LV.—*The Quantitative Estimation of Mixtures of Isomeric Unsaturated Compounds. Part I. A Bromine Addition Method.*

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ALTHOUGH the structural conditions necessary to promote the movement of the double bond in the three-carbon system (Birch, Kon, and Norris, J., 1923, **123**, 1361, and subsequent papers by

Kon and his collaborators) have been studied, the quantitative aspect of the subject has been somewhat neglected owing to the difficulty of analysing the mixtures of isomerides obtained. Examination of the position of equilibrium in systems possessing retarded mobility (Kon and Linstead, J., 1925, **127**, 815) would, however, enable the effects of various substituent groups to be compared and the figures thus obtained would be of interest for comparison with the Thorpe-Ingold values for valency distortion and with the values for the *o*-, *p*-, and *m*-directing powers of the same groups when substituted in the benzene nucleus (compare Ingold, Shoppee, and Thorpe, J., 1926, 1477).

In the determination of the position of equilibrium in a three-carbon system,

$$\text{HC—C}\!\equiv\!\text{CX} \qquad\qquad \text{C}\!\equiv\!\text{C—CHX}$$
$$\alpha\beta\text{-form} \qquad\qquad\qquad\quad \beta\gamma\text{-form}$$

the isomerides present in the equilibrium mixture must first be isolated under conditions precluding further change and their proportion can then be estimated either by physical separation of the individuals, by optical measurements, or by separation through derivatives. The results so obtained are not completely trustworthy and the best methods at present available are those based upon the selective action of reagents such as dilute sulphuric acid (Fittig, *Annalen*, 1894, **283**, 47) and hypoiodous acid (Bougault, *Ann. Chim.*, 1908, **14**, 145), both of which are stated to combine with $\beta\gamma$-unsaturated acids but not with the $\alpha\beta$-isomerides.

The principle of the new method herein described is that the composition of a mixture of $\alpha\beta$- and $\beta\gamma$-isomerides can be determined by comparing its velocity of addition to halogens with the velocities for the two pure substances, and is based upon the observations of Sudborough and Thomas (J., 1910, **97**, 715, 2450) that halogens react additively much more rapidly at a $\beta\gamma$- than at an $\alpha\beta$-double bond. Notwithstanding the observations of Bougault (*loc. cit.* ; *Ann. Chim.*, 1908, **15**, 296), it is doubtful whether halogens ever react completely at a $\beta\gamma$-double bond under conditions in which the $\alpha\beta$-isomeride is unchanged. It has therefore been necessary to measure the percentage reaction over a definite interval of time.

In general, the reacting substances are used in molecular quantities, the halogen being present in the form of a stable standardised solution. Other conditions, such as the nature and state of activation of the halogen, temperature, light, concentration, the nature of the solvent, and the presence of catalysts, may be varied to bring the reaction within the region of convenient experimental investigation; *e.g.*, in a given series the unsaturated acids will require

conditions more favourable to addition than will the corresponding, more positive ketones. The method has so far been used to determine the compositions of various mixtures of unsaturated acids. Preliminary work has been carried out on ketones and esters and it is hoped to communicate these results shortly.

1. *Examination of the Pure Acids.*

Materials.—The acids examined were: (1) *cyclo*Hexylideneacetic acid (Wallach, *Annalen*, 1909, **365**, 261), (2) Δ^1-*cyclo*hexenylacetic acid (Kon and Speight, J., 1926, 2727; Farrow and Kon, *ibid.*, p. 2128), (3) $\beta\beta$-diethylacrylic acid, (4) β-ethyl-Δ^β-pentenoic acid, and (5) β-methyl-β-ethylacrylic acid, all three prepared by Kon and Linstead's method (*loc. cit.*), and (6) β-methyl-Δ^β-pentenoic acid, which was made by boiling β-hydroxy-β-methylvaleric acid with $12\frac{1}{2}\%$ sulphuric acid for $2\frac{1}{2}$ hours and obtained, in 35% yield, almost free from its isomeride; it was purified by fractional distillation. The acids used in the analytical work had the following physical properties : (1) Plates, m. p. 90—91°, b. p. 159—160°/22 mm., from light petroleum; (2) plates, m. p. 36—38°, b. p. 152°/23 mm.; (3) b. p. 124°/13 mm., $[R_L]_D$ 36·59 (*p*-toluidide, m. p. 81°); (4) b. p. 112°/10 mm., $[R_L]_D$ 35·82 (*p*-toluidide, m. p. 94°); (5) flattened needles, m. p. 45°, b. p. 104°/13 mm., from light petroleum (*p*-toluidide, m. p. 67°); (6) b. p. 101°/14 mm., $[R_L]_D$ 31·07 (*p*-toluidide, m. p. 84°).

