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STUDY OF HYDROGEN BONDS IN CRYSTALLINE MONOSACCHARIDES

THE SPECTRA OF MONOSACCHARIDE DERIVATIVES IN THE MIDDLE- AND FAR-INFRARED REGIONS

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ABSTRACT

The spectra of a series of monosaccharide derivatives in the middle- and far-infrared region were investigated. An explanation is provided for the band shifts in the OH stretching region at 3100–3400 cm^{-1} and in the region of hydrogen-bond vibrations at 180–120 cm^{-1} under effect of low temperatures. A comparison of i.r., X-ray, and neutronographic data indicates the absence of intramolecular hydrogen-bonds in the crystalline monosaccharide derivatives investigated.

INTRODUCTION

Interpretation of the infrared (i.r.) spectra of monosaccharides is complicated by the fact that, up to the present, no calculations have been performed for the vibrational spectrum of a pyranose compound, and, moreover, there are no characteristic modes in the spectra of monosaccharides. However, investigation of these compounds has developed in the direction of accumulating experimental data for sugars in the solid state by means of i.r. spectroscopy, as their poor solubility in many organic solvents does not permit obtaining necessary information for solutions thereof. In such cases, deuteration of hydroxyl groups[1,2] has been used for assignment, along with the effect of low temperatures and analysis of the spectra of substituted monosaccharides.

As regards significance for structural analysis, all i.r. spectra have conventionally been divided into three regions: 1, 3650–3100 cm^{-1}; 2, 1500–1300 cm^{-1}; and 3, 900–150 cm^{-1}. The first region contains stretching modes of the hydroxyl groups, which may involve free or associated hydrogen bonds. Owing to the large number of hydroxyl groups in monosaccharides and their derivatives, and because of coupling vibrations, this region is quite complicated, and the spectrum becomes diffuse and thus difficultly interpretable. Band positions corresponding to the hydroxyl stretching-modes may depend upon the configuration and the conformation of the molecule. In some cases, similar conclusions have been drawn from a comparison of i.r. spectra for a solution and the solid state[3,4].

The second region covers the scissoring and wagging types of bending modes of CH_2 and CH_3 groups, as well as to the plane bending, hydroxyl modes[2]. The CH_2 and CH_3 groups do not participate in hydrogen-bond formation, but CH_2 is a part of the CH_2OH group, which produces hydrogen bonds. For cellulose, cellobiose, and other mono-, di-, and poly-saccharides, for example, change in the CH_2 bending modes was observed on greatly lowering the temperature[5]; this was explained by a change of character of the intermolecular hydrogen bonds. On the other hand, it has been found[6] that this explanation is rather inadequate. Due to its low intensity and noncharacteristic nature, the band of a plane bending, hydroxyl mode cannot be used in the study of hydrogen bonds in monosaccharides. Thus, the second i.r. region is not particularly promising, and will not be considered here.

Of specific interest is the region of 900–150 cm^{-1}, which contains bending modes of the pyranose ring[7] and CH groups at the asymmetric carbon atoms in the pyranose ring[7–10], the nonplanar bending vibrations of hydroxyl groups[11], and the skeletal vibrations[11] and stretching vibrations of the hydrogen bonds. Band sensitivity towards change in temperature is so great in this region that the i.r. spectra of monosaccharides and their derivatives change considerably, even above the boiling point of liquid nitrogen[6]. Reliable band assignments for this region have not yet been made, but it may prove to be the most interesting region in view of the possibility of investigating compounds in the solid state.

Below 150 cm^{-1}, modes for the crystalline lattice are found; they have been studied insufficiently, although they could be employed in oligosaccharide investigations[12].

