242. *Infra-red Spectroscopy and Structural Chemistry. Part IV.**
*The Infra-red Spectra of Some Tetronic Acids.*

By L. A. Duncanson.

The infra-red spectra have been measured of some tetronic acids as solids and as solutions in various solvents. In some cases it has been found that the keto-forms of the acids predominate in solution.

The production of tetronic acid derivatives (*i.e.*, lactones of γ-hydroxy-β-keto-acids, I) by micro-organisms (Raistrick, *Proc. Roy. Soc.*, 1950, **136**, *B*, 481) and the biological interest concerning them made it desirable that the infra-red spectra of some simple tetronic acids should be investigated more fully than hitherto. During this work it has become apparent that infra-red spectra can provide a useful means of identification for this type of compound. The vibrational spectra of some substances related to tetronic acid (II; R = R' = R'' = H) have been described by Trotter, Thompson, and Wokes (*Biochem. J.*, 1948, **42**, 601), whose studies included the infra-red spectra of hydroxytetronic acid and ascorbic acid, and by Edsall and Sagall (*J. Amer. Chem. Soc.*, 1943, **65**, 1312), who measured the Raman spectra of tetronic acid, nitrotetronic acid, ascorbic acid, and their sodium salts in aqueous solutions. The ultra-violet absorption spectra of some tetronic
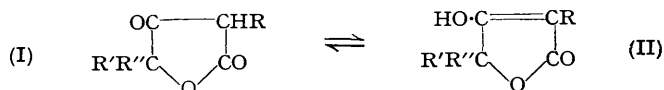
acids have been described by Herbert and Hirst (*Biochem. J.*, 1935, **29**, 1881) and by Jones and Whiting (*J.*, 1949, 1419) who concluded that, in alcoholic solutions, tetronic acids exist in the enol form (II). A similar conclusion for dioxan solutions was reached by Kumler (*J. Amer. Chem. Soc.*, 1940, **62**, 3292) by means of dipole-moment measurements. The work now described includes a study of the infra-red spectra of some tetronic acids in solution and this provides evidence that in some solvents an equilibrium between the ketonic and the enolic forms (I and II) can exist, with the keto-form predominating.

EXPERIMENTAL

M. p.s are corrected. Microanalyses are by Mr. W. Brown.

The tetronic acids were prepared by known methods. They were carefully purified to constant m. p. before use, and found to be analytically pure.

Tetronic acid was prepared by Wolffe and Schwabe's method (*Annalen*, 1896, **292**, 231) except that the intermediate bromotetronic acid was reduced catalytically (palladium–charcoal) instead of with sodium amalgam. Purified by sublimation *in vacuo*, it had m. p. 139—140°. α-Acetyltetronic acid was prepared as described by Benary (*Ber.*, 1909, **42**, 3912), the isolation of the product being modified slightly as follows. The alkaline solution remaining after the hydrolysis of the α-acetyltetronic acid amide was treated with chloroform and then acidified with 6N-nitric acid while the mixture was shaken. Crude α-acetyltetronic acid was obtained as a yellowish solid from the chloroform layer and was purified by sublimation *in vacuo* and crystallisation from benzene, then having m. p. 80—81°. α-Ethyl- and (±)-γ-methyl-tetronic acids, prepared according to Clutterbuck, Raistrick, and Reuter's method (*Biochem. J.*, 1935, **29**, 316, 1308), had m. p. 126° and 118°, respectively.

Samples of the lactone of β-hydroxy-β-1-hydroxy*cyclo*hexylacrylic acid and its methyl ether were kindly provided by Professor E. R. H. Jones, F.R.S., and samples of terrestic and carolic acids by Professor H. Raistrick, F.R.S.

Infra-red measurements were made with a modified Hilger D 209 spectrometer (Grove and Willis, *J.*, 1951, 877). Solid samples were finely ground and suspended in " Nujol " between rock-salt plates in the usual way. Ultra-violet absorption was measured with a Unicam S.P. 500 spectrophotometer.