The halogen used was bromine, purified by the method of Sudborough and Thomas (*loc. cit.*). The solvents were carefully freed from traces of acid and were dried and fractionated twice before use.

Reaction.—The reaction was carried out under conditions differing from those of Sudborough and Thomas (*loc. cit.*) in several details (compare also Mills, J., 1883, **43**, 435). The solutions of the reagents were mixed in bulk instead of in aliquot portions. Immediately before readings were taken, quantities of 50 c.c. each were drawn into a pipette connected by a three-way tap with a low vacuum and were run, after definite intervals of time, into a solution of potassium iodide; the liberated iodine was titrated with $N/20$-thiosulphate. The other conditions observed were as follows :

Solvent. For acids (1) and (2), carbon tetrachloride; for acids (3), (4), (5), and (6), chloroform.

Concentration. 1/60 G.-mol. per litre (1/120 g.-mol. of the acid was dissolved in 250 c.c. of the inert solvent. The equivalent amount of bromine was obtained by making the necessary quantity of a freshly standardised solution of bromine up to 250 c.c.).

Temperature. 25°, controlled by a thermostat.

Lighting. All the reactions were carried out in blackened flasks.

Results.—The absorption of bromine is abnormally fast during the first 2 minutes of the reaction, but thereafter it pursues a bimolecular course and can easily be followed. As observed by previous workers, in general the readings do not give very concordant values for the velocity coefficient, $k = x/at(a - x)$, but there is no steady rise or fall indicating the occurrence of a secondary reaction.* The results are in Table I; the values of a and $a - x$ are given by the number of c.c. of thiosulphate required at the beginning and the end of a period of t hours. All the reaction velocities are derived from figures representing fractional changes and therefore are directly comparable (with the exception of those for the *cyclo*hexane acids, where a different solvent was used). The figures are thus independent of the strength of the thiosulphate solution, which was renewed and restandardised from time to time. Two of Sudborough and Thomas's results at 15°, marked * in the table, are given for comparison.

TABLE I.

Unsaturated Acids + Bromine at 25°.

Acid.	Solvent.	k.			No. of readings
		Minimum.	Maximum.	Mean.	
*cyclo*Hexylideneacetic	CCl₄	0.65×10^{-2}	2.08×10^{-2}	1.04×10^{-2}	6
Δ^{1}-*cyclo*Hexenylacetic	,,	0.43	1.91	1.07	9
$\beta\beta$-Diethylacrylic	CHCl₃	1.17×10^{-3}	2.28×10^{-3}	1.91×10^{-3}	4
β-Ethyl-$\Delta\beta$-pentenoic	,,	0.74×10^{-2}	5.67×10^{-2}	1.15×10^{-2}	4
β-Methyl-β-ethylacrylic ...	,,	0.44×10^{-3}	3.53×10^{-3}	2.08×10^{-3}	3
β-Methyl-$\Delta\beta$-pentenoic	,,	1.35×10^{-2}	2.75×10^{-2}	2.03×10^{-2}	6
β-Methyl-Δa-butenoic *......	CCl₄	3.1×10^{-3}	7.3×10^{-3}	—	—
Δa-Butenoic*	,,	4.68×10^{-6}	6.16×10^{-6}	—	—

Analysis of the Results.—From the structural point of view several interesting points arise from these results. In the first place, the effect of conjugation in the $\alpha\beta$-acids is to give a velocity coefficient $1/10-1/100$ of that found for the $\beta\gamma$-acid. Secondly, substitution of positive groups for hydrogen leads to an increased velocity of reaction, the *cyclo*hexane ring having an exceptionally great effect. Finally, the results for the addition of bromine to $\beta\beta$-diethylacrylic acid and its $\Delta\beta$-isomeride show that the latter (*p*-toluidide, m. p. 94°; amide, m. p. 114°) has the greater velocity of reaction and is therefore the $\beta\gamma$-acid—a result in agreement with the observations of Kon and Linstead (*loc. cit.*) on the structure of these acids.

2. *Examination of Mixtures of the Acids.*

Materials.—The investigation of mixtures of isomeric acids was carried out with mixtures obtained by the action of alkali on the pure acids under various conditions, and with artificial mixtures

* Hydrogen bromide is slowly liberated from the reaction product after some time, the change being facilitated by the presence of water.

of known compositions prepared by mixing together the pure isomerides.

