

15. *Investigations of the Olefinic Acids. Part VI.*
Lactonisation and Allied Additive Reactions. Part
I. The System $\alpha\beta$ -Acid- $\beta\gamma$ -Acid- γ -Lactone.

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PREVIOUS communications in this series have dealt mainly with the tautomeric changes of unsaturated acids. A study is now being made of another very interesting reaction of these substances, their lactonisation. This has hitherto only been generally observed for acids with the double bond in the $\beta\gamma$ - or $\gamma\delta$ -position with respect to the carboxyl group and is here regarded as involving a process of self-addition, in which the portions of the carboxyl group, H and R·CO·O, become attached to the unsaturated centre. A connexion may be looked for between addition of this type and that of such similar groups as hydrogen halide, a reaction which has recently been the subject of theoretical study by Ingold and others.

These heterogeneous additions may be affected both in velocity and in orientation by the nature of the unsaturated molecule. The double bond being regarded as an anionoid centre (Lapworth, *Nature*, 1925, **115**, 625; Allan, Oxford, Robinson, and Smith, J., 1926, 401), and hydrogen halide as normally initiating its attack by means of its more active kationic component, addition will proceed most readily in the direction such that hydrogen is added to the more negative or potentially negative carbon atom (Ingold and Ingold, J., 1931, 2354). In unsaturated acid systems this will be the simple controlling factor and steric effects may be expected to exercise a minor influence. Moreover, in unsaturated acids other than those with an $\alpha\beta$ -double bond, orientation of addition will be mainly determined by permanent (inductive) molecular polarisations and hence may be expected to be largely independent of the nature of the active addendum, whether polarised molecule or free ions.

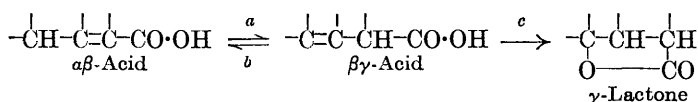
In lactonisation no such simple effect is present: the polar activation of the double bond will certainly act in the same way and will be altered by the same factors, but a number of other influences must come into play. Addition will be largely determined both in ease and in orientation by the stability of the lactone ring and by the ease of approach of the two active centres. A combination of these factors accounts, for example, for the comparative ease of formation of γ - and δ -lactones. As regards the "approach factor," as Mills (Reports Inst. Solvay, 1930, p. 23) has pointed out in a similar connexion, self-addition may be expected

to be more ready when the carboxyl group is adjacent to the double bond and hence to be favoured in those compounds the molecules of which (viewed statistically) deviate most under the conditions of reaction from the normal zig-zag configuration or, alternatively, are mostly in a bent condition. Other (probably minor) factors which may affect lactonisation are the variation in activity of the carboxyl group with substitution and the influence of valency deflexion and the steric impedance of bulky groups on the approach of the reacting centres.

In this series of investigations it is hoped to throw light on the relative importance of these factors. The present paper deals with a critical study of the classical work on the lactonisation of $\alpha\beta$ - and $\beta\gamma$ -acids.

The general relationship between $\beta\gamma$ -acids and γ -lactones was mainly established by Fittig and his school during the period 1880—1894. In 1883 (*Ber.*, **16**, 373) it was shown that certain unsaturated acids could be converted into lactones by boiling 50% sulphuric acid, and later (*Ber.*, 1893, **26**, 40; *Annalen*, 1894, **283**, 47) it was emphasised that this was confined to $\beta\gamma$ -acids and to allylacetic acid (the one $\gamma\delta$ -acid then known) but that $\alpha\beta$ -acids were completely unchanged by such treatment. As is well known, Fittig applied this difference in reactivity to the analysis of mixtures of $\alpha\beta$ - and $\beta\gamma$ -acids and maintained its rigidity in a strongly worded statement [*loc. cit.* (1894), p. 53], although little definite experimental support was adduced. Later workers have shown that in systems containing a chain branched at the β -carbon atom the $\alpha\beta$ -acids readily yield γ -lactones on treatment with hot 50% sulphuric acid (Fichter and collaborators, *Ber.*, 1909, **42**, 4707, 4710; Blaise and Luttringer, *Compt. rend.*, 1905, **140**, 148; Kon and Linstead, *J.*, 1925, **127**, 616) and it has been concluded that such acids provide an exception to the general rule (compare Willstätter and Hatt, *Annalen*, 1918, **418**, 148).

In the present work it is shown that all acid-lactone systems of this kind can be interpreted in one general scheme :



Fittig's observations are shown to be incorrect, simple $\alpha\beta$ -acids such as he used giving appreciable quantities of lactone under his experimental conditions. The variations between different systems can be attributed to differences in the ratio of the velocity of the tautomeric change (a and b) to that of ring closure (c). Three, possibly four, types of acid can be distinguished :

(i) Those in which both changes are slow but lactonisation is much faster than tautomeric change (acids with one γ -alkyl and no β -alkyl substituent).

