215. *Electrometric Titration Curves of Dibasic Acids. Part V. Dissociation Constants of* cyclo*Pentanedicarboxylic Acids. An Attempted Check on Methods proposed for Calculation of Molecular Dimensions.*

By CHRISTOPHER K. INGOLD and H. G. G. MOHRHENN.

THIS series is concerned with the measurement of the distance between the carboxyl groups of dibasic acids through the use of their electrometrically determined ionisation constants. The underlying principle, which has reference to the electrical effects at the seat of a reaction of an ionic substituent situated elsewhere in the molecule, may be traced to Ostwald (*Z. physikal. Chem.*, 1892, **9**, 553), although it was first given definite mathematical form by Bjerrum (*ibid.*, 1923, **106**, 219). It has been shown (Gane and Ingold, Parts I, II, and III; J., 1928, 1594, 2267; 1929, 1691), however, that in this form the theory fails quantitatively, because it neglects (1) the propagation of electrical influences through the bonds of the reacting molecule itself, and (2) the local variations in the dielectric properties of the surrounding medium. Disturbance (1) is serious only for very short molecules such as oxalic and malonic acids; disturbance (2), however, is general, and in Part IV (*idem*, J., 1931, 2153) an attempt was made to correct for it. For this purpose, it was necessary to allow for interaction between (*a*) ions and ions, and (*b*) ions and solvent molecules. Correction (*a*) was applied by means of an empirical extrapolation to zero ionic strength, but correction (*b*) could not be dealt with thus empirically. Resort was therefore had to a theoretical calculation in which Bjerrum's equation was extended to take account of local electrical effects within the solvent.

It seemed desirable to attempt an experimental check on this purely theoretical correction, which mathematically is very far from rigorous. We therefore undertook measurements on acids the dimensions of which could be considered to be known approximately in order to examine the application both of Bjerrum's original formula and of the extended equation for the distance between the acidic groups.

The appropriate acids are few. Oxalic and all the malonic acids are too short; and the succinic and higher acids are unsuitable in any saturated open-chain form because the dimension we measure is affected by the possibility of rotation around the single bonds. Unsaturated chains, and unsaturated or aromatic rings, are excluded because internal electrical propagation could not then be neglected. Saturated rings of more than five atoms are inappropriate, because their shape is not fixed; and so also are those with less than five atoms, because their extracyclic valencies suffer an undetermined deflection due to ring strain. Thus we are left with the *cyclo*pentane-1 : 2- and -1 : 3-dicarboxylic acids as the only acids which are sufficiently extended, non-conducting, rigid, and strainless. The *cis*- and *trans*-forms of these acids cover a range of distances of about 3—7 Å.U.

In the model used to represent these acids we assume rigidity. All C—C distances are given the value 1·54 Å.U., and each pair of extracyclic valencies is assumed to include the angle 109·5°. The distance between the centre of action of the charge of a carboxylate ion and the nucleus of the corresponding carbon atom is taken as 1·00 Å.U., as in Part IV (*loc. cit.*). Except that the C—C distance is known with some certainty, it is probable that all these assumptions involve an appreciable misrepresentation of reality.

The observational results for the ionisation constants, together with the previous literature, will be found in the section headed " Results." The comparison between the distances obtained from the model and those calculated from the experimental data by Bjerrum's formula and by the extended equation is shown in Table I. It will be seen that the validity, as a second approximation, of the correction for local electrical effects is confirmed, although deviations remain the causes of which will be considered later in conjunction with other data.

EXPERIMENTAL.

Materials.—The isomeric *cyclo*pentane-1 : 2-dicarboxylic acids were prepared from trimethylene bromide and malonic ester as described by Perkin (*Ber.*, 1885, **18**, 3250; J., 1887, **51**, 240; 1894, **65**, 572), and both were purified by repeated crystallisation from water. The *trans*-acid

TABLE I.

