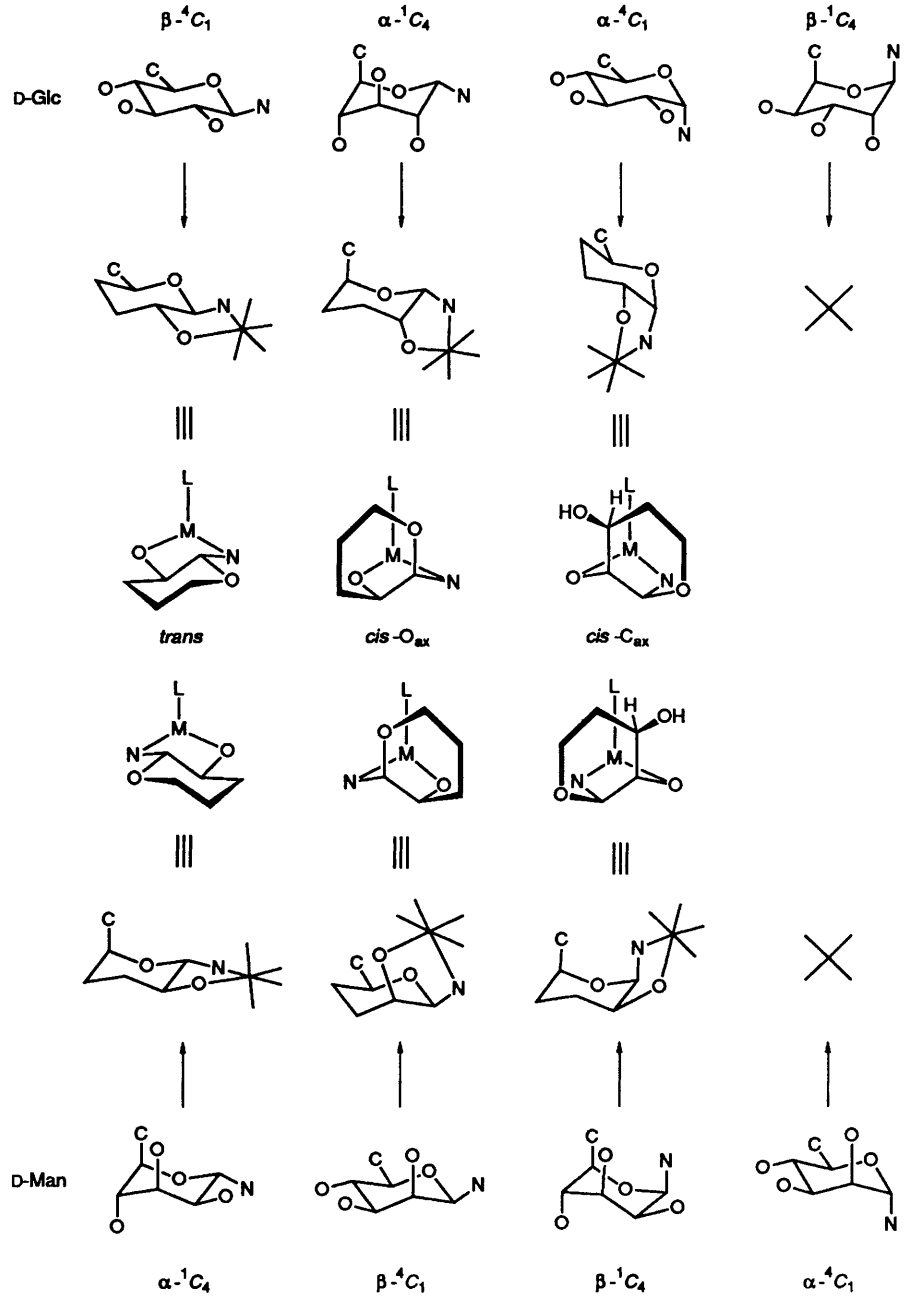

Fig. 5 Possible chelating forms of the $^4C_1$ chair conformer of D-Glc and D-Man