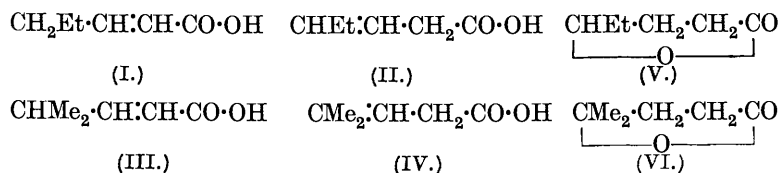
(ii) Those in which lactonisation is fast and tautomeric change slow (acids with two γ -alkyl substituents).

(iii) Those in which tautomeric change is faster than lactonisation (acids with one γ - and one β -substituent).

(iv) (?) Those in which tautomeric change is fast and irreversible in the direction $\beta\gamma \rightarrow \alpha\beta$, no lactonisation being possible (acids without γ -substituents).

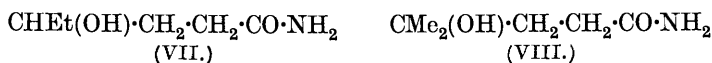
Lactonisation (c) has been formulated above as irreversible. Careful search has as yet given no definite evidence of the formation of $\beta\gamma$ -acid from a simple lactone by treatment with sulphuric acid or by prolonged heating. It is of interest, however, that such a reaction is possible in more complicated systems such as lactonic acids of the paraconic type; for instance, pyrolysis of terebic acid gives a considerable quantity of teraconic acid (Fittig and Geisler, *Annalen*, 1881, **208**, 37; Goldberg and Linstead, J., 1928, 2343).

The experimental section describes the cyclisation of $\alpha\beta$ - and $\beta\gamma$ -acids of the *n*- and *iso*-hexenoic series (I, II, III, IV) into *n*- and *iso*-hexolactones (V, VI) respectively.



The methods used for the analysis and separation of mixtures of acids and lactone are there fully described.

The *n*-hexenoic acids serve as an example of type (i). The solid $\beta\gamma$ -acid (II) of m. p. 12° (Boxer and Linstead, J., 1931, 740) is very rapidly changed by boiling 50% sulphuric acid (Fittig's method) into the lactone (V), characterised by its conversion by ammonia into the γ -hydroxy-amide (VII) of m. p. $74\text{--}75^\circ$. Fittig and



Dubois (*Annalen*, 1890, **256**, 152) obtained the same derivative (m. p. 74°) from a lactone prepared from hydrosorbic acid. At room temperature, sulphuric acid of this concentration has little effect on the $\beta\gamma$ -acid, but 60% acid is completely miscible with it and lactonisation is fairly rapid (half-change, about 4 hours). The $\alpha\beta$ -isomeride (I) is completely unaffected by cold 60% acid, but boiling 50% acid rapidly produces the γ -lactone (V) identical with

that formed directly from the $\beta\gamma$ -acid and yielding the same γ -hydroxy-amide (VII). Lactonisation is almost complete in an hour (half-change, about 25 minutes), while in the time generally used by Fittig the lactone formed amounts to about 11% of the initial material.* On protracted boiling alone, neither the $\alpha\beta$ - nor the $\beta\gamma$ -acid yields any perceptible quantity of lactone. These results show that, as regards the $\alpha\beta$ -acid, tautomeric change into the $\beta\gamma$ -isomeride precedes lactonisation and, as the slower reaction, is that which determines the velocity of the ring formation. In the cold, no tautomerism occurs and there is no lactonisation of the $\alpha\beta$ -acid under conditions under which the $\beta\gamma$ -acid lactonises.

The isohexenoic acids belong to type (ii) and differ from the n -acids in the extraordinary ease of lactonisation of the $\beta\gamma$ -isomeride, pyroterebic acid (IV). Fittig and Geisler (*loc. cit.*) observed that this acid passed almost completely into the γ -lactone (VI) on being boiled alone for an hour, and this result has been confirmed, the change being not quite complete in $3\frac{1}{2}$ hours. Other $\gamma\gamma$ -dialkyl $\beta\gamma$ -unsaturated acids show a similar ease of lactone formation (von Braun and Münch, *Annalen*, 1928, 465, 52) and it is clear that this is connected with molecular substitution but is independent of the nature of the specific process used to effect lactonisation. In agreement with this, in the present work it is shown that pyroterebic acid is almost completely lactonised by 15 minutes' treatment in the cold with 50% or 60% sulphuric acid. The lactone formed is in every way identical with that produced by the action of heat on terebic acid or on pyroterebic acid. It melts at 8—9° and yields the same hydroxy-amide, m. p. 101° (compare Ström, *J. pr. Chem.*, 1893, 47, 220, who gives m. p. 101°).† This difference between the $\beta\gamma$ -acids of the n - and *iso*-series is most striking and can be illustrated by a simple comparative experiment. A small amount of the acid is allowed to stand for 15 minutes with 5 volumes of 60% sulphuric acid. When the solution is poured into ice and water and, if necessary, saturated with ammonium sulphate, an oil separates which rapidly solidifies; the solid obtained from n -hexenoic acid is the unchanged acid, that from the *iso*-acid is the lactone.