The equilibration of the acids was carried out in the manner described in the following paper. With the exception of the *cyclo*-hexyl acids, the resulting mixtures were distilled under reduced pressure, a fraction covering the boiling points of both isomerides being collected in each case. The absence of saturated impurity—*e.g.*, hydroxy-acids formed by the addition of water at the double bond—was proved by determinations of the total capacity of the mixtures for nascent bromine by Vaubel's method (*J. pr. Chem.*, 1893, **48**, 75) as modified by Callan and Russell Henderson (*J. Soc. Chem. Ind.*, 1922, **41**, 161T). In all the analyses made in this way, the titration figures agreed with those required for the addition of two atoms of bromine. The results are in Table II.

TABLE II.

Acids + Nascent Bromine.

Series.	*cyclo*Hexyl.							
	αβ	βγ	αβ	αβ	αβ	βγ	βγ	βγ
Initial material	αβ	βγ	αβ	αβ	αβ	βγ	βγ	βγ
% Alkali used	—	—	60	50	40	60	50	40
Br added ∫ found	87·4	86·3	81·5	73·9	46·5	42·7	39·5	53·7
(mg.). \ calc.*	87·4	87·7	78·7	70·4	45·8	42·3	39·5	53·7

Series.	β-Ethylpentenoic.			β-Methylpentenoic.		
	αβ	βγ	αβ	αβ	βγ	αβ
Initial material	αβ	βγ	αβ	αβ	βγ	αβ
% Alkali used	—	—	60	—	—	60
Br added ∫ found	59·3	43·3	60·3	49·9	60·7	86·3
(mg.). \ calc.*	57·9	43·3	57·2	47·5	61·4	87·7

* Calculated for the addition of two atoms of bromine per molecule.

After proof of their purity had been obtained in this way, the mixtures of acids were examined by the bromine-addition method, the reactions being carried out exactly as with the pure acids.

Analysis of Results.—The mixtures of acids gave figures for the addition of bromine intermediate between those obtained for the parent substances. The velocity coefficients for the pure acids were not sufficiently accurate to allow of their use as constants in a mathematical analysis of the subject, and the compositions of the mixtures were therefore determined empirically by comparing the addition figures for the mixtures with those for mixtures prepared from definite quantities of the pure isomerides. This was most conveniently done in the manner indicated below.

The addition curves for the β-methylpentenoic acids (Fig. 1) show that at the end of the first 2 minutes the addition is proceeding comparatively slowly. Determinations made in this region are

therefore not liable to appreciable experimental error; moreover there is little danger of discrepancies arising from side reactions which may develop later, such as that due to the catalytic effect of hydrogen bromide liberated from the products of the reaction. The connexion between composition and addition is given in Table III, which shows the percentage addition of bromine in 2 minutes to various mixtures of acids of known composition.
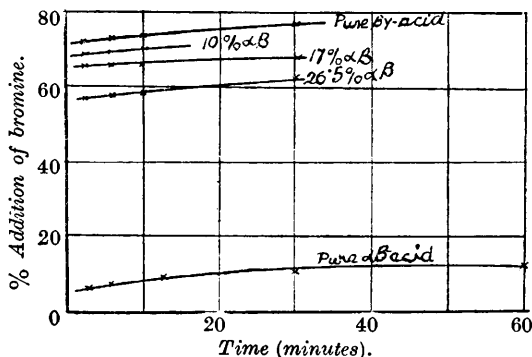
FIG. 1.

Time (minutes).

TABLE III.

Comp. of acid.		Addition.	Comp. of acid.		Addition.
% αβ.	% βγ.	%.	% αβ.	% βγ.	%.
*cyclo*Hexane series.			β-*Ethylpentenoic series.*		
0	100	95·6	0	100	81·3
14·3	85·7	88·1	5·1	94·9	74·5
20·9	79·3	84·0	8·2	91·8	70·0
46·0	54·0	59·9	100	0	15·0
58·0	42·0	54·3	β-*Methylpentenoic series.*		
79·7	20·3	34·7	0	100	70·2
90·1	9·9	24·0	10·1	89·9	67·9
100	0	10·4	17·0	83·0	64·2
			26·5	73·5	57·6
			100	0	7·2

It will be seen that the amount of addition is roughly proportional to the percentage of βγ-acid. The variation from this relationship is shown in Fig. 2, where the two-minute addition figures for the three series are plotted against composition. The complete curve has been obtained only for the *cyclo*hexane acids; in the other series, only mixtures in the neighbourhood of the equilibrium point were examined.