on C^2 with respect to the chelate ring; consequently, **b** will have less steric hindrance compared with **c**. Fig 5 shows the correspondence between the three co-ordination patterns on Fig. 4 and the $^4C_1$ and $^1C_4$ conformers of each anomer of D-glucopyranoside and D-mannopyranoside as typical cases. Among them, the structures having the $^1C_4$ conformation rarely exist in solutions of these monosaccharides.[37] Considering the relative stabilities of both the pyranoid ring and chelate ring, for D-Glc structure **a** will have the minimum energy of the three whereas **b** will be preferred for D-Man. Between these two structures the relative geometry of the two substituents on C^1 and C^2 of the pyranoid ring is clearly seen. In the glycosylamine chelate of complex **1**, the glycosidic nitrogen on C^1 and hydroxy-group on C^2 are oriented with *cis* geometry, whereas in **4** a *trans* geometry is observed. Thus these two typical co-ordination structures of sugar units can be named as the *cis* and *trans* type respectively. Further, in accordance with the correlation in Fig. 5, the ring oxygen of the sugar unit of **1** is axial and that of **4** is equatorial with respect to the chelate ring formed by the sugar units. In contrast, the substituents on C^2 in both **1** and **4** are equatorial. These glycosylamine complexes have been found to contain such sugar parts co-ordinated meridionally to the metal ion as a tridentate chelate. All the natural aldohexoses can be divided into two groups with respect to their relative absolute configurations on C^5 and C^2 shown in Fig. 6. Sugars classified in each group are presumed to adopt an identical co-ordination skeleton, *trans* or *cis*, corresponding to the similar co-ordination skeleton of *trans*- and *cis*-chxn (chxn = cyclohexane-1,2-diamine) respectively. The sugars D-Glc, D-Gal and L-Fuc are classified as *trans*; their absolute configurations at C^2 and C^5 are the same. In contrast, D-Man, D-Tal and L-Rha contain opposite absolute configurations at C^2 and C^5 and are thus classified as *cis*. Since the co-ordination behaviour of aldohexoses discussed above makes no difference

Table 4 Bond distances (Å)

Ni–O(1)	2.169(5)	Ni–O(5)	2.180(5)	Ni–N(1)	2.083(6)
Ni–N(2)	2.108(6)	Ni–N(3)	2.090(6)	Ni–N(4)	2.094(5)
O(1)–C(5)	1.442(9)	O(2)–C(6)	1.410(9)	O(3)–C(7)	1.421(9)
O(4)–C(4)	1.427(8)	O(4)–C(8)	1.440(9)	O(5)–C(14)	1.434(9)
O(6)–C(15)	1.414(9)	O(7)–C(16)	1.433(9)	O(8)–C(13)	1.421(8)
O(8)–C(17)	1.442(9)	O(9)–C(19)	1.431(16)	N(1)–C(1)	1.469(10)
N(2)–C(3)	1.503(9)	N(2)–C(4)	1.472(9)	N(3)–C(10)	1.477(10)
N(4)–C(12)	1.499(9)	N(4)–C(13)	1.464(9)	C(1)–C(2)	1.512(11)
C(2)–C(3)	1.525(11)	C(4)–C(5)	1.537(10)	C(5)–C(6)	1.516(10)
C(6)–C(7)	1.530(10)	C(7)–C(8)	1.515(10)	C(8)–C(9)	1.515(11)
C(10)–C(11)	1.508(11)	C(11)–C(12)	1.519(10)	C(13)–C(14)	1.520(10)
C(15)–C(16)	1.531(10)	C(16)–C(17)	1.541(10)	C(17)–C(18)	1.495(12)

Table 5 Bond angles (°)