In the present work, the i.r. spectra of some monosaccharide derivatives (see Table I) have been recorded for the regions of 4000–3000 cm^{-1} and 900–40 cm^{-1}. Attention was mainly given to the hydrogen-bond character attending conformational

TABLE I

DISPOSITION OF BONDS TO RING-HYDROGEN ATOMS IN THE PYRANOID COMPOUNDS STUDIED

Compound No.	*Compound*	*Disposition of bonds*[a]
1	Methyl α-D-glucopyranoside	*eaaaa*
2	Methyl α-D-mannopyranoside	*eeaaa*
3	Methyl α-D-galactopyranoside	*eaaea*
4	Methyl β-D-galactopyranoside	*aaaea*
5	Methyl β-D-xylopyranoside	*aaaa*
6	Benzyl 2-acetamido-6-bromo-2,6-dideoxy-α-D-glucopyranoside	*eaaaa*
7	1,2,3,4,6-Penta-*O*-acetyl-α-D-glucopyranose	*eaaaa*
8	Benzyl 2-acetamido-3,4-di-*O*-acetyl-6-bromo-2,6-dideoxy-α-D-glucopyranoside	*eaaaa*
9	Methyl 2-acetamido-2-deoxy-α-D-glucopyranoside	*eaaaa*
10	Methyl 2-acetamido-2-deoxy-β-D-glucopyranoside	*aaaaa*

[a] For proton positions for the *C1* (D) conformation[13,14] of **1–5**, and **7**. For compounds **6** and **8–10**, the *C1* (D) conformation is assumed on the basis of analysis of their molecular models.

changes of molecules, and, moreover, we determined the band assignments specific for certain conformations.

EXPERIMENTAL

Compounds **1**–**5**, **7**, **9**, and **10** (Chemapol products, Czechoslovakia) were further purified by recrystallization from suitable solvents, and were then dried *in vacuo* over phosphorus pentaoxide at 80°. Compounds **6** and **8** were synthesized as described[15]. The i.r. spectra were recorded on a Perkin–Elmer Model 257 (4000–625 cm^{-1}) or a Hilger Model H800 (1000–400 cm^{-1}; KBr prism) i.r. spectrophotometer, as well as on a spectrometer provided with grating FIS-21 (for the region of 500–40 cm^{-1}). In the region of 4000–400 cm^{-1}, the spectra were recorded for KBr pellets, and at 500–40 cm^{-1}, for a Nujol mull between polyethylene windows. The KBr powder was carefully dried before pressing, in order to avoid sample hydration[10].

The low-temperature, i.r. spectra were recorded at 900–400 cm^{-1} and 500–40 cm^{-1} at ~130 K. The temperature was measured with a copper-constantin thermocouple. For the Hilger H800 instrument, a low-temperature, vacuum cell having KBr windows (made in our laboratory) was used. The low-temperature spectra of the samples in KBr pellets and Nujol mulls were identical. In the region of 500–40 cm^{-1}, a Hitachi vacuum cryostat having high-density polyethylene windows was used.

Monosaccharides were deuterated by dissolving in deuterium oxide and evaporating the solution to dryness, the process being performed three times. The degree of deuteration was determined from the band intensity of the OH and OD stretching vibrations.

Frequencies were measured to an accuracy of within ± 3 cm^{-1} (at 4000–3000 cm^{-1}) and ± 2 cm^{-1} (at 1000–40 cm^{-1}). The instruments were calibrated by use of the i.r. spectra recorded for polystyrene and for water vapor.

RESULTS AND DISCUSSION

As already noted, the large number of hydroxyl groups in monosaccharides and their derivatives gives rise to a variety of hydrogen bonds. Therefore, the i.r. spectra change noticeably from one compound to another. In view of this, compounds having the same type of conformation were investigated (see Table I), and thus the spectral changes were due only to the hydrogen-bond specificity.

