

52. *Acid Salts of Monobasic Organic Acids. Part IV. The Salting-out Effect.*

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The manner in which the extent of compound formation between mandelic acid and metallic mandelates is modified by the salting-out effects of the latter has been studied by an examination of the solubilities of the acid in a series of metallic chlorides and nitrates. After applying a correction for the salting-out effect of the metallic ions, we conclude that the extent of compound formation in all the systems studied is the same, and, therefore, independent of the nature of the metallic ion present. The extent of compound formation for racemic mandelic acid is found to be about twice as great as with the active acid.

THE extent of compound formation between mandelic acid, both racemic and active, and various metallic mandelates has already been studied by us (J., 1933, 1016; 1936, 867; 1937, 608). In all the systems examined it is notable that the solubility of racemic and active mandelic acid increases with increasing concentration of the normal salt, whereas the law of mass action would lead one to expect a decrease in solubility on addition of a salt containing an ion in common with the acid. Larsson (*Z. physikal. Chem.*, 1930, **148**, 148; 1931, **153**, 306) and Kolthoff and Bosch (*J. Physical Chem.*, 1932, **36**, 1685) have shown that the solubility of benzoic acid is increased by the addition of sodium and potassium benzoates, and a similar result is recorded by Osol and Kilpatrick (*J. Amer. Chem. Soc.*, 1933, **55**, 4430) for *o*-chlorobenzoic acid and its sodium salt.

Some of those investigators agree that the simplest way of explaining this increase in solubility is to assume that complex formation of some type occurs in solution between the acid and its salt, so that the active mass of the acid in solution is kept constant by the dissolution of more acid. Since complexes can be isolated in the solid form from such solutions, this assumption seems to be justified.

The salts of γ -mandelic acid affect its solubility to a decreasing extent in the following order: Univalent ions, Cs > Tl > Rb > K > NH₄ > Na > Li; bivalent ions, Ba > Sr > Mg. For the active acid and its salts the order of the effect is similar: Univalent ions, Tl > Cs > Rb > K > NH₄ > Na > Li; bivalent ions, Sr > Ba > Ca > Mg. We might conclude from these results alone that the tendency towards acid salt formation is in both cases greatest for thallium and cæsium, and least for lithium and magnesium. However, it is well known that metallic ions produce a salting-out effect, which is dependent on the size of the ions, being greatest for the small lithium ions and least for the larger

cæsium ions. This affects the solubility of the acid in the opposite direction to that of compound formation, which corresponds to a salting-in effect. By a study of the variation of the solubility of mandelic acid in presence of a series of chlorides and nitrates of the alkali and alkaline-earth metals, we have obtained data which enable us to calculate the extent of this salting-out effect, and so apply a correction for it.

It is found that the salting-out effects of the metallic ions on *r*-mandelic acid increase in the following order: Cs < Rb < K < NH₄ < Na < Li; Ba < Sr < Mg; and for the active acid the order is the same for the alkali metals, but Sr < Ba < Ca < Mg for the alkaline earths. In Table I the solubility (g.-equiv./1000 g. of water) of mandelic acid is recorded along with the concentration of added salt (*c*) and the solubility ratio *s/s*₀, where *s* and *s*₀ are the solubilities of mandelic acid in the salt solution and in water respectively. From these figures the values of *K* have been found, *K* being the well-known salting-out constant obtained from the equation $\log s/s_0 = Kc$ (Setschenow, *Mém. Acad. Imp. Sci. St. Petersburg*, 7, 22, No. 6; *Z. physikal. Chem.*, 1889, 4, 117). Since this equation holds accurately only for sparingly soluble weak electrolytes, *K* cannot in this case be expected to be absolutely constant, and its average value from *c* = ca. 0.1 to *c* = ca. 0.4 has been chosen as representative: for values of *c* less than 0.1, the value of *s/s*₀ differs very little from 1.0, and so calculated values of *K* are unreliable.

TABLE I.

Solubility of *r*-mandelic acid = 1.335.
Solubility of (–)mandelic acid = 0.738.