O(1)–Ni–O(5)	85.1(2)	O(1)–Ni–N(1)	168.7(2)
O(1)–Ni–N(2)	78.1(2)	O(1)–Ni–N(3)	88.9(2)
O(1)–Ni–N(4)	92.2(2)	O(5)–Ni–N(1)	89.1(2)
O(5)–Ni–N(2)	89.5(2)	O(5)–Ni–N(3)	168.1(2)
O(5)–Ni–N(4)	79.2(2)	N(1)–Ni–N(2)	92.2(2)
N(1)–Ni–N(3)	98.5(2)	N(1)–Ni–N(4)	96.2(2)
N(2)–Ni–N(3)	99.3(2)	N(2)–Ni–N(4)	165.8(2)
N(3)–Ni–N(4)	90.9(2)	Ni–O(1)–C(5)	113.9(4)
C(4)–O(4)–C(8)	111.7(5)	Ni–O(5)–C(14)	110.3(4)
C(13)–O(8)–C(17)	112.4(5)	Ni–N(1)–C(1)	118.9(5)
Ni–N(2)–C(3)	117.2(4)	Ni–N(2)–C(4)	110.8(4)
C(3)–N(2)–C(4)	111.6(5)	Ni–N(3)–C(10)	118.7(5)
Ni–N(4)–C(12)	117.2(4)	Ni–N(4)–C(13)	111.0(4)
C(12)–N(4)–C(13)	111.8(5)	N(1)–C(1)–C(2)	113.8(7)
C(1)–C(2)–C(3)	115.4(7)	N(2)–C(3)–C(2)	109.5(6)
O(4)–C(4)–N(2)	107.0(5)	O(4)–C(4)–C(5)	110.4(6)
N(2)–C(4)–C(5)	109.6(6)	O(1)–C(5)–C(4)	105.3(5)
O(1)–C(5)–C(6)	110.6(6)	C(4)–C(5)–C(6)	111.6(6)
O(2)–C(6)–C(5)	110.0(6)	O(2)–C(6)–C(7)	108.0(6)
C(5)–C(6)–C(7)	112.5(6)	O(3)–C(7)–C(6)	110.2(6)
O(3)–C(7)–C(8)	110.2(6)	C(6)–C(7)–C(8)	112.0(6)
O(4)–C(8)–C(7)	110.6(6)	O(4)–C(8)–C(9)	106.2(6)
C(7)–C(8)–C(9)	111.4(6)	N(3)–C(10)–C(11)	114.4(6)
C(10)–C(11)–C(12)	115.0(6)	N(4)–C(12)–C(11)	110.5(6)
O(8)–C(13)–N(4)	107.4(5)	O(8)–C(13)–C(14)	109.3(6)
N(4)–C(13)–C(14)	109.1(6)	O(5)–C(14)–C(13)	107.5(6)
O(5)–C(14)–C(15)	110.6(6)	C(13)–C(14)–C(15)	111.3(6)
O(6)–C(15)–C(14)	111.1(6)	O(6)–C(15)–C(16)	107.9(6)
C(14)–C(15)–C(16)	112.1(6)	O(7)–C(16)–C(15)	108.9(6)
O(7)–C(16)–C(17)	109.4(6)	C(15)–C(16)–C(17)	111.1(6)
O(8)–C(17)–C(16)	110.8(6)	O(8)–C(17)–C(18)	107.3(6)
C(16)–C(17)–C(18)	114.0(7)		

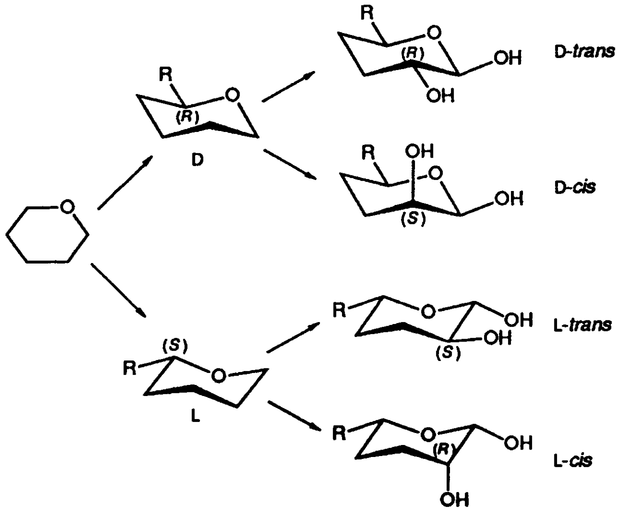

Fig. 6 All the chair conformers for D-Glc and D-Man together with the correspondences with the three types of co-ordination structures

