The Redetermination of the Crystal and Molecular Structure of Chloral Hydrate

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From a chemical point of view, aldehyde hydrate in the form of the gem-dihydroxy compound is usually said to be unstable and seldom isolable. However, when the electon cloud of the carbon atom of a carbonyl group is attracted towards a strongly electron-attracting group by the inductive effect, giving rise to a positive charge on the carbon atom, the hydrate, with its two gem-C–OH bonds, often

becomes stable. In this sense, the crystal of chloral hydrate may not contain the water of crystallization, as is shown by its name, but it may form a part of the molecule, as is evidenced upon its solution by its inability to react with Schiff's reagent.

As for the molecular structure of chloral hydrate, Davies[1] has shown from his infrared study of its carbon tetrachloride solution that there is considerable interaction between the

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1) M. M. Davies, *Trans. Faraday Soc.*, **36**, 333, 1114 (1940).

OH groups and the adjacent CCl_3 radical, and that the OH groups are locked in the cis-position. Novak and Whalley[2] have obtained almost the same results from their infrared study of crystalline chloral hydrate and its solution. They inferred that in solutions of chloral hydrate one of the hydrogen bonds due to the two OH groups might be relatively weakly bonded to one, and the other relatively strongly bonded to the remaining one, of the two chlorine atoms in the same molecule.

According to the quadrupole spectra of chloral hydrate reported by Allen[3], there are three split lines, of which the two with a higher frequency make a pair, while the third is almost 1.25 Mc. lower. It was suggested that two of the three C–Cl bonds are nearly the same, while the third is somewhat different. Theoretical considerations indicated that the hydrogen-bonded chlorine should have a lower C–Cl frequency.

The crystal structure of this substance has been reported by Kondo and Nitta[4] using the X-ray method. However, it was later found by the present author that their results were in error. In view of these circumstances it was felt necessary to determine a new, correct structure for this substance.

Experimental

Chloral hydrate could be recrystallized from a chloroform solution by the evaporation method. At the first stage of crystallization, needle crystals are rapidly formed, but upon repeating recrystallization hexagonal tabular crystals come to grow slowly. The crystals grown along the monoclinic b axes and specimens cut out of hexagonal tabular crystals parallel to the a and c axes respectively were sealed in thin-walled glass capillary tubes to protect the specimens from sublimation by X-rays and from the humidity in the air.

Using Ni-filtered copper K_α radiation, oscillation and Weissenberg photographs were taken of the b and a axes. The photographs were indexed on the basis of a monoclinic unit cell of these dimensions:

$$a = 11.50 \pm 0.03 \qquad b = 6.04 \pm 0.02$$
$$c = 9.60 \pm 0.03 \text{ Å} \qquad \beta = 120 \pm 0.5°$$

These dimensions agreed with values determined by Elliot[5] and by Kondo and Nitta within the range of experimental error. The well-developed face referred to by Groth as the c-face was taken here as (100), and the a, b and c axes designated by Groth agreed with the directions of the −c, b and [101] axes respectively in the present work. Re-

flections of the $0k0$ type with k odd and of the $h0l$ type with l odd were systematically absent from all single crystal photographs. The space group is therefore $P2_1/c$, which finding is different from that reported by previous workers[4,5]. The density of chloral hydrate is 1.91, so there are four molecules in the unit cell.

Intensity data were obtained from multiple film photographs using a Nonius-integrating Weissenberg goniometer for $(hk0)$, $(h0l)$, $(h1l)$, $(h2l)$, $(h3l)$ and $(h4l)$. MoK_α radiation was used for precession photographs of $(hk0)$ and $(0kl)$ around the b axis. Several precession photographs were taken under various exposures in order to correlate all reflections with a linear scale. Intensities were estimated visually by comparison with a calibrated scale of time exposures. The usual Lorentz and polarization corrections were applied. The linear absorption coefficients of this crystal are 15.0 and 132.6 for MoK_α and CuK_α respectively. Thin-walled glass capillary tubes prevented the precise determination of the crystal size, however, so that corrections for the absorption of CuK_α could be applied only roughly and those for MoK_α were not be applied.