Comparison of Inter-carboxylic Distances (Å.U.) *of the* cyclo*Pentanedicarboxylic Acids as given by Models and as calculated from the First and Second Electrolytic Dissociation Constants determined in Water at* 25°.

		cis-1 : 2-.	*trans*-1 : 2-.	*cis*-1 : 3-.	*trans*-1 : 3-.
From K_1 and K_2 by	Bjerrum's equation	2·0	2·4	4·8	6·2
	extended equation	3·9	4·2	5·7	6·8
Model		3·3	5·2	5·3	6·7

had m. p. 161·5°, and the *cis*-acid, m. p. 132—141° depending on the rate of heating (cf. Kuhn and Wassermann, *Helv. Chim. Acta*, 1928, **11**, 600).

The *cyclo*pentane-1 : 3-dicarboxylic acids were prepared by three methods, the first being a malonic ester synthesis according to Pospischill (*Ber.*, 1898, **31**, 1950; cf. Perkin and Scarborough, J., 1921, **119**, 1400). Ethyl *n*-butane-ααδδ-tetracarboxylate was cyclised by means of methylene iodide, and the crude *cyclo*pentanetetracarboxylic ester was hydrolysed by boiling with 15% ethyl-alcoholic potassium hydroxide. After the hydrolysis, most of the alcohol was removed by evaporation, and the slightly acidified residue was then evaporated almost to dryness, and heated at 160° (oil-bath) until carbon dioxide ceased to be evolved. An acetic anhydride extract of the residual material was boiled for several hours and then distilled completely, the required product being collected at 125—130°/0·05 mm. This appeared to be crude *cis*-acid, instead of the expected anhydride (cf. Kuhn and Wassermann, *loc. cit.*). Purified by repeated crystallisation from water, the acid had m. p. 121·5°.

The starting point of the second method is santene, which is oxidised first to 1 : 3-diacetyl*cyclo*pentane and thence to a mixture of the *cis*- and *trans*-1 : 3-acids (Semmler and Bartlett, *Ber.*, 1907, **40**, 4594; 1908, **41**, 125, 385, 866). The yields were unsatisfactory, the weight of crude mixed acids being only 5% of that of the santene. The modified method of Fuson, Lewis, and Du Puis (*J. Amer. Chem. Soc.*, 1932, **54**, 1114) did not constitute an improvement.

The third method is based on the union of *cyclo*pentadiene and benzoquinone. The addition product is reduced, first with respect to the ethylenic bond in the dihydroquinone ring by means of zinc and acetic acid, and then in the *cyclo*pentene ring by catalytic methods. The resulting 1 : 4-*endo*methylene-5 : 8-diketodecahydronaphthalene on oxidation with nitric acid yields a mixture of stereoisomeric 1 : 3-*cyclo*pentane acids (Albrecht, *Annalen*, 1906, **348**, 31; Diels and Alder, *ibid.*, 1928, **460**, 107; Alder and Stein, *ibid.*, 1933, **501**, 281). Excellent yields were obtained in the first three stages, the third of which was accomplished with the aid of a platinum catalyst supported on "norit," instead of the colloidal palladium employed by Diels and Alder; the singly unsaturated diketone (30 g.) was thus hydrogenated under 2 atm. in 30 mins. The final oxidation was less satisfactory, 90 g. of the saturated ketone yielding 16 g. of the crude *cis*-acid.

The conversion of the *cis*-acid into a mixture of both stereoisomerides was accomplished by Pospischill's method (*loc. cit.*), that of Hückel and Goth (*Ber.*, 1925, **58**, 447) having given unsatisfactory results. The product from the treatment with hydrochloric acid, when decolorised by means of charcoal and crystallised once from carbon tetrachloride, had m. p. 90—95°. This product was stirred at 60—65° with about 250 parts of carbon tetrachloride. The filtrate, kept below 0°, deposited crystals richer in the *trans*-acid. This process was repeated about 12 times, always with the fraction which had been enriched in the *trans*-compound. The m. p. of this fraction fell from 90—95° to 77°, then rose to 83—85°, and finally remained constant. This was the *trans*-acid, the m. p. of which, after prolonged desiccation over phosphoric oxide, was 88—89°, although crystallisation from carbon tetrachloride again reduced it to 83—85°. The various fractions which remained undissolved in the warm carbon tetrachloride during this fractionation were either re-extracted with the same solvent, if they contained considerable quantities of the *trans*-acid, or were heated with hydrochloric acid preparatory to further fractionation, if they contained only a small proportion of *trans*-form.