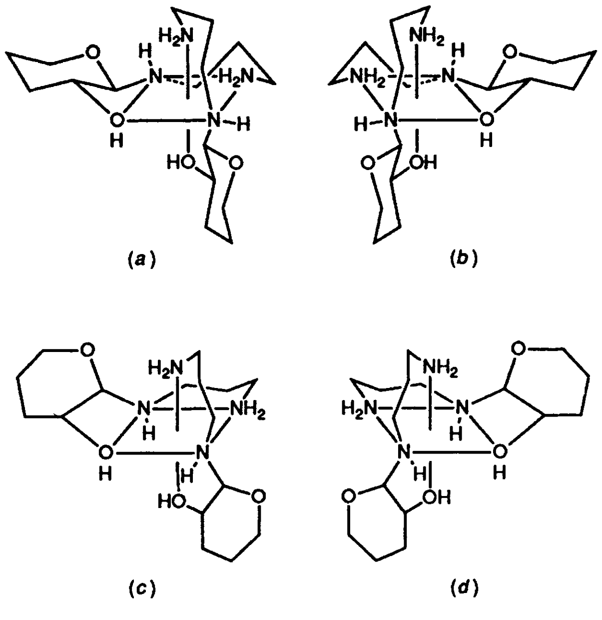

Fig. 7 Overall skeletons of glycosylamine complexes derived from natural aldohexoses and $[Ni(tn)_3]^{2+}$: (*a*) Λ-$[Ni(D\text{-}Glc\text{-}tn)_2]^{2+}$, Λ-$[Ni(D\text{-}Gal\text{-}tn)_2]^{2+}$; (*b*) Δ-$[Ni(L\text{-}Fuc\text{-}tn)_2]^{2+}$; (*c*) Λ-$[Ni(D\text{-}Man\text{-}tn)_2]^{2+}$, Λ-$[Ni(D\text{-}Tal\text{-}tn)_2]^{2+}$; (*d*) Δ-$[Ni(L\text{-}Rha\text{-}tn)_2]^{2+}$

except for the absolute configuration at C^2 and C^5, monosaccharides classified in the same group will adopt the same co-ordination skeleton, and the overall structure of the complexes will be strongly influenced by these partial co-ordination skeletons.

The CD spectra of the glycosylamine complexes from D-Glc and D-Gal exhibit very similar shapes and are nearly enantiomeric to that of L-Fuc. Moreover, the spectra of the complexes from D-Man and D-Tal have a mutually very similar shape which is enantiomeric to that of L-Rha. Thus, the glycosylamine complexes from aldohexoses of the same group have mutually very similar CD spectra. These CD spectral similarities are clearly observed especially as regards the first and the second absorption bands which correspond to d–d transitions of octahedral nickel(II) ions.[32] For such complexes containing saturated ligands, the CD spectra in this region will be more strongly dependent upon the immediate environment of the metal ion. So complexes containing the same co-ordination skeleton will exhibit similar spectra in this region. Consequently the presumptions of the four major co-ordination patterns are also supported by the CD spectral similarities.

Consideration of the overall complex structure reveals *mer* and *fac* isomers involving the two tridentate glycosylamine ligands. The X-ray crystal analyses showed two glycosylamine complexes adopting a meridional mode. Other X-ray crystallographic studies performed so far on octahedral nickel(II) complexes containing two tridentate ligands involving 2 : 2 and 3 : 3 carbon chains in chelate rings also revealed the *mer* form.[38] X-Ray analyses suggest that the glycosylamine ligand will also adopt the *mer* form preferentially. Further consideration of the complex structures reveals the configurational isomers around the metal. Suffice it to say that the *cis*-type glycosylamine ligands will adopt a similar co-ordination skeleton to that of $[Ni(\text{L-Rha-tn})_2]^{2+}$ presently described, because the *cis*-type complexes exhibit mutually very similar patterns in the CD spectra.

Finally, we propose the overall structures of all the glycosylamine complexes derived from aldohexoses to be as shown in Fig. 7. These are the most preferred for all the glycosylamine complexes isolated.

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