One of the main, yet still unsolved, problems in the study of the i.r. spectra of monosaccharides and their derivatives consists in assignment of certain bands observed in the spectra to inter- or intra-molecular hydrogen bonds. A useful approach was proposed by Zhbankov[8], who observed a shift of the bands at 3400–3100 cm^{-1} at low temperatures of the sample in relation to those in the region of 3550–3400 cm^{-1}. The bands in the first region were assigned to the stretching vibrations of hydroxyl groups participating in intermolecular, hydrogen-bond formation, and those in the second region were assigned to intramolecular hydrogen-bonds. On the basis of the temperature-dependence of the band shifts in the OH stretching region, Michell[1] assigned the 3465-cm^{-1} band of methyl β-D-xylopyranside (5) to intramolecular hydrogen-bonds, but such an assignment has not been made[1] for cellobiose (having an intramolecular hydrogen-bond[16]). In his investigation of the spectra of other monosaccharides and their derivatives, Michell[1–4,11] did not assign the bands at 3550–3400 cm^{-1}, despite the fact that they shift but little at low temperatures. Moreover, in the spectra of β-D-glucopyranose and β-L-arabinose, the bands at 3550 cm^{-1} and 3530 cm^{-1} were respectively assigned to the so-called "long" intermolecular hydrogen-bonds[4]. Such inconsistency led us to realize the necessity for a more-accurate analysis of the X-ray and neutronographic data on monosaccharides and their derivatives reported in the literature, and for a comparison of these data with specificity of their i.r. spectra. Thus, it has been established that such compounds as β-D-glucopyranose[17,18], α-D-glucopyranose[19,20], β-L-arabinopyranose[21], α-D-glucopyranose monohydrate[22], α-D-xylopyranose[23,24], and methyl β-D-xylopyranoside[25,26] (the i.r. spectra of which have been described[1]), as well as other monosaccharides[27], show no intramolecular hydrogen-bonds. They have only a system of intermolecular hydrogen-bonds (length 2.6 to 3 Å). Intermolecular hydrogen-bonds having a length >3 Å were found, in addition to the ordinary ones, in β-D-glucopyranose and β-L-arabinopyranose. Moreover, they were produced at the O-4 atom. It should be noted that β-D-lyxopyranose[28] may have a weak hydrogen-bond; however, reliable facts supporting this assumption have not been obtained.

Hence, because monosaccharides and their derivatives do not have intramolecular hydrogen-bonds, the assignment of hydroxyl-stretching vibrations must be made somewhat differently. Bands in the 3570–3520-cm^{-1} region should probably be attributed to long, intermolecular hydrogen-bonds, whereas the 3520–3100-cm^{-1} range accounts for a system of intermolecular hydrogen-bonds of 3 Å length, or shorter.

The region of hydroxyl-stretching modes for compounds **1**–**5** is shown in Fig. 1. First of all, attention may be drawn to the difference in the spectra caused by relatively negligible configurational changes in the molecule. Similar specificity can be explained

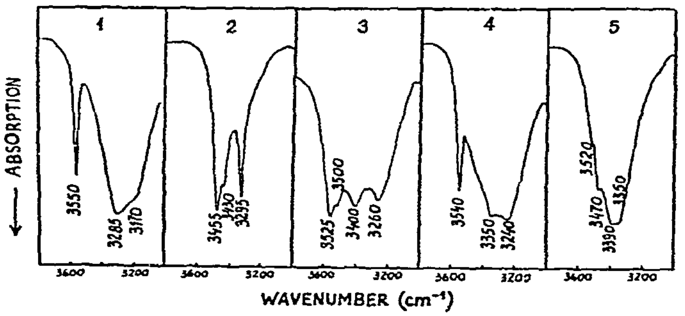

Fig. 1. The i.r. spectra of compounds **1**–**5** (*in* KBr *pellets*) in the OH-stretching region.

by mode coupling of hydroxyl groups. The coupling generally arises with formation of donor–acceptor hydrogen bonds by hydroxyl groups (*cf.*, Fig. 2)[27]. Existence of the donor–acceptor hydrogen-bonds leads to symmetrical disposition of hydroxyl groups in the crystalline lattice and, hence, to the appearance of both symmetric and antisymmetric stretching-vibrations, *e.g.*, to their coupling, as is the case for the methanol molecule[29].