Determination of Structure

Sharpened Patterson projections on $(0kl)$, $(hk0)$, and $(h0l)$ were computed. The predominant peaks were considered to be due to the intra- or inter-molecular Cl–Cl interactions. The intra-molecular Cl–Cl vectors were sought, at first, within a radius of 2.95Å from the origin based on a model given by electron diffraction[6]. These vectors must be constructed from a projected figure of the planar regular hexagon with a side length of 2.95Å. It was expected that the Patterson projection on $(h0l)$ along the short b axis would show a more or less satisfactory resolution of the Cl–Cl vectors. Thus, four possible orientations of the projected hexagon around the point of origin were found in the Patterson projection on $(h0l)$. With these orientations, the Patterson projection on $(hk0)$ was also allowed for. The Patterson projection on $(0kl)$ was not useful, because the number of predominant peaks which could be considered Cl–Cl vectors was so few. Each case of the eight possible molecular arrangements in the unit cell, consistent with the Patterson projections on $(h0l)$ and $(hk0)$, was tried on the basis of the orientations of the projected hexagons mentioned above. After several false starts, electron-density projections along [010] were computed which showed fairly good agreement with the assumed model. The several starting false models were the so-called false or pseudo structures, which show a convergence to some extent in the R factors. With the correct

2) A. Novak and E. Whalley, *Spectrochim. Acta*, **16**, 521 (1960).

3) H. C. Allen, Jr., *J. Am. Chem. Soc.*, **74**, 6074 (1952); *J. Phys. Chem.*, **57**, 501 (1953).

4) S. Kondo and I. Nitta, *X-Rays*, **6**, 53 (1950).

5) N. Elliot, *Z. Krist.*, **98**, 180 (1937).

6) C. Degard, *Bull. soc. roy. sci. Liége*, **7**, 36 (1938).

TABLE I.   ATOMIC COORDINATES AND ISOTROPIC TEMPERATURE FACTORS

	x	y	z	B($h0l$)	B($hk0$)	B($0kl$)
Cl(1)	0.2323	0.0378	−0.2289	3.71	2.51	3.11
Cl(2)	0.3139	−0.3547	−0.0267	4.22	2.80	3.19
Cl(3)	0.4051	0.0844	0.1146	4.14	2.44	3.50
O(1)	0.105	0.178	−0.035	3.4	2.7	2.8
O(2)	0.038	−0.200	−0.126	4.2	2.9	2.5
C(1)	0.256	−0.061	−0.048	3.4	2.4	3.4
C(2)	0.145	−0.065	−0.008	3.5	2.6	1.7
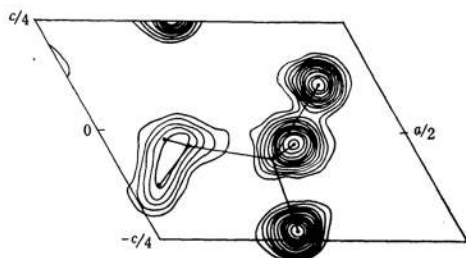
Fig. 1.   The b-axis projection of electron density.   Contours are at equal arbitrary intervals.
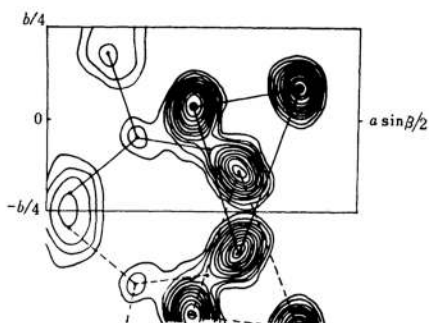

Fig. 2.   The c-axis projection of electron density.   Contours are at equal arbitrary intervals.

Fig. 3.   The a-axis projection of electron density.   Contours are at equal arbitrary intervals.