The introduction of the second γ -alkyl group thus produces a

* Similar results have since been obtained by Mr. E. J. Boorman in collaboration with the author, working with Δ^2 -pentoic acid, which is rapidly lactonised by boiling 50% sulphuric acid, contrary to Fittig and McKenzie's statement (*Annalen*, 1894, 283, 86).

† The fact that this lactone gives an amide is contrary to the generalisations of H. Meyer (*Monatsh.*, 1899, 20, 717), who states that lactones containing a quaternary γ -carbon atom yield lactams, not hydroxy-amides, on treatment with ammonia. It seems certain that in this respect Meyer's rules are based on insufficient data.

marked effect on lactonisation in agreement with that required on the assumption of kationic attack in the β -position. As, however, the part played by the "approach" factor is as yet obscure, it is proposed to withhold further comment on this point.

Unlike the $\beta\gamma$ -acid, Δ^{α} -isohexenoic acid (III) is lactonised with but little more readiness than is Δ^{α} -*n*-hexenoic acid. With cold 60% sulphuric acid, lactonisation is inappreciable, while under Fittig's conditions the change is virtually complete in an hour, with a half-change period of about 25 minutes, the lactone produced being identical with that obtained from the $\beta\gamma$ -acid. This is in agreement with the hypothesis that the tautomeric change is slower than and precedes the formation of lactone. The tautomeric mobilities of the two series would be expected to be of the same order and the greater facility for ring formation of the *iso*- $\beta\gamma$ -acid would make no appreciable difference.

It has been observed (Linstead, J., 1930, 1603) that $\alpha\beta$ - and $\beta\gamma$ -unsaturated acids pass slowly into equilibrium mixtures at or near their boiling points. Further, Δ^{β} -isohexenoic acid passes rapidly and irreversibly on boiling into the γ -lactone. It was therefore to be expected that Δ^{α} -isohexenoic acid would be lactonised slowly and irreversibly on boiling. This has been realised experimentally, the solid γ -lactone (m. p. 8—9°) being obtained. The change is so slow that side reactions intervene to some extent, but after 6 days' boiling the purified product contains 63% of the γ -lactone.

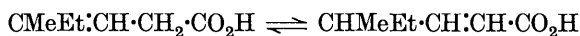
No new experimental work is here presented as to the behaviour of the two other types (iii) and (iv), but the major differences from the types discussed above are indicated by means of data already recorded. For instance, $\alpha\beta$ -acids of the $\beta\beta$ -dialkylacrylic series are lactonised by boiling 50% sulphuric acid as fast as are their $\beta\gamma$ -isomerides (*loc. cit.*). Mr. J. M. Wright, working in collaboration with the author, has recently found that *trans*- β -methyl- β -ethylacrylic acid is lactonised in the cold by 60% sulphuric acid at roughly the same rate as is the corresponding $\beta\gamma$ -unsaturated acid. It is necessary to assume here that the tautomeric change is unusually facile (type iii). As regards type (iv), it would appear from the work of Fichter and Sonneborn (*Ber.*, 1902, **35**, 938) that vinylacetic acid, the simplest $\beta\gamma$ -acid, yields no lactone but only the $\alpha\beta$ -acid (crotonic) on treatment with sulphuric acid, suggesting a definite abnormality. Examples of both these types are now under study and further comment may therefore be reserved.

The fact that lactonisation can occur in pure dry $\beta\gamma$ -acid in the absence of reagent (*e.g.*, in the acid IV) shows that self-addition is a simple process and makes it unnecessary at present, in the absence

of any positive evidence, to assume the operation of a more complicated mechanism in the sulphuric acid reaction. It might be supposed that γ -hydroxy-acids are first formed from the $\beta\gamma$ -acids and then lose water to give the lactones, but this explanation fails to account satisfactorily for the large difference between the *n*- and *iso*-hexenoic series; for it has been shown by Hjelt (*Ber.*, 1891, 24, 1236) that lactones are formed from the γ -hydroxy-*n*- and *iso*-hexenoic acids at very similar rates. As some doubt existed as to the purity of Hjelt's *n*-hexolactone (which might have been prepared from "hydrosorbic acid"), these experiments were repeated with lactone prepared from "solid" Δ^{β} -*n*-hexenoic acid, and gave results in substantial agreement with those of Hjelt.