Solvents were dried and distilled before use. The chloroform used contained about 1% of ethyl alcohol as a stabiliser and no precautions were taken to remove it.

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RESULTS AND DISCUSSION

It is proposed to limit the discussion principally to the 5·0—6·5 μ region of the spectra, wherein double-bond stretching modes usually produce well-marked absorption bands. At longer wave-lengths it is difficult to assign bands to particular vibrational modes of complex molecules and at shorter wave-lengths the poor resolving power of the rock-salt prism makes accurate observations difficult. The 5·0—6·5 μ region is adequate for the purpose of discussing the structure of tetronic acids and, in conjunction with the spectra of the solids between 3 and 4 μ, seems to provide a useful means of determining in many cases whether a substance is a tetronic acid or not.

In Table 1 are listed the frequencies of the absorption maxima observed for the different

TABLE 1. *Frequencies of double-bond stretching bands of some tetronic acids in the solid state and in solution.*

| Compound	Solid	CHCl$_3$ + 1% EtOH	Solvents C$_2$H$_4$Cl$_2$	CCl$_4$
Tetronic acid : R = R′ = R″ = H	OH {2620, 2530} 1690 s, 1636 m, 1565 s	~1820 w, 1778 *, 1738 s, 1632 s (0·03; 0·25 mm.)	—	—
α-Ethyltetronic acid : R = Et, R′ = R″ = H	OH 2690, 1720 m, 1650 s, 1580 *	1744 s, 1675 s (0·051; 0·25 mm.)	3470 w, 1760 s, 1675 s (0·021; 0·25 mm.) (0·00116; 5·5 mm.)	1818 m., 1771 s, 1731 m, 1672 s (Sat.; 10·5 mm.)
γ-Methyltetronic acid : R′ = Me, R = R″ = H	OH {2640, 2540} 1720 s, 1634 m, 1575 s	~1810 w, 1758 m, 1739 s, 1632 s (0·039; 0·25 mm.)	1811 m, 1762 s, 1640 w (0·028; 0·25 mm.)	1811 m, 1765 s (Sat.; 10·5 mm.)
β-Hydroxy-β-1-hydroxy*cyclo*-hexylacrylic lactone : R′R″ = [CH$_2$]$_5$>, R = H	OH {2695, 2510} 1683 s, 1565 s	~1790 w, 1746 s, 1630 s (0·03; 0·25 mm.)	1793 m, 1757 s, ~1680 w, ~1620 w (0·018; 0·25 mm.)	—
α-Acetyltetronic acid : R = Ac, R′ = R″ = H	OH 3080, 1758 s, 1675 s, 1600 s	1772 s, 1705 s, 1675 m, 1610 s (0·031; 0·25 mm.)	1772 s, 1700 s, 1673 m, 1615 s (0·021; 0·25 mm.)	1784 s, 1706 s, 1676 m, 1617 s (0·035; 0·25 mm.) (0·0011; 5·5 mm.)

Intensities denoted by : s = strong; m = medium; w = weak.
Molar concentrations and cell lengths given in parentheses.
* Shoulder.

tetronic acids as solids and in solutions. The Figure shows a few of the spectra in order that the general pattern of the changes produced by different solvents can be visualised.