TABLE II.   BOND LENGTHS AND BOND ANGLES

	Å		Degree
C(1)-Cl(1)	1.72	C(2)-C(1)-Cl(1)	122.4
C(1)-Cl(2)	1.87	C(2)-C(1)-Cl(2)	104.9
C(1)-Cl(3)	1.86	C(2)-C(1)-Cl(3)	109.5
C(1)-C(2)	1.51	Cl(1)-C(1)-Cl(2)	108.0
C(2)-O(1)	1.53	Cl(1)-C(1)-Cl(3)	107.3
C(2)-O(2)	1.44	Cl(2)-C(1)-Cl(3)	103.2
Cl(1)-Cl(2)	2.91	C(1)-C(2)-O(1)	99.6
Cl(2)-Cl(3)	2.92	C(1)-C(2)-O(2)	108.0
Cl(3)-Cl(1)	2.89	O(1)-C(2)-O(2)	109.8
O(1)···Cl″(1)	3.07	Cl(1)-Cl(2)-Cl(3)	59.4
O(1)···O′(2)	2.76	Cl(2)-Cl(3)-Cl(1)	60.0
O′(2)···Cl″(1)	3.12	Cl(3)-Cl(1)-Cl(2)	60.6
O′(2)···O″(1)	2.91	C(2)-O(1)···Cl″(1)	114.5
		C′(2)-O′(2)···Cl″(1)	156.8
		C(2)-O(1)···O′(2)	99.5
		C(2)-O(2)···O′(1)	94.0

structure mentioned above, the electron-density projection along the b axis was refined by the usual Fourier successive approximations. The final electron-density projection along [0 1 0] showed clearly the molecule of chloral hydrate as a whole (Fig. 1), but the electron-density peaks of the two carbon atoms did not show clear resolution owing to the overlapping with those of the oxygen or chlorine atoms. The Fourier projection along [0 0 1] was then computed on the basis both of approximate y parameters as determined from the molecules in the unit cell and of x parameters as known from the ($h\,0\,l$) projection. The Fourier projection along the c axis was also refined in the usual way. The final findings are shown in Fig. 2. The electron-density projection along the a axis was computed on the basis of y and z parameters determined from the Fourier projections along [0 1 0] and [1 0 0]. The results are shown in Fig. 3.
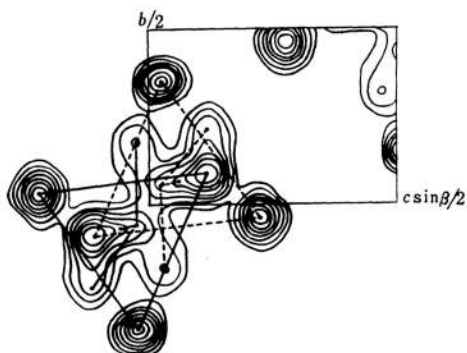
The atomic parameters indicated by the final electron-density map projected along [0 1 0], [1 0 0] and [0 0 1] were further refined by the method of least squares. This least-squares refinement was calculated on the NEAC-2203 computer. In this case, off-diagonal terms were neglected except for those for x and z parameters and those for the scale and overall temperature factors. These results, with the values of the temperature factors for each atom, are listed in Table I. Bond lengths and bond angles calculated from the atomic parameters as determined by the least-squares
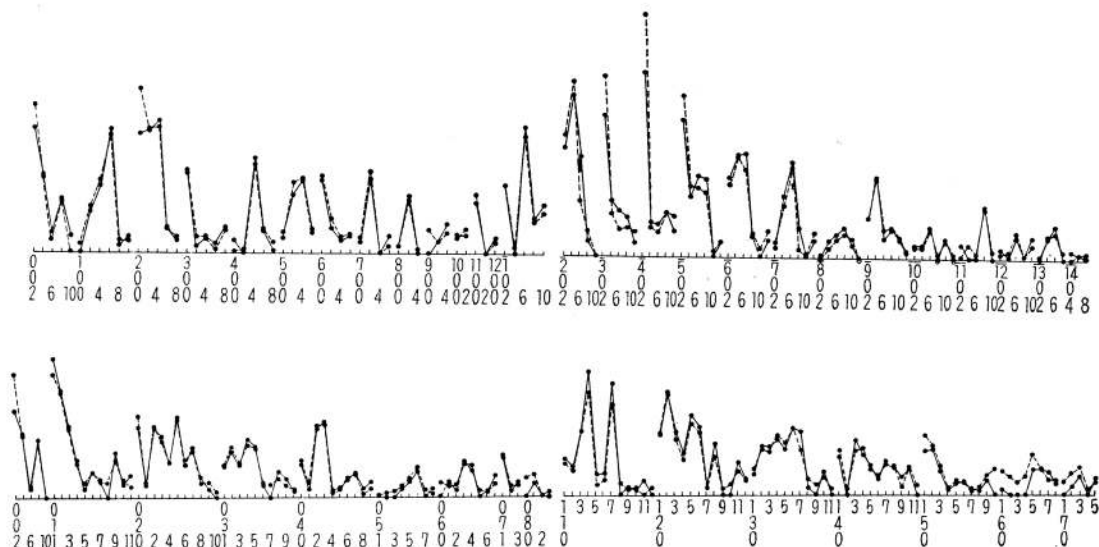
Fig. 4. Comparison between the observed F-values (solid lines) and calculated F-values (dotted lines).