The compositions of the various mixtures of acids obtained on equilibration were readily determined from the addition values and reference to the appropriate curves. The positions of the

equilibrium mixtures are shown by the dotted lines in Fig. 2, and the addition values and the compositions calculated from them are in Table IV.
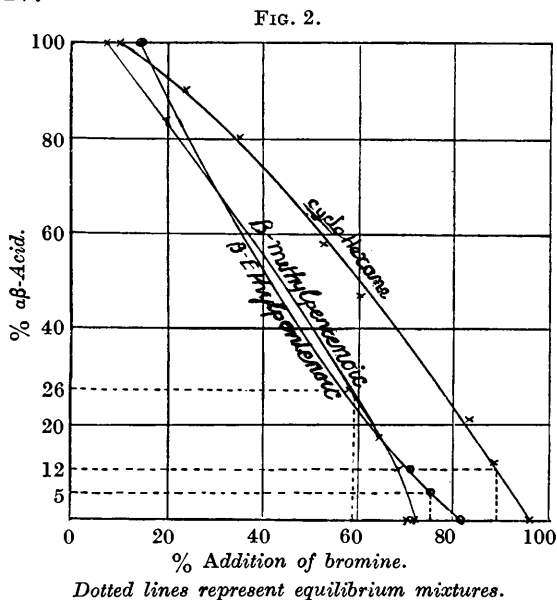
FIG. 2.

Dotted lines represent equilibrium mixtures.

TABLE IV.

Addition Values and Compositions of Equilibrium Mixtures.

Series.	Initial acid.	% Alkali.	Time (hrs.).	% Addition of bromine (2-min.).	% $\alpha\beta$-Acid in mixture.
cycloHexane	$\alpha\beta$	60	1·0	87·9	13
	$\alpha\beta$	60	24·0	89·4	11
	$\alpha\beta$	50	1·55	87·8	13
	$\alpha\beta$	50	24·0	89·08	11
	$\alpha\beta$	40	24·0	87·8	13
	$\beta\gamma$	60	23·0	89·4	11
	$\beta\gamma$	50	24·0	87·8	13
	$\beta\gamma$	40	24·0	87·8	13
β-Ethylpentenoic	$\alpha\beta$	60	0·33	76·4	4
	$\alpha\beta$	60	0·33	74·1	5
	$\beta\gamma$	60	0·5	73·5	6
β-Methylpentenoic	$\alpha\beta$	60	0·33	58·3	26
	$\beta\gamma$	60	0·25	58·5	26

The positions of equilibrium between the pairs of acids in boiling potassium hydroxide solution * are therefore :

cycloHexane acids .... $12·0 \pm 0·8\%\ \alpha\beta$ $\quad 88 \mp 0·8\%\ \beta\gamma$
β-Ethylpentenoic acids .... $5\%\ \alpha\beta$ $\quad 95\%\ \beta\gamma$
β-Methylpentenoic acids .... $26\%\ \alpha\beta$ $\quad 74\%\ \beta\gamma$

* The effect of alterations in the conditions on the position of equilibrium will be discussed in a future paper.

These are genuine equilibria in that they can be reached from either side and are unchanged by further action. Beesley, Ingold, and Thorpe (J., 1915, **107**, 1081), who first observed the change of *cyclo*hexylideneacetic acid into Δ^1-*cyclo*hexenylacetic acid, described it as complete and irreversible. That statement is, however, easily explained when it is remembered that the *cyclo*hexenyl acid separates from the equilibrium mixture in a solid form and, on the small scale on which those investigators worked, the 12% of $\alpha\beta$-acid might easily escape detection. As a result of the earlier work on the equilibration of the substituted pentenoic acids, Kon and Linstead (*loc. cit.*) stated that, whereas in the β-ethyl series the conversion of the $\alpha\beta$- into the $\beta\gamma$-form was apparently complete, in the β-methyl series the equilibrium was further on the side of the $\alpha\beta$-acid, although the $\beta\gamma$- still preponderated. The figures now obtained confirm this earlier work in all respects.

A curious feature of the present work is that equilibrium is reached in about 20 minutes in the substituted pentenoic acids, but only in an hour in the *cyclo*hexane acids. Thus the aliphatic acids appear to be the more mobile, although in the corresponding ketones the reverse is true.