Measurements.—The electrical equipment, which was of the usual type, included a Pye standard cadmium cell and a potentiometer by the Cambridge Instrument Company. The whole set-up, except the potentiometer, was well insulated with paraffin wax. The saturated calomel half-cell, 14 cm. long, was prepared as usual with distilled, purified mercury, which was covered to a depth of 1 cm. with calomel paste. The junction through saturated potassium chloride–calomel solution to the titration vessel was made by an agar bridge, prepared and preserved in the customary manner. Before each experiment the hydrogen electrode, of "bell" type, was replatinised in a solution (50 c.c.) of platinic chloride (1 g.) and lead acetate (0·01 g.) with 10 reversals of current from a 4-volt accumulator at intervals of 0·5 min. The electrode was then used as cathode in electrolysis of dilute sulphuric acid for 5 mins., and was well washed and dried. Hydrogen from a cylinder having been found difficult to purify completely, the gas was generated by electrolysis of a cooled barium hydroxide solution with a current of 6 amps.; it was passed successively through cotton-wool and soda-lime, then over a red-hot nichrome spiral, and finally through distilled water. Carbonate-free sodium hydroxide was prepared by centrifuging a solution of sodium hydroxide in an equal weight of water, and diluting the clear liquid with carbon dioxide-free water, freedom from carbonate being confirmed by titration with sulphuric acid with the differential use of phenolphthalein and bromophenol-blue as indicators. The hydroxide solutions were preserved in wax bottles with rubber stoppers, fitted with the usual syphons and soda-lime tubes. Solutions for titration were prepared with carbon dioxide-free water. The accumulators for the potentiometer, and the hydrogen supplied to the hydrogen electrode, were always turned on about 2 hours before any measurements of potential were to be made; and 10—15 mins. were usually necessary for the attainment of potentiometric equilibrium to within the accuracy, 10^{-4} volt, of the readings. All measurements were made at 25·00° ± 0·05°. As heretofore, the cell system was standardised against Walpole's data for acetate buffers. The standardisation was made both before the commencement of the measurements and 14 months later, after their completion, with identical results. The p_H was given by the equation $p_H = (E + \delta E - 0{\cdot}2509) \times 17{\cdot}32$, where E is the observed *E.M.F.*, and δE the correction to normal pressure of hydrogen. The method of calculating the dissociation constants was exactly the same as that employed in the previous parts, where it was attributed to Auerbach and Smolczyk, although the unnecessary approximations introduced by those authors were always avoided. No mention has previously been made of this small improvement on their mathematical methods, and it is referred to now only because their approximations have been criticised. The procedure outlined in Part IV was used for the correction to zero ionic strength.

Results.—Table II exhibits the detailed record of a single experiment, Table III the complete series of results for a single acid, and Table IV a summary of the results for all the acids. The dissociation constants shown in Table II are calculated from neighbouring readings, a method of computation well suited to showing up the observational irregularities. The previous determinations, given in Table IV, include a complete set obtained by Wassermann with rather different potentiometric technique. Where possible, the value of log $(K_1/4K_2)$ is tabulated, since this is the important quantity for the calculation of the distance. The following additional abbreviations are employed: c = concentration of solution (150 c.c.) of acid; s = concentration of alkali; t = titre; t'' = equivalent titre; K_1 and K_2 = first and second dissociation constants. Volumes are in c.c., and potentials in volts.

TABLE II.