method are listed in Table II. The observed and calculated values of the structure factors are shown in Fig. 4. Isotropic temperature corrections were included in the above calculated values. The R factors for the final coordinates are: $R(h\,0\,l)=18.3\%$, $R(0\,k\,l)=17.7\%$, $R(h\,k\,0)=25.5\%$. In this calculation, only observed structure factors were used.

Discussion and Description of the Structure

As shown in the electron-density maps of Figs. 1, 2 and 3, there is found no existence of the independent molecule of water, as in crystallization, but instead two OH groups attached to one of the two carbon atoms, as given by $CH(OH)_2CCl_3$. The conformation of these OH groups can be described as the staggered gauche referred to as the $C-Cl_3$ group. It is interesting to note that Davies[1] proposed a cis-conformation for this substance on the basis of his infrared study of its solution. Whether these different conclusion are due to the difference in states of aggregation will be an interesting point for further study.

The molecular arrangement in the crystal is shown in Fig. 5. For the sake of a description of the structure, let us first consider those layers of molecules in the structure parallel to the (0 1 0) plane. In each layer, a molecule is surrounded by six molecules. Such layers are juxtaposed in the direction of the b axis, the spacing of these layers being 6.04Å. The three chlorine atoms of a CCl_3 radical make a nearly regular triangle and face another triangle of chlorine atoms of the neighboring molecule related by a center of symmetry, but
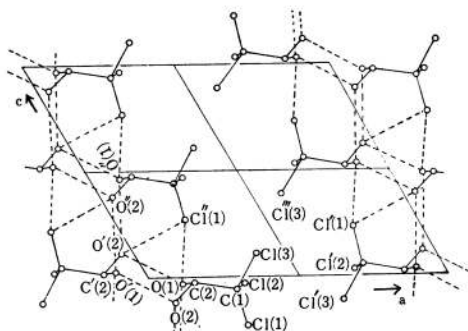

Fig. 5. Projection of the unit cell of chloral hydrate along the b-axis. Hydrogen bonds are shown by dotted lines.

the line joining the two centers of gravity of these triangles is not perpendicular to their triangular planes. The shorter Cl···Cl contracts between these triangles are of the lengths of 3.81, 4.08 and 4.92Å for $Cl(1)···Cl'(3)$, $Cl(2)···Cl'(3)$ and $Cl(1)···Cl'(2)$ respectively, all of which values are greater than the sum of Pauling's van der Waals radius, 3.60Å. Around the $Cl(1)$ atom the shortest approach to another Cl atom is 3.60Å, between $Cl(1)$ and $Cl(2)$ of the next layer above. Around the $Cl(3)$ atom, the separation of 3.79Å is found between the $Cl(3)$ and $Cl'''(3)$ atoms of the molecule approaching diagonally in the same (0 1 0) layer. These circumstances, together with the hydrogen bond formation discussed below, explain the easy cleavage of the crystals parallel to (1 0 0).