It has been stated that all the $\alpha\beta$ -acids yet examined, except those of type (iv), readily yield γ -lactones on being boiled with 50% sulphuric acid. This change indicates a general method for the preparation of these substances, which should be preferable to any at present available, in those cases where the $\alpha\beta$ -acids are easily accessible. For example, in the present work, γ -*n*-hexolactone was obtained in 65% yield from butaldehyde in two simple operations. The value of the original method of Fittig for the analysis of $\alpha\beta$ - $\beta\gamma$ -mixtures is destroyed by these new results. On the other hand, if such mixtures are treated with 60% sulphuric acid in the cold for a convenient time, the $\beta\gamma$ -acid is lactonised almost quantitatively, and analysis of the acid-lactone content gives the $\alpha\beta$ - $\beta\gamma$ -ratio in the original sample. By means of this method results have been obtained in good agreement with those obtained by iodometric analysis, but its applicability is obviously limited to acids of types (i) and (ii). Similarly, cold 60% sulphuric acid may be used for freeing $\alpha\beta$ -acids of these types from small amounts of their isomerides.

The present reinvestigation of the *isohexenoic* acids has explained a puzzling discrepancy with regard to the equilibrium of the 3-carbon tautomeric system (III \rightleftharpoons IV) in alkali. For these acids, Goldberg and Linstead (*loc. cit.*) found the following mean iodine additions: $\alpha\beta$ -, 1.8%; $\beta\gamma$ -, 73.4%; equilibrium mixture, 71.3%, giving a value of 95% $\beta\gamma$ -acid at equilibrium. More recently Linstead and Mann (*J.*, 1930, 2064) made the corresponding determinations for the homologous acids



which gave iodine additions: $\alpha\beta$, 0.5%; $\beta\gamma$, 94%; equilibrium mixture, 77%, corresponding to 77% $\beta\gamma$ -acid. This difference in the point of equilibrium is unexpected, as the nature of a γ -alkyl group generally has no effect on a three-carbon equilibrium.

It is now found that pyroterebic acid as usually prepared either

from terebic or Δ^{α} -isohexenoic acid is always contaminated with the γ -lactone even after purification through bicarbonate solution. This contamination is due partly to physical dissolution of the lactone in the aqueous solution and partly to the lactonisation of the acid on liberation from the solution of its salt by mineral acid. Both these disadvantages can be avoided by careful work and pyroterebic acid has now been obtained almost free from lactone. This material gives iodine additions both before and after equilibration in striking agreement with those found for the higher homologues :

Mean % Iodine Addition to Lactone-free Material.

	$\gamma\gamma$ -Dimethyl series.	γ -Methyl- γ -ethyl series.
$\alpha\beta$ -Acid	0.6	0.5
$\beta\gamma$ -Acid from		
paraconic acid	95.5	95.8
equilibrium mixture	94.4	93.9
Equilibrium mixture		
from $\alpha\beta$ -acid	75.4	75.9
from $\beta\gamma$ -acid	78.7	78.3

The true position of equilibrium is precisely that found for the methyl ethyl series, namely 22—23% $\alpha\beta$ -acid.

Solidification and the determination of melting points at low temperatures is of considerable value for the estimation of the purity of unsaturated acids and lactones generally, and many simple substances of these types have now been obtained solid for the first time. A marked tendency to supercooling often prevents their solidification in ordinary freezing mixtures, although their melting points may be reasonably high. Of the substances relevant to the present paper, pure pyroterebic acid readily solidifies in solid carbon dioxide-ether to a mass of shining white leaflets, resembling solid Δ^{β} -*n*-hexenoic acid in appearance and melting at -4.5° (corr.). Solid Δ^{α} -isohexenoic acid has m. p. -22° (corr.), but *n*-hexolactone remains liquid at -78° .

EXPERIMENTAL.

(Recorded densities and refractive indices are for d_{4}^{20} and n_{D}^{20} respectively. Concentrations of sulphuric acid are expressed as volume percentages throughout.)

Analysis and Separation of Mixtures of Acids and Lactones.—The free acid was determined by direct titration in aqueous alcoholic solution with *N*/10-baryta. A known excess of the baryta was then added, and the solution heated for 10 minutes on the steam-bath under a reflux condenser fitted with a soda-lime tube. The excess of baryta in the cooled solution was determined by back-titration with *N*/10-sulphuric acid. The results obtained are

expressed below as % reactions (to the nearest $\frac{1}{2}$ %), the equivalent for the acids and lactones being assumed to be 114.1. For separation, mixtures were dissolved in saturated sodium bicarbonate solution and the lactone was thoroughly extracted with ether. The acids were recovered from the bicarbonate solution by cautious acidification (to Congo-red) at 0° and were immediately extracted with ether. The acids and lactone were then recovered and dried in the usual way, the samples being finally left over calcium chloride and paraffin wax in a vacuum desiccator. Iodine additions (*J*) of acid mixtures were determined by the method of Linstead and May (J., 1927, 2565), a 10-minute reaction being used for the *n*-acids and a 5-minute reaction for the *iso*-acids, and a temperature of 20° (Linstead and Mann, J., 1931, 723).

n-Hexenoic Acids.