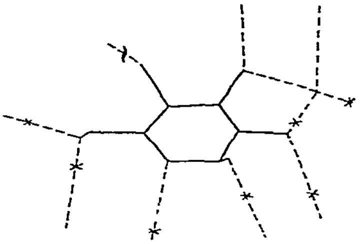

Fig. 2. The character of intermolecular hydrogen-bonds in α-D-glucopyranose monohydrate[21]. Intermolecular hydrogen-bonds are shown by dotted lines.

Bands at 3550–3520 cm^{-1} in the spectra of compounds **1**, **3**, and **4** could be due to the presence of long, intermolecular hydrogen-bonds, and those in the region of 3520–3100 cm^{-1}, to the stretching vibrations of interacting hydroxyl groups producing the shorter, donor–acceptor hydrogen-bonds. From this point of view, the effect of low temperature on monosaccharides and their derivatives may be understood. As it is probable that the system of donor–acceptor hydrogen-bonds is less strong than that generated by the pure donor hydroxyl groups[30,31], it should thus be more sensitive to temperature; this concept also agrees with the observed changes[1,8] in the i.r. spectra in the region of 3520–3100 cm^{-1} of the compounds investigated.

Fig. 3 shows the i.r. spectra of compounds **1**–**10** in the region of 900–400 cm^{-1}. In these series, configurational changes at the asymmetric carbon atoms of the pyranoid ring, and different substitutions at the hydroxyl groups, permit observation of some regularities in the spectra. Band positions of CH bending-modes at 900–750 cm^{-1} have been analyzed[8]. It has been found that, for the CH–OH system in compounds **1**–**4**, depending on the group configuration of the adjacent groups at C-1, C-2, C-3, and C-4 of the pyranoid ring, or for the system C-1–H–OCH$_3$, a band at 925–885 cm^{-1} is found for the *aa* compound, and bands at 855–820 and 885–860 cm^{-1} for the *ea* and *ae* compounds, respectively. For compounds **5**–**10**, the bands for the *aa* and *ea* dispositions appear in the same regions. For compound **10** (having only the *aa* orientation), it may be noted that the position of the CH bending mode is independent of the substituent at the CH group. The band at 882 cm^{-1} in the spectrum of this compound should be assigned to the C–C stretching mode[32] of the amide group in the substituent NHCOCH$_3$. In compound **9**, the latter band is probably shifted to 858 cm^{-1}.