In view of the difficulty, for several reasons, in obtaining sufficiently accurate intensity data, the atomic arrangement in the crystal, especially

that of carbon and oxygen, can not be discussed with sufficient precision. In addition to this, the position of the carbon atom bonded with the chlorine atom was still less accurately determined because of the overlapping in the three projected planes seen in Figs. 1, 2 and 3. The discrepancy between C–Cl values, therefore, may not be significant. The C–Cl, C–C and C–O bond lengths may roughly be supposed to be within the range of normal single bond distances.

Hydrogen bond formation is usually determined, in X-ray analysis, from the values of bond lengths and angles. In the crystal of chloral hydrate, the possible hydrogen bonds and angles are:

$O(1)\cdots O'(2)$	2.8 Å	$C(2)-O(1)-O'(2)$	100°
$O(2)\cdots O'(1)$	2.8	$C(2)-O(2)-O'(1)$	94
$O(1)\cdots Cl''(1)$	3.1	$C(2)-O(1)-Cl''(1)$	115
$O'(2)\cdots Cl''(1)$	3.1	$C'(2)-O'(2)-Cl''(1)$	157
$O'(2)\cdots O''(1)$	2.9	$C'(2)-O'(2)-O''(1)$	143

There seem to be two kinds of bifurcated hydrogen bonds between $O(1)$ and $O'(2)$ or $Cl''(1)$, and between $O'(2)$ and $O''(1)$ or $Cl''(1)$. Such a bifurcated hydrogen bond of the $O-H\overset{\cdot O}{\underset{\cdot Cl}{\cdots}}$ type has been found in the crystal of tetrachlorohydroquinone[7] and pentachlorophenol[8] by Sakurai. In the case of chloral hydrate crystal, the existence of one hydrogen-bonded chlorine atom is consistent with the results of the quadrupole study of Allen[3].

Some Further Structural Studies of Chloral Hydrate

Though the crystal structure of chloral hydrate at room temperature has been determined as stated above, it seemed necessary to examine further whether there is another phase in the crystal. A thermal differential analysis of this substance from room temperature to about 70°C was carried out*. The results thus obtained show that it is transformed into a high-temperature form at 52.6°C on heating and melts at 55.0~64.5°C. The staggered curve shown at a temperature above the melting point appears to suggest the complex nature of chloral hydrate in the molten state. It could be seen with chemical reagents that the decomposition into chloral and water partially took place.

The structure of a possible high-temperature phase could not be determined, but the Norelco

7) T. Sakurai, *Acta Cryst.*, **15**, 443 (1962).
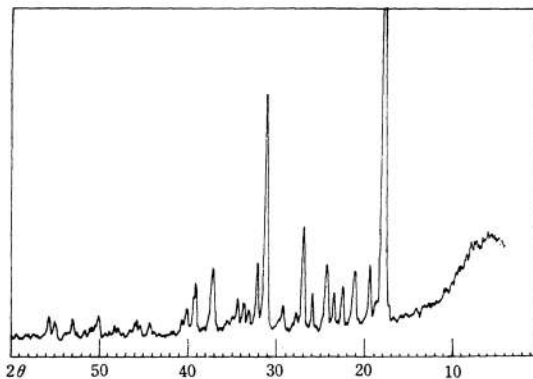8) T. Sakurai, ibid., **15**, 1164 (1962).

Fig. 6-a. Norelco diffraction powder pattern of chloral hydrate of room-temperature phase.
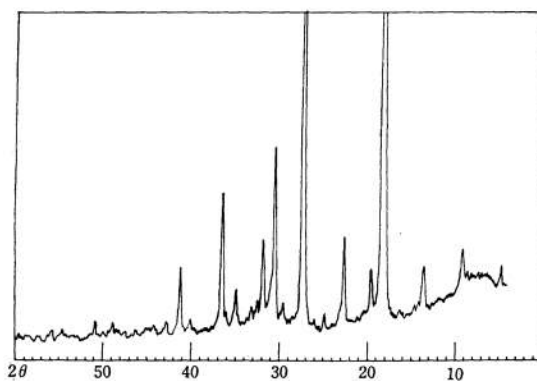