Electrometric Titration of trans-cyclo*Pentane*-1 : 2-*dicarboxylic Acid.*

$c = 0{\cdot}002493$; $s = 0{\cdot}04540$; $t'' = 16{\cdot}48$; $\delta E = 0{\cdot}0004$.

t.	E.	10^4K_1.	t.	E.	10^4K_1.	t.	E.	10^6K_2.	t.	E.	10^6K_2.
—	0·4402	—	5·32	0·4912	1·35	7·78	0·5248	1·35	12·79	0·5939	1·41
1·05	0·4496	1·23	6·16	0·5005	1·24	8·61	0·5391	1·47	13·58	0·6036	1·44
1·88	0·4567	1·39	7·01	0·5129	1·38	9·50	0·5527	1·43	14·35	0·6150	1·36
2·70	0·4645	1·32	7·78	0·5248	1·25	10·28	0·5637	1·48	15·26	0·6326	1·29
3·58	0·4728	1·36	8·61	0·5391	1·24	11·03	0·5729	1·44	16·02	0·6616	1·29
4·44	0·4815	1·35		Mean	1·31	11·90	0·5832	1·41		Mean	1·40

TABLE III.

Uncorrected Electrometric Dissociation Constants of cis-cyclo*Pentane*-1 : 2-*dicarboxylic Acid.*

10^3c	4·939	2·490	1·674	1·250	1·246	1·258
10^5K_1	4·47	3·88	4·18	3·91	3·85	3·72
10^7K_2	3·66	3·06	3·27	3·04	3·02	2·83
log $(K_1/4K_2)$	1·385	1·501	1·505	1·507	1·503	1·516

Correction.—The opportunity is taken to correct a numerical error, originally in Part II but reproduced in Part IV, to which Dr. F. G. Soper kindly called our attention. The calculated K_2 values of the three monoalkylglutaric acids are wrong by a power of ten, the tabulated figures being values of 10^6K_2 and not 10^7K_2 as stated. The dependent distances (r values) should be: Me, 8·57; Et, 7·54; n-Pr, 7·12 Å.U. These molecules are thus essentially extended zig-

TABLE IV.

Summary of Dissociation Constants of cyclo*Pentanedicarboxylic Acids in Water.*

Isomeride.	10^5K_1.	10^6K_2.	$\log K_1/4K_2$.	Temp.	Authors.	Method.	Ref.
cis-1 : 2-	15·8	—	—	25°	Walker	C	(i)
„	4·3	0·31	1·54	19	Wassermann	P	(vi)
„	3·7	0·27	1·54	25	This paper	P	
trans-1 : 2-	12·0	—	—	25	Walker	C	(i, ii)
„	11·3	—	—	25	Smith	C	(iii)
„	—	0·37	—	100	Smith	S	(iii)
„	13	1·2	1·43	18·5	Wassermann	P	(v)
„	11	1·4	1·29	25	This paper	P	
cis-1 : 3-	5·36	—	—	25	Pospischill	C	(iv)
„	5·9	3·0	0·69	21·5	Wassermann	P	(vi)
„	5·5	3·1	0·65	25	This paper	P	
trans-1 : 3-	5·04	—	—	25	Pospischill	C	(iv)
„	4·0	3·5	0·45	22	Wassermann	P	(v)
„	4·8	3·8	0·50	25	This paper	P	

Key.—C, conductivity; P, potentiometric; S, sugar inversion. (i), J., 1892, **61**, 706; (ii), J., 1894, **65**, 572; (iii), *Z. physikal. Chem.*, 1898, **25**, 205; (iv), *Ber.*, 1898, **31**, 1950; (v), *Helv. Chim. Acta*, 1930, **13**, 207; (vi) *ibid.*, p. 223.

zags, and the coiling of the glutaric acid chain with β-substitution becomes marked only in the presence of *two* β-substituents.

UNIVERSITY COLLEGE, LONDON.

[*Received, June* 1*st*, 1935.]