The acids (I and II), prepared by the methods of Boxer and Linstead (*loc. cit.*), melted sharply at 33° and 12° respectively.

Action of Sulphuric Acid on the $\beta\gamma$ -Acid.—(1) *Hot 50% acid* (compare Fittig, *loc. cit.*, 1894). The hexenoic acid (10 g.) and 50 c.c. of 50% sulphuric acid were heated as rapidly as possible to the boiling point and the homogeneous solution was kept boiling under reflux for 5 minutes. The mixture was cooled somewhat, diluted with 100 c.c. of water, and again boiled for 10 minutes. The cold solution was saturated with ammonium sulphate and thoroughly extracted with ether. The residue after removal of ether was separated into acid (0.55 g.) and lactone (7.4 g.). *n*-Hexolactone so obtained boiled steadily at 86°/10 mm., remained liquid at -78°, and had *n* 1.4387, *d* 1.0261. Titration showed 0.5% of acid and 99% of lactone. The acid fraction failed to solidify in a freezing mixture: this indicates some conversion of $\beta\gamma$ - into $\alpha\beta$ -acid (equation *b*, p. 116).

The lactone (2 g.) was cooled to 0° and mixed with 1 c.c. of aqueous ammonia saturated at 0°. On standing in a closed vessel, the mixture became homogeneous within an hour and was then kept in an open dish over sulphuric acid in a vacuum desiccator. In 2 hours it set to a deliquescent crystalline mass, which was washed with ether and drained on a porous tile in the desiccator (1.7 g.; 74%). γ -Hydroxy-*n*-hexoamide (VII) so obtained crystallised from chloroform in thick prisms, m. p. 74—75°, and when pure was stable in moist air (compare Fittig and Dubois, *loc. cit.*) (Found: N, 10.9. Calc., 10.7%).

(2) *Cold 50% acid.* The $\beta\gamma$ -acid (5.25 g.) was shaken for 15 minutes with 50% sulphuric acid (5 vols.) at room temperature. No heating and only partial solution occurred. The product was

poured into ice and water (120 c.c.) and saturated with 75 g. of ammonium sulphate; the solid acid then separated. It was extracted and dried as usual without removal of lactone. After distillation 92% was recovered, b. p. 92°/8 mm., n 1.4395, d 0.9653, containing 98.5% of acid and 2.5% of lactone. This solidified in ice in the characteristic foliated leaflets of the $\beta\gamma$ -acid and melted at 10–11°.

(3) *Cold 60% acid.* The acid (3 g.) was kept for 15 minutes with 15 c.c. of 60% sulphuric acid. Solution was complete but no heating occurred on mixing. The product was worked up as in expt. (2) and yielded 2.90 g. of acid, without distillation. This had m. p. 8–9° (acid, 95.5%; lactone, 2.5%).

(4) *Cold 60% acid (8 hours).* After distillation, which left a viscous residue, 53% of a product was obtained, b. p. 87–89°/9 mm. (acid, 21%; lactone, 78%).

(5) *Cold 60% acid (41 hours).* Lactonisation was almost complete and the product (60% after distillation) had b. p. 86°/9 mm., n 1.4402, d 1.0252 (acid, 6%; lactone, 94%).

(6) *Cold 90% acid in ether.* 3.4 G. of acid, 3.3 g. of the sulphuric acid solution, and 7 c.c. of sodium-dried ether gave a homogeneous solution, which was left for 50 hours and worked up as before. Distillation yielded 83% of material, b. p. 102°/9 mm. (acid, 97%; lactone, 4%), m. p. 9–11°.

Action of Sulphuric Acid on the $\alpha\beta$ -Acid.—(7) *Hot 50% acid.* This reaction was carried out exactly as in expt. (1), solution being very incomplete on boiling. The lactonic product (13%), which had b. p. 85–89°/8 mm., n 1.4434, d 1.0116, was not completely free from acid (25% acid, 74% lactone). The solid unchanged acid (72%) was almost pure $\alpha\beta$ -acid (J 0.3%, acid 98%, lactone 1.5%).

(8) *As (7).* Boiling was carried out first for 21 minutes and, after dilution, for another 10 minutes. The lactonic product (28%) had b. p. 86–88°/10 mm., n 1.4394, d 1.0228; 3.5% acid, 95.5% lactone.