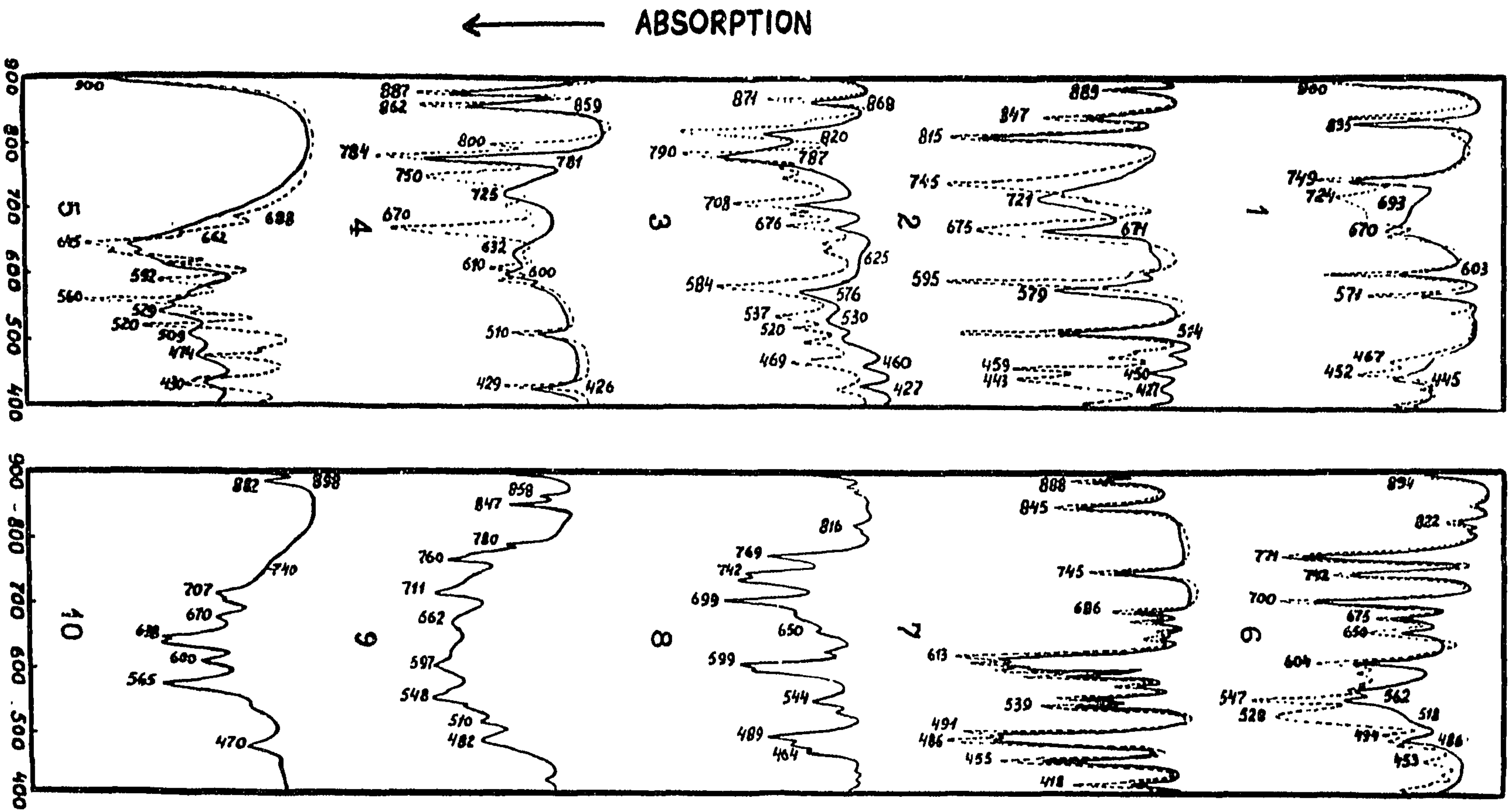

Fig. 3. The i.r. absorption spectra of compounds **1–10** (in KBr pellets) at 900–400 cm^{-1}. The spectra at ~130 K are shown by dotted lines.

As already mentioned, there are several bands in the 3600–3100-cm^{-1} range. These bands should be accompanied by the corresponding, nonplanar, hydroxyl-bending vibrations. To find these, we used the following technique: we deuterated the hydroxyl groups in compounds **1**–**3**, and examined the low-temperature spectra of compounds **1**–**7** (see Fig. 3, dotted lines). In the spectrum of dueterated methyl α-D-glucopyranoside (degree of deuteration, ~90%), the broad band at ~693 cm^{-1} is absent (see Fig. 4). Moreover, essential changes in the region of 500–400 cm^{-1} occur. In the spectra of partially deuterated **2** and **3**, the changes occur in the same regions, but, in the spectrum of methyl α-D-glucopyranoside[11], at 780–600 cm^{-1} and 500–400 cm^{-1}. Under the effect of low temperature, the spectra of compounds **1**–**5** (see Fig. 3) and of methyl α-D-glucopyranoside[11] change in the same regions as for deuterated samples. This is most obvious in the spectrum of compound **1**, which shows a new, intensive band at 724 cm^{-1} and significant changes at 470–400 cm^{-1}. From this observation, it follows that the nonplanar, hydroxyl bending vibrations are sensitive to change in temperature. Taking into account these data, as well as using the results on the low-frequency spectra for hydrogen bonds in phenolic derivatives[33] and in methanol in the solid state at low temperature[34], the bands corresponding to the nonplanar, bending hydroxyl vibrations may be assigned to the regions of 750–600 and 500–400 cm^{-1}. To confirm this conclusion, we studied the