It is seen that, with the exception of α-acetyltetronic acid, all the acids have much lower-frequency carbonyl bands in the solid state than would normally be expected for five-membered-ring lactones (see Grove and Willis, *loc. cit.*). This is interpreted to mean that strong intermolecular association through hydrogen bonds occurs in the solids. In this respect, tetronic acid and the alkyltetronic acids studied show a strong resemblance to the enolised six-membered-ring 1 : 3-diketones such as dimedone (Rasmussen, Tunnicliff, and Brattain, *J. Amer. Chem. Soc.*, 1949, **71**, 1068) and this similarity is further emphasised by the relatively low frequencies of their OH stretching bands (2530—2650 cm.$^{-1}$) in the solid state. The spectrum of α-acetyltetronic acid has a band at 1758 cm.$^{-1}$ which is assigned to the lactone-carbonyl group. It is apparent that in this case the lactone-carbonyl group does not take part in hydrogen-bond formation in the solid state. Bands at 3080, 1675, and 1600 cm.$^{-1}$ are assigned respectively to vibrations involving OH stretching, >C=O stretching, and C=C stretching in the system ·C(OH):C·C:O which forms part of structures (III) and (IV). An analogy can again be found in the case of the enolised 1 : 3-diketones by comparing the carbonyl absorption of dimedone

(1605 cm.$^{-1}$; Rasmussen *et al., loc. cit.*) with the corresponding band in its 2-acetyl derivative (1670 cm.$^{-1}$) reported by Birch (*J.*, 1951, 3026). In this case, as with the tetronic acids, the acetyl-carbonyl group presumably forms an intramolecular hydrogen bond with the enolic hydroxyl group, thereby leaving the remaining carbonyl free from intermolecular bonding.

(III)

(IV)
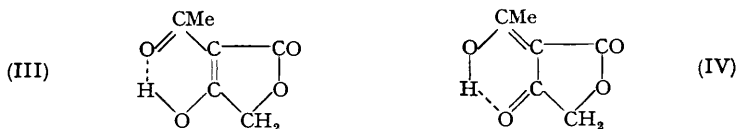
Before leaving the subject of the spectra in the solid state, it must be pointed out that the assignment of bands to specific groups is complicated in many cases by the appearance of more bands in the double-bond stretching region than there are double bonds in the molecules concerned. There are various possible explanations of this anomaly which are however, outside the scope of this paper.

Absorption spectra of some tetronic acids.
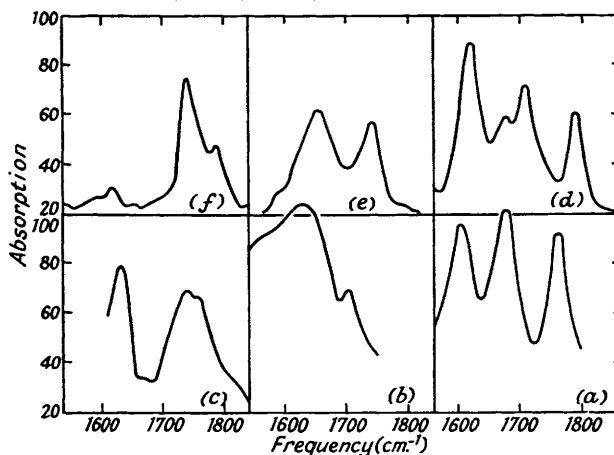
(a) α-Acetyltetronic acid (solid).
(b) α-Ethyltetronic acid (solid).
(c) γ-Methyltetronic acid in CHCl$_3$ (0·039M; 0·25-mm. cell).
(d) α-Acetyltetronic acid in CCl$_4$ (0·025M; 0·25-mm. cell).
(e) α-Ethyltetronic acid in CH$_2$Cl·CH$_2$Cl (0·22M; 0·25-mm. cell).
(f) γ-Methyltetronic acid in CH$_2$Cl·CH$_2$Cl (0·028M; 0·25-mm. cell).