(9) 10 G. of the $\alpha\beta$ -acid were boiled for 1 hour with 50 c.c. of 50% sulphuric acid, the dilution and re-boiling being omitted. The solution was distilled in steam and the distillate, after being saturated with ammonium sulphate, was extracted continuously for 24 hours with ether. The extract was dried, and the solvent removed. 8.5 G. of almost pure n -hexolactone were obtained. b. p. 89°/9 mm., n 1.4398, d 1.0245 (acid 4%, lactone 96%). With ammonia, this gave an 80% yield of the γ -hydroxy-amide, m. p. and mixed m. p. 75°.

(10) *Cold 60% acid.* The $\alpha\beta$ -acid was treated exactly as was the $\beta\gamma$ -acid in expt. (3). On mixing, nearly the whole dissolved

without development of heat. After 72 hours, 100% of hard solid $\alpha\beta$ -acid was recovered after the usual procedure (J 0.4%; acid 98.5%, lactone 0.5%).

Action of Heat on n-Hexenoic Acids.—The $\alpha\beta$ - and the $\beta\gamma$ -acid have previously been shown to equilibrate on boiling. Mr. E. G. Noble, who is extending this investigation, kindly supplied the accumulated non-acidic fractions obtained by him in the prolonged heating of, in all, 76 g. of $\beta\gamma$ -acid and 185 g. of $\alpha\beta$ -acid. This material was mainly composed of high-boiling viscous products and no lactone could be found in it.

isoHexenoic Acids.

The $\alpha\beta$ -acid (III) (Goldberg and Linstead, *loc. cit.*) was twice fractionated and the material used had b. p. 100°/6 mm., n 1.4487, d 0.9534 (J 0.8%; acid 100%, lactone 0%). It solidified at -75° in bunches of flattened needles, m. p. -22° (corr.). Solidification was rather slow and possibly the acid contained a geometrical isomeride as impurity. This would also account for the low m. p.

Purification of Pyroterebic Acid (IV).—(a) *From terebic acid.* In one preparation of teraconic acid from acetone and succinic ester (Stobbe, *Ber.*, 1893, **26**, 2314) the entire product consisted of a mixture of the two acid esters, one liquid and one solid, crystallising from hot water in long needles, m. p. 118—119° (compare Stollé, *J. pr. Chem.*, 1903, **67**, 199). Both of these gave terebic acid on hydrolysis with hydrochloric acid.

Terebic acid (124 g.) was pyrolysed in six portions and the products were separated by Goldberg and Linstead's procedure into terebic and teraconic acids (14 g.), isohexolactone (26 g.), and pyroterebic acid (30 g.).

The lactone (VI) so obtained was free from acid and had a pleasant odour somewhat resembling that of coconut. It had b. p. 68°/3 mm., n 1.4337, d 1.0125, and solidified to a mass of flattened needles, m. p. 9°. The liquid lactone could be kept supercooled in a freezing mixture for a considerable time without solidification, but when it was seeded or touched with a glass rod a rapid growth of crystals took place very much as in the case of supercooled benzophenone. The lactone was stable and developed no acidity in 2 months. Treated with ammonia exactly as was the *n*-lactone, it gave a 40% yield of γ -hydroxyisohexoamide, glassy prisms, m. p. 101° (Found : N, 10.7%) (Fittig, *Annalen*, 1881, **208**, 21, gives m. p. 7—8° for the lactone; Ström, *J. pr. Chem.*, 1893, **48**, 220, gives m. p. 101° for the amide).

The pyroterebic acid, b. p. 83—84°/4 mm. (acid 78.5%, lactone 23%), was further freed from lactone by dissolution in sodium

carbonate solution, extraction of the lactone, and liberation from the alkaline solution with a calculated deficiency (5%) of acetic acid. The acid so obtained was left over soda-lime and paraffin wax in a vacuum desiccator for 3 days without loss in weight, but was not distilled. It had n 1.4451, d 0.9759 (acid 98%, lactone 2.5%). Like its ethyl ester (Linstead, J., 1929, 2498), the acid deteriorates on standing and the above sample, after being kept for 6 weeks in a stoppered bottle, had n 1.4492, d 0.9961. On distillation this left a viscous residue and the almost pure acid came over at $92^{\circ}/6$ mm., with n 1.4457, d 0.9787 (acid 97%, lactone 2.5%; J 95.5%) (sample A).