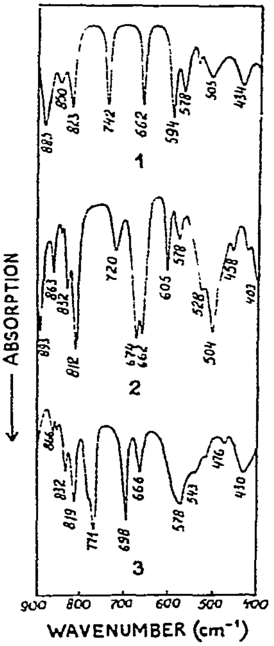

Fig. 4. The i.r. specıra of partially deuterated compounds **1**–**3** (in KBr pellets) in the region of 900–400 cm^{-1}.

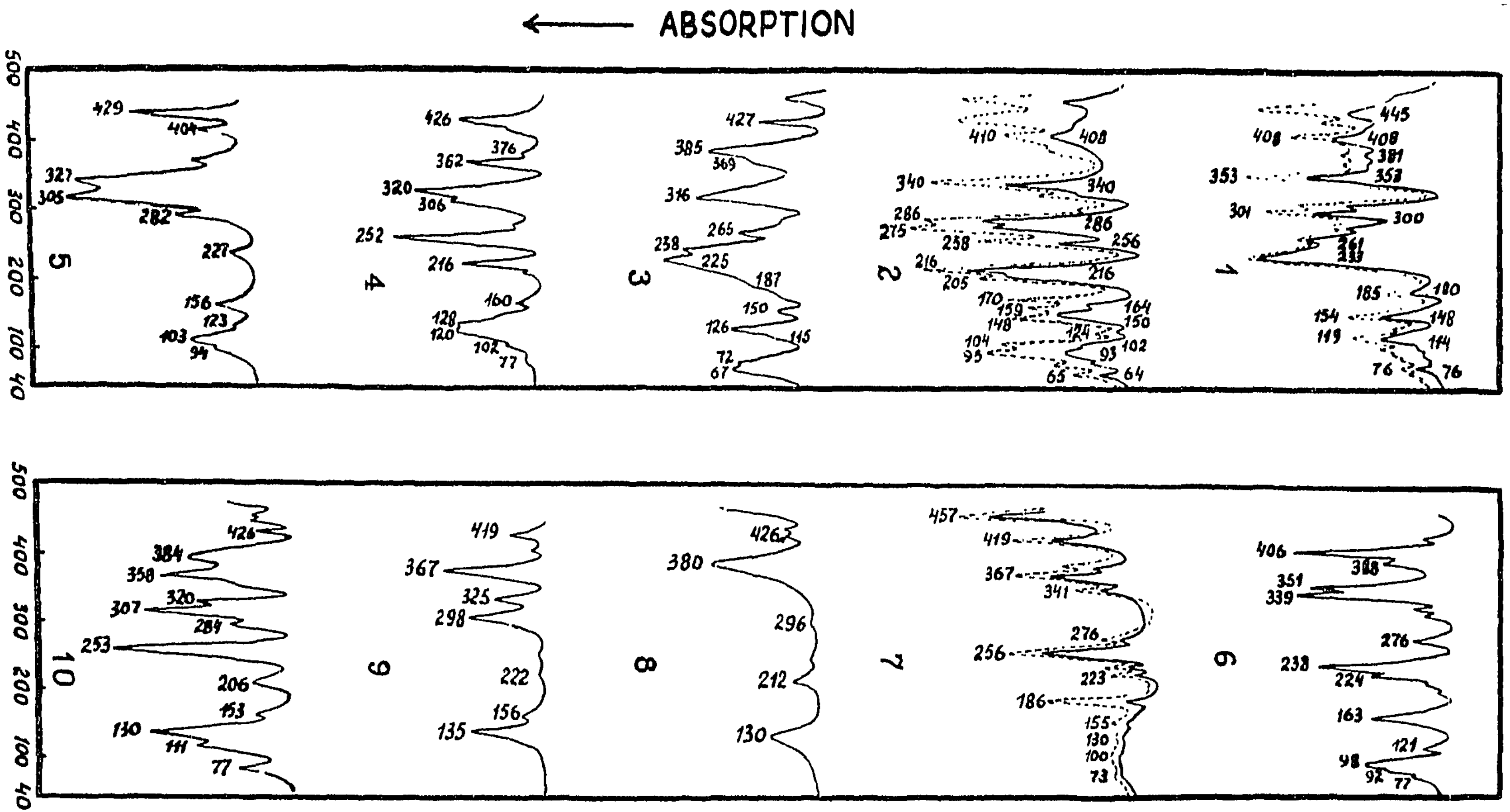

Fig. 5. The i.r. spectra of compounds **1–10** (Nujol mull) in the region of 500–40 cm^{-1}. The spectraat ~130 K are shown by dotted lines.

low-temperature spectrum of **7** (see Fig. 3), which has no hydrogen bonds. No other changes were observed in the spectrum, except for some decrease in half-widths and increase in intensities of the bands.

Fig. 5 shows the i.r. spectra in the region of 500–40 cm^{-1} of compounds **1–10**. Besides skeletal vibrations, this region shows the stretching vibrations of O–H···O groups[34] of the hydrogen bonds themselves. A great variety of changing bands in the region of 400–150 cm^{-1} indicates that they belong to the O–H···O groups participating in intermolecular, hydrogen-bond formation, because skeletal vibrations should not change essentially from one such compound to another. This suggestion is also confirmed by the spectra of **1** and **8**, compounds having no hydrogen bonds. If the bands at 341, 296, 223, and 130 cm^{-1} from the ester groups[35,36] are excluded, it is seen that the remaining spectrum of these compounds contains a negligible number of bands.

Study of solid methanol[34] revealed that the stretching vibration of an intermolecular hydrogen-bond may be found at 360–120 cm^{-1}. We assumed for monosaccharides, analogously to methanol, the same frequency region for intermolecular hydrogen-bonds. As it is probable that