The effect of dissolving tetronic acid and the alkyltetronic acids in chloroform is to shift the bands assigned to double-bond stretching modes to higher frequencies, thereby confirming that the compounds are associated by intermolecular hydrogen bonds in the solid state. The frequencies occurring in the chloroform solutions are consistent with the acids being lactones of γ-hydroxy-β-keto-carboxylic acids in the enolic form (II). Thus the strong bands occurring in all the spectra at 1740—1750 cm.$^{-1}$ are due to the $\Delta^{\alpha\beta}$-five-ring lactone-carbonyl groups, and those near 1630 cm.$^{-1}$ to the C=C stretching modes. The effect of an alkyl substituent on this double-bond frequency, *e.g.*, in the case of α-ethyl-tetronic acid, is to raise it to 1675 cm.$^{-1}$. Under similar conditions α-acetyltetronic acid shows a less marked change in its lactone-carbonyl band compared with that in the solid, which confirms that intermolecular bonding does not take place in the crystalline state of this compound. The spectra of solutions of α-acetyltetronic acid all have the strong band which occurs for the solid at 1675 cm.$^{-1}$ replaced by a strong band near 1700 cm.$^{-1}$ together with a somewhat weaker one near 1675 cm.$^{-1}$. This may mean that in solution the acid exists as an equilibrium mixture of (III) and (IV), the ketonic carbonyl groups in the two cases having different frequencies owing to their different situations in the molecule.

In the spectra of tetronic and the γ-substituted tetronic acids in chloroform solution it

can be seen that weak bands occur at frequencies higher than 1750 cm.$^{-1}$ and this suggests that a keto–enol equilibrium is present with the enol predominating. This equilibrium can be altered by changing the solvent, a suitable one being ethylene dichloride. This solvent absorbs in the region 1650—1800 cm.$^{-1}$ which makes it unsuitable for use with very dilute solutions in thick cells, but for cell thicknesses up to 0·25 mm. it is quite satisfactory and only tetronic acid itself is too insoluble for useful observations to be made. With the other acids in this solvent some interesting results were obtained. γ-Methyltetronic acid and the lactone of β-hydroxy-β-1-hydroxy*cyclo*hexylacrylic acid both show well-marked absorption bands near 1800 and 1760 cm.$^{-1}$, which are the frequencies expected for saturated 5-ring lactone and saturated 5-ring ketone carbonyl groups respectively. Hence it must be presumed that in ethylene dichloride the keto-forms of these acids predominate (I; R = R′ = H, R″ = Me; I; R = H, R′R″ = [CH$_2$]$_5$ >). This is confirmed by the almost complete disappearance of the band due to the C=C stretching modes near 1630 cm.$^{-1}$. α-Ethyltetronic acid, on the other hand, gives no indication of the presence of the keto-form and it must be concluded that the α-alkyl substituent stabilises the enol form. This stabilisation may be due, at least in part, to hyperconjugation. The spectrum of α-acetyl-tetronic acid in ethylene dichloride shows no appreciable differences from that in chloroform, again demonstrating the insensitivity of this molecule to changes in environment.

By using a 10-mm. cell it was also possible to measure the absorption spectra of saturated solutions of α-ethyl- and γ-methyl-tetronic acids in carbon tetrachloride. The latter acid again showed bands corresponding to the keto-form, while bands in the spectrum of α-ethyltetronic acid at 1818, 1770, 1731, and 1672 cm.$^{-1}$ indicate the presence of a keto–enol mixture. In neither of these carbon tetrachloride solutions could OH absorption be found, but better resolution might make such an observation possible in the case of α-ethyl-tetronic acid.

TABLE 2. *Ultra-violet absorption.*

Compound	$\lambda_{max.}$ (mμ)	log $\varepsilon_{max.}$	Compound	$\lambda_{max.}$ (mμ)	log $\varepsilon_{max.}$
α-Ethyltetronic acid (concn. in C$_2$H$_4$Cl$_2$, 8·28 × 10^{-4}M) :			γ-Methyltetronic acid (concn. in C$_2$H$_4$Cl$_2$, 11·1 × 10^{-4}M) :		
(i) In ethylene dichloride	225	4·0	(i) In ethylene dichloride	~219	2·9
(ii) In aqueous H$_2$SO$_4$	233	4·1	(ii) In aqueous H$_2$SO$_4$	226—227	4·2

Cell length, 0·1 cm. The values for solutions in dilute mineral acid are taken from Herbert and Hirst (*loc. cit.*).