Fig. 6-b. Norelco diffraction powder pattern of chloral hydrate of high-temperature phase which may contain that of room-temperature phase.
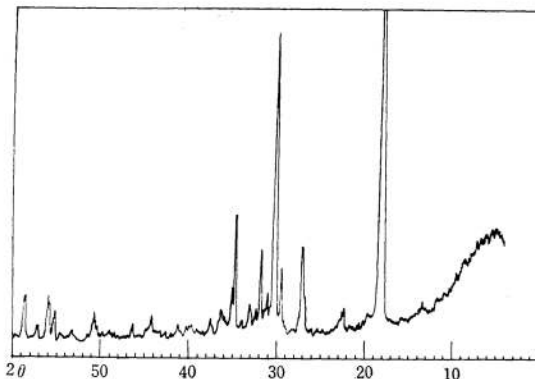

Fig. 6-c. Norelco diffraction powder pattern of chloral hydrate of high-temperature phase after 36 hr. passed from the experiment of Fig. 6-b.

diffraction powder patterns at different times after crystallization from the molten state appear to show that the high-temperature phase changes slowly and partially towards the room-temperature phase. (Fig. 6) The unit cell of the high-temperature phase seems to

be large compared with that of the room-temperature phase, because the spacings of the former cell contain 19.19, 9.71 and 6.51Å, which correspond to those of (0 0 1/2), (0 0 1) and (010) of the latter cell; these later values are absent because of the limitations of the space group and of the size of the latter cell.

To obtain further information on the molecular structure and on the nature of the intermolecular hydrogen bonds, the infrared spectra of chloral hydrate in a solid and in solutions of several kinds of solvents (benzene, chloroform, carbon tetrachloride and carbon disulfide) have been taken. The measurements were made with a Hitachi model EPI-2 spectrometer equipped with a NaCl or LiF prism. The chief absorption bands noticed are:

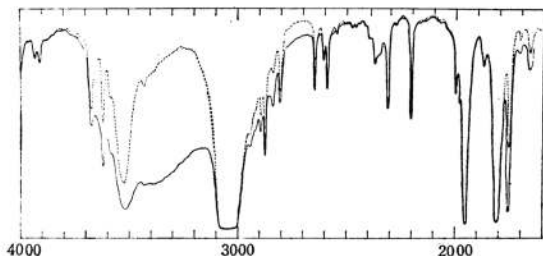|	O–H cm^{-1}	C=O cm^{-1}	H_2O cm^{-1}
Solid (KBr disk)	3360 (broad)	—	—
Benzene solution	3617, 3525	1770	1605

Fig. 7-a. Infrared spectra: (a) solid line, chloral hydrate in benzene solution; (b) dotted line, about one-third of concentration of a.
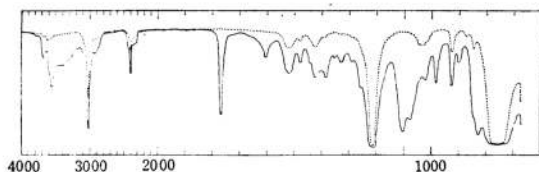
Fig. 7-b. Infrared spectra: (a) solid line, chloral hydrate in chloroform solution; (b) dotted line, pure chloroform.
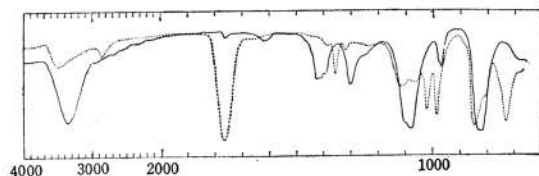
Fig. 7-c. Infrared spectra: (a) solid line, solid chloral hydrate as KBr disk; (b) dotted line, pure chloral.

9) D. M. W. Anderson, L. J. Bellamy and R. L. Williams, *Spectrochim. Acta*, **12**, 233 (1958).
10) L. P. Kuhn, *J. Am. Chem. Soc.*, **74**, 2492 (1952).