(b) *From Δ^{α} -isohexenoic acid.* 41 G. of crude pyroterebic acid (b. p. $102-106^{\circ}/14$ mm.) obtained by equilibration of the $\alpha\beta$ -acid (see p. 128) were esterified with 41 c.c. of *N*-alcoholic hydrogen chloride and 164 c.c. of absolute alcohol for $5\frac{1}{2}$ hours at room temperature (compare Eccott and Linstead, J., 1929, 2153; the quantities of reagents here used are much less than those first recommended, but the efficiency of the process is not affected). The $\beta\gamma$ -ester, isolated in the usual way (36 g.), was hydrolysed with 6% alcoholic-aqueous potash at room temperature, and the acid distilled without separation of the lactone. The fraction, b. p. $83-84^{\circ}/4$ mm., was purified through bicarbonate in the usual manner and redistilled; it then gave a homogeneous product, b. p. $82^{\circ}/3$ mm. (acid 99.5%; lactone 0.5%; J 94.4%). This product solidified at -78° to yield the solid acid of m. p. -4.5° already referred to (sample B).^{*} Apart from proofs already adduced and the concordance of the iodine additions, the identity of this product with that from terebic acid was shown by its quantitative conversion into isohexolactone (see below).

Action of Sulphuric Acid on the $\beta\gamma$ -Acid.—(11) 4.5 G. of the purified acid (sample A) and 1 equivalent of 5% sulphuric acid were allowed to stand over-night. After 22 hours, two layers still remained and after extraction and distillation the product had b. p. $97^{\circ}/11$ mm., n 1.4457, d 0.9795 (acid 93%, lactone 6%).

(12) A solution of 5 g. of the acid (lactone content 4%) in aqueous sodium bicarbonate was thoroughly extracted with ether and decomposed with 10% excess of 10% sulphuric acid. The acid,

^{*} It is a matter of some difficulty to decide on the most trustworthy physical constants for pyroterebic acid owing to its comparative instability, which was only fully realised as the present work progressed. It is considered that these are best represented by the figures: b. p. $82^{\circ}/3$ mm., $97^{\circ}/10$ mm., m. p. -4.5° , n 1.4465, d 0.978. The acid is a colourless mobile liquid with a sour smell, more unpleasant than that of the $\alpha\beta$ -acid or of $\Delta\beta$ -*n*-hexenoic acid. With due care it can be distilled at low pressures and can be liberated from solutions of its salts without lactonisation.

isolated in the usual way, had b. p. $94^{\circ}/7$ mm. (acid 96%, lactone 3%).

(13) *Cold 50% acid.* The acid from expt. (12) was shaken with 50% sulphuric acid (5 vols.). In contrast to the $\beta\gamma$ -*n*-acid, the upper layer disappeared in 2 minutes and there was a slight evolution of heat. The smell of acid was replaced by that of lactone in 7 minutes and after $\frac{1}{4}$ hour the product was worked up as in expt. (2). It distilled at $77^{\circ}/9$ mm., and had n 1.4329, d 1.0112 (acid 1.5%, lactone 99%). It readily set on cooling to a solid of m. p. $8-9^{\circ}$, and gave a 34% yield of the γ -hydroxy-amide, m. p. and mixed m. p. 100° .

(14) *Cold 60% acid.* This experiment is described on p. 118. The product (1.90 g.) from 2 g. of $\beta\gamma$ -acid (sample B) after 15 minutes' treatment contained 2.5% of acid and 97.5% of lactone and melted at 8° .

Action of Heat on the $\beta\gamma$ -Acid.—(15) Pyroterebic acid from the pyrolysis of terebic acid (lactone content, 23%) was boiled under reflux for 30 minutes. The product had n 1.4395, d 1.0024 (acid 31%, lactone 67.5%).

(16) This material was boiled for a further 3 hours and was then distilled over at $75^{\circ}/5$ mm. The distillate had n 1.4332, d 1.0127; m. p. $5-8^{\circ}$ (acid 4.5%, lactone 95.5%).

Action of Sulphuric Acid on the $\alpha\beta$ -Acid.—(17) *Hot 50% acid.* Under the conditions of expt. (1) the acid (10 g.) yielded 1.6 g. of lactonic product, b. p. $81^{\circ}/6$ mm., n 1.4360, d 1.0065 (acid 12.5%, lactone 86.5%), which was semi-solid in a freezing mixture. The recovered acid (7.5 g.) contained 97% of acid and 2.5% of lactone (J , 0.4%).

(18) *As in (17).* The mixture was boiled for 30 minutes, and for an additional 10 minutes after dilution; 48% of lactonic product was formed, b. p. $78-79^{\circ}/8$ mm., m. p. $4-6^{\circ}$, n 1.4409, d 1.0130 (acid 0.5%, lactone 98%).

(19) The $\alpha\beta$ -acid was boiled for 1 hour with 50% sulphuric acid (5 vols.), and the product extracted exactly as in expt. (9). There was much more gross decomposition than with the *n*- $\alpha\beta$ -acid, only 40% of product being recovered after distillation. This was almost pure γ -lactone, b. p. $80^{\circ}/10$ mm., m. p. $8-9^{\circ}$; n 1.4346, d 1.0096 (acid 1%, lactone 98.5%). It gave a 28% yield of the γ -hydroxy-amide, m. p. $95-98^{\circ}$ (crude), 101° (after crystallisation) (mixed m. p. 101°).