Some ultra-violet absorption measurements were made on solutions in ethylene dichloride of α-ethyl- and γ-methyl-tetronic acids, which confirm the conclusions drawn from the infra-red spectra. It was found that 0·1 cm. of the solvent only transmitted about 3% of the incident light at 220 mμ, but by using very wide slits (2 mm.) it was just possible to make measurements in this region. They are presented in Table 2, together with the corresponding results of Herbert and Hirst (*loc. cit.*) for the undissociated molecules in aqueous solution. The figures show that α-ethyltetronic acid absorbs strongly near 225 mμ in ethylene dichloride and at 233 mμ in aqueous solution, while γ-methyl-tetronic acid absorbs much more weakly in this region when dissolved in ethylene dichloride. This indicates that in both ethylene dichloride and dilute aqueous mineral acid α-ethyltetronic acid exists as the enol form, but that the enol form of γ-methyltetronic acid is not present to any great extent in ethylene dichloride solution.

It can now be seen how infra-red spectroscopy may be used to identify tetronic acids and, in some cases, to draw conclusions about the positions of substituent groups. It must be emphasised, however, that these results have been obtained from a study of only five compounds and it is possible that other tetronic acids might behave differently. This being borne in mind, the infra-red absorption of tetronic acids can be summarised as follows : (i) In the solid state, alkyltetronic acids have strong hydroxyl absorption bands in the range 2500—2700 cm.$^{-1}$ and strong double-bond stretching bands near 1650—1700 cm.$^{-1}$ and 1565—1580 cm.$^{-1}$, due to the enol forms associated through strong inter-molecular hydrogen bonds. (ii) Dilute solutions of alkyltetronic acids in chloroform containing a trace of alcohol show bands near 1740 and 1630 cm.$^{-1}$ (1740 and 1675 cm.$^{-1}$

for α-substituted acids) corresponding to the monomeric enol forms. (iii) γ-Alkyltetronic acids dissolved in ethylene dichloride have absorption bands near 1800 and 1760 cm.$^{-1}$, which correspond to the keto-forms. (iv) α-Acyltetronic acids do not show a marked change in the general pattern of their absorption spectra in passing from the solid state to solution. The last generalisation presumably applies to all tetronic acids in which the enolic OH group is able to form an intramolecular hydrogen bond with an oxygen atom. This class includes ascorbic and hydroxytetronic acids, which were found by Trotter *et al.* (*loc. cit.*) to have absorption maxima at 1750 cm.$^{-1}$ (lactone $>C\!=\!O$) and 1650 cm.$^{-1}$ ($C\!=\!C$) in the solid state.

The spectra of terrestric and carolic acids, two naturally occurring compounds related to tetronic acid, have been measured and they are consistent with the structures proposed for the acids by Raistrick *et al.* (*Biochem. J.*, 1935, **29**, 871; 1936, **30**, 2194). The spectra of the solids include strong bands near 1745, 1710, and 1610 cm.$^{-1}$ which are assigned to the tetronic acid (lactone) $>C\!=\!O$ group, the side-chain aliphatic ketone group, and the carbon–carbon double bond, respectively. Under anhydrous conditions these compounds are more closely related to the alkyl ethers of tetronic acids than to the acids themselves, and, for comparison, the spectrum of the methyl ether of β-hydroxy-β-1-hydroxy*cyclo*-hexylacrylic acid was measured in the solid state. It had strong bands at 1735 and 1628 cm.$^{-1}$ corresponding to those near 1745 and 1610 cm.$^{-1}$ in the spectra of terrestric and carolic acids. The spectra of the acids dissolved in chloroform are similar to those of the solids, there being strong bands in the double-bond stretching region near 1760, 1710, and 1610 cm.$^{-1}$. Neither of these compounds shows OH absorption near 3 μ, which is also in agreement with the proposed structures.

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