As has been indicated by previous workers[3,9,10], there are two sharp absorption bands due to two kinds of OH groups in solutions of chloral hydrate, of which the one with the higher frequency is due to the relatively weakly hydrogen-bonded groups and the other, to the relatively strongly hydrogen-bonded groups, whereas the crystalline chloral hydrate has a broad band which is of a lower frequency than the two bands in solutions and which is due to the intermolecular-bonded OH, as is shown in Fig. 7. The solution spectra of chloral hydrate show a strong absorption band at 1770 cm^{-1} and a weak broad band near 1605 cm^{-1}. The former band appears also in chloral, while the latter band often appears in substances containing water molecules, so that it can be considered that the former is due to carbonyl-stretching vibration and the latter, to the in-plane OH deformation vibration of a water molecule. Though the 1770 and 1605 cm^{-1} absorption bands appear very faintly in the solid state, they are caused by the dissociation of crystalline chloral hydrate into chloral and water, because a small part of the solid will dissolve either in moisture within a KBr disk or in Nujol.

On the one hand, chloral hydrate fails to show color with Schiff's reagent and reacts with Tollen's reagent or Fehling's solution, while these three reagents are said to be specific to aldehydes. On the other hand, it is to be noticed that aldose, in general, reduces Fehling's solution and Tollen's reagent, while it does not react with the Schiff reagent. It is said that this is due to the cyclic hemiacetal structure of aldose. From the characteristic chemical reactivity and the interpretation of the infrared absorption bands, it might be inferred that the following dissociation equilibrium would take place in a solution of chloral hydrate as seen in ordinary aliphatic aldehyde. Then, the water and chloral molecules produced by dissociation would re-combine without delay, as shown in the following equilibrium schemes:
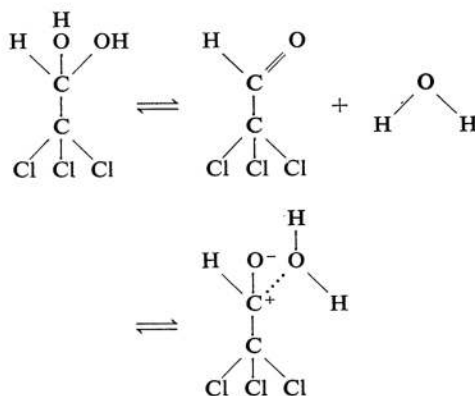
This water molecule would be combined with a chloral molecule by a weak bond, but it would be loosened upon being heated more or less, so that chloral hydrate might react differently with the Schiff reagent upon being heated according to the degree of dehydration in the solvents employed, and the color produced by the combination with the Schiff reagent would fade away sooner or later on cooling. At any rate, the molecular structure of chloral hydrate in a solution or liquid state seems to be different from that of a solid state and is so complex that other equilibrium schemes should be considered. Of these possible equilibria, the most predominant one would have the structure cited above.

Summary

The crystal structure of chloral hydrate has been redetermined by the two-dimensional Fourier method and the least-squares method on the NEAC-2203 computer. It is monoclinic and belongs to the $P2_1/c$ space group, with four molecules in a cell of the dimensions $a=11.50$, $b=6.04$, $c=9.60$ Å and $\beta=120.0°$. The molecular structure of chloral hydrate is of the gem-dihydroxy compound type with the two OH groups in the staggered gauche-position referred to the adjacent C–Cl_3 group. The molecules of chloral hydrate in the crystal are held together mainly by the van der Waals attraction of Cl···Cl and by the bifurcated hydrogen bonds of O–H$\overset{\textstyle .Cl}{\underset{\textstyle \cdot O}{\vdots}}$. As a result of differential thermal analysis, a high-temperature phase has been found between 53.6° and the melting point, which was ascertained by X-ray diffraction powder patterns. Some of the molecules of chloral hydrate appear to dissociate into water and chloral and attain equilibrium with them. This is inferred from infrared study and from the chemical reactivity with the Schiff reagent.

Recently, according to a private communication from Dr. George Marshall Brown of the Oak Ridge National Laboratory to Professor Isamu Nitta, he is now analyzing the structure of this crystal by the neutron diffraction method.

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