donor–acceptor, intermolecular hydrogen-bonds are less stable than the ordinary donor bonds, their stretching vibrations should be more sensitive to temperature change than the corresponding vibrations of ordinary bonds. Hence, the bands due to these stretching vibrations of intermolecular bonds should shift to the high-frequency region. The low-temperature spectra were investigated in the region of 500–40 cm^{-1} for compounds **1**, **2**, and **7** (see Fig. 4, dotted line). For compound **1**, the bands at 180–114 cm^{-1} shifted an average of over 5 cm^{-1}. For compound **2**, still more changes occur at 170–140 cm^{-1}. The bands did not shift in the spectrum of **7**, which forms no hydrogen bonds. It may be concluded that the region of 180–120 cm^{-1} contains the bands corresponding to the vibrations of the donor–acceptor, intermolecular hydrogen-bonds.

In assigning the bands at 180–120 cm^{-1}, the possibility that they also arise from coupled vibrations, with predominant participation of the donor–acceptor, intermolecular hydrogen-bonds, should be taken into account.

Below 120 cm^{-1}, compounds **1–10** show bands corresponding to the crystalline-lattice vibrations. Recently[12], in a study of the low-frequency spectra of D-glucose and sucrose, strong bands at 87 and 61 cm^{-1} found for the latter compound were assigned to interfering vibrations. This assignment should, in our opinion, be supported by additional evidence, because, for the substituted monosaccharides, strong bands are also observed at 100–60 cm^{-1} (see Fig. 4).

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