(20) *Cold 50% acid.* 3.1 G. of the $\alpha\beta$ -acid and 15.5 c.c. of 50% sulphuric acid were shaken together for 15 minutes, there being no mixing of the upper layer. Ether extracted the almost unchanged acid (2.7 g.) with b. p. $99^{\circ}/7$ mm.; n 1.4488, d 0.9542 (acid 100%, lactone 1%).

(21) *Cold 60% acid.* Treated for 72 hours under the conditions of expt. (10), the $\alpha\beta$ -acid gave a 97% recovery, without distillation, of material with J 0.4% (acid 97%, lactone 3%).

Action of Heat on the $\alpha\beta$ -Acid.—(22) The acid, after being boiled under reflux for 22.5 hours, had n 1.4486, d 0.9607 (acid 93.5%, lactone 5%). Further boiling of this sample for a total of 65 hours gave a product containing neutral material, 70.5% of acid, and 24% of lactone. From this the acid (64%, after distillation) and lactone were separated in the usual way. The latter (19% after distillation) had b. p. 75°/5 mm., m. p. 7–8°, n 1.4341.

(23) 9.1 G. of the acid were heated for 142 hours under a ground-in glass reflux condenser fitted with a calcium chloride tube. Distillation of the product gave a fraction, b. p. 80–100°/7 mm., and a thick high-boiling liquid. The low fraction had n 1.4404, d 0.9975 (acid 34%, lactone 62.5%), and did not solidify in a freezing mixture.

Attempts to reverse the Lactonisation.

(24) *n*-Hexolactone was boiled under reflux for 8 hours, and after distillation gave 93% of a product boiling steadily at 96°/14 mm., with n 1.4389, d 1.0262 (1% acid, 99.5% lactone).

(25) This material was treated with 60% sulphuric acid (5 vols.) for 48 hours at room temperature. The product, recovered in 98% yield by the method of expt. (2), contained 1% of acid and 97.5% of lactone.

(26) *iso*Hexolactone, m. p. 9°, after being boiled for 75 minutes showed no sign of acidity, and boiling was continued for a total of 4 $\frac{3}{4}$ hours. After distillation the product had n 1.4337 (acid 0%, lactone 102%).

(27) This material was further heated for 50 hours; after distillation, 80% was recovered with b. p. 76°/6 mm., m. p. 8–9°, n 1.4336, d 1.0130 (acid 1%, lactone 99%). The concordance between these physical constants and those of the original material is very close.

(28) *iso*Hexolactone, treated exactly as in expt. (25), was recovered in 90% yield as a pure acid-free product.

The stability of the lactones to heat and acids shows that the occasional low yields of lactone, *e.g.*, from Δ^{α} -*isohexenoic acid*, are to be attributed to gross decomposition of the unsaturated acid and not of the lactonic product.

Lactonisation of γ -Hydroxy-acids.

The method resembled that of Hjelt (*loc. cit.*), a deficiency of mineral acid being used to liberate the hydroxy-acids from their

barium salts in order to avoid any possibility of catalysis by strong acid.

(29, 30) Approximately $M/250$ -quantities of the pure *iso*- and *n*-hexolactones were accurately weighed out and neutralised with

in the usual way. $N/10$ -Hydrochloric acid (95% of the equivalent quantity) was then added to the cold solutions, which were made up to 100 c.c., and the amounts of water necessary to make them exactly $N/20$ with respect to the lactone were added from a burette. The procedure thereafter followed Hjelt's, the amount of unlactonised acid remaining after definite periods of reaction at 100° being determined by titration with $N/100$ -baryta. Values concordant to 1% were obtained but no special accuracy was aimed at. The mean values for the two series are given below :

Time of heating (mins.)	5	6	10	15	30	60
% Lactonisation (<i>n</i> -)	5	—	12	18	34	48
(<i>iso</i> -)	12	16	—	31	45	64

The product was worked up as in expt. (2), 1.7 g. being recovered (22.5% acid, 75.5% lactone). As it has been shown that under these conditions the $\alpha\beta$ -acid is unaffected while the $\beta\gamma$ -acid is completely lactonised, these figures provide a confirmation of those obtained iodometrically.

(35) Two mixtures of the *n*-hexenoic acids were analysed by the same method by Mr. E. G. Noble, 24 hours being allowed for the lactonisation of the $\beta\gamma$ -acid to be completed. These mixtures contained 32.8% and 32.5% of the $\beta\gamma$ -acid respectively (iodometric) and both gave products containing 33% of lactone and 65% of acid.

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