Acid, concn.	<i>s/s</i> ₀	<i>c</i>	<i>K</i>	Acid concn.	<i>s/s</i> ₀	<i>c</i>	<i>K</i>	Acid concn.	<i>s/s</i> ₀	<i>c</i>	<i>K</i>
<i>Cæsium r-mandelate.</i>				<i>Thallous r-mandelate.</i>				<i>Rubidium r-mandelate.</i>			
1.714	1.283	0.128	0.85	1.583	1.186	0.112	0.66	1.652	1.237	0.143	0.65
2.039	1.527	0.217	0.85	1.790	1.341	0.177	0.71	1.851	1.387	0.210	0.67
Average = 0.85				Average = 0.68				Average = 0.66			
<i>Cæsium (–)mandelate.</i>				<i>Thallous (–)mandelate.</i>				<i>Rubidium (–)mandelate.</i>			
0.777	1.054	0.112	0.20	0.874	1.184	0.153	0.48	0.766	1.039	0.100	0.17
0.857	1.161	0.210	0.30	0.915	1.240	0.222	0.42	0.837	1.135	0.200	0.27
0.971	1.316	0.310	0.38	1.084	1.470	0.324	0.51	0.922	1.250	0.300	0.32
Average = 0.30				Average = 0.47				Average = 0.28			
<i>Potassium r-mandelate.</i>				<i>Ammonium r-mandelate.</i>				<i>Sodium r-mandelate.</i>			
1.646	1.233	0.160	0.57	1.598	1.197	0.171	0.46	1.442	1.080	0.113	0.30
1.909	1.430	0.269	0.58	2.050	1.536	0.366	0.51	1.584	1.187	0.213	0.35
2.360	1.768	0.415	0.60	2.330	1.746	0.476	0.51	1.690	1.266	0.277	0.37
Average = 0.58				Average = 0.49				Average = 0.34			
<i>Potassium (–)mandelate.</i>				<i>Ammonium (–)mandelate.</i>				<i>Sodium (–)mandelate.</i>			
0.803	1.089	0.193	0.19	0.757	1.025	0.157	—	0.737	0.998	0.059	—
0.970	1.315	0.384	0.36	0.884	1.199	0.358	0.22	0.755	1.023	0.112	—
Average = 0.27				Average = 0.25				Average = 0.22			
<i>Lithium r-mandelate.</i>				<i>Barium r-mandelate.</i>				<i>Strontium r-mandelate.</i>			
1.413	1.058	0.100	0.25	1.450	1.086	0.062	0.58	1.380	1.031	0.031	0.43
1.491	1.117	0.200	0.24	0.783	1.060	0.120	0.21	0.776	1.052	0.104	0.22
1.555	1.165	0.250	0.26	0.815	1.105	0.166	0.26	0.812	1.101	0.140	0.30
Average = 0.25				Average = 0.25				Average = 0.26			
<i>Lithium (–)mandelate.</i>				<i>Barium (–)mandelate.</i>				<i>Strontium (–)mandelate.</i>			
0.756	1.024	0.146	0.08	0.840	1.139	0.198	0.28	0.776	1.052	0.104	0.22
0.766	1.039	0.186	0.09	Average = 0.25				0.812	1.101	0.140	0.30
0.788	1.068	0.246	0.11	Average = 0.25				Average = 0.26			
Average = 0.09				<i>Magnesium r-mandelate.</i>				<i>Magnesium (–)mandelate.</i>			
<i>Calcium r-mandelate.</i>				<i>Magnesium r-mandelate.</i>				<i>Magnesium (–)mandelate.</i>			
(See p. 267.)				1.407	1.054	0.130	0.18	0.758	1.028	0.186	0.06
<i>Calcium (–)mandelate.</i>				<i>Magnesium (–)mandelate.</i>				<i>Magnesium (–)mandelate.</i>			
0.747	1.012	0.030	0.17	0.792	1.074	0.294	0.10	Average = 0.08			
0.755	1.023	0.063	0.15	Average = 0.08				Average = 0.08			
0.776	1.052	0.075	0.29	Average = 0.08				Average = 0.08			
Average = 0.20				Average = 0.08				Average = 0.08			

The solubility of the acid was found in solutions of metallic chlorides and nitrates at concentrations up to 1.0 g.-equiv./1000 g. of water. In order to eliminate the effect caused

by the two electrolytes having no common ion, solubility determinations were carried out in solutions containing also the normal mandelate of the metal at a concentration of 0.05 g.-mol./1000 g. of water. This has the effect of reducing the degree of dissociation of the acid to a very small constant value, and eliminates the initial rise in solubility which would otherwise result from double decomposition of the components.

The chlorides, nitrates, and mandelic acid used were all purified as far as possible. Two identical experiments in which potassium chloride was used with (-) and with (+)-mandelic acid having given the same results, the latter acid was employed in the experiments.

5 G. of a solution containing 0.05 mol. of mandelate per 1000 g. of water were taken for each solubility determination, and weighed portions of the chloride or nitrate added. Duplicate experiments were carried out in each case : in one, excess acid was stirred for 4—5 hours at 25°, and in the other, excess acid was dissolved at a higher temperature, allowed to crystallise at 25°, and stirred for the same time. The acid in the filtered solution was estimated by titration. Owing to their deliquescent nature, the concentration of the chlorides of lithium, calcium, and magnesium was found by titration.

In order to obtain comparative figures for thallos salts, experiments were carried out with the nitrate, the chloride being too sparingly soluble. The introduction of a nitrate ion in this case introduced a further complication, so it was deemed advisable to compare the effect with those of the nitrates of the alkali metals.

The experimental results are in Table II, the rows labelled ν and (+) referring to ν - and (+) mandelic acid respectively. Negative values of K represent a salting-out effect.

TABLE II.

	Acid concn.	s/s_0	c	K	Acid concn.	s/s_0	c	K	Acid concn.	s/s_0	c	K
	<i>Cæsium chloride.</i>				<i>Rubidium chloride.</i>				<i>Potassium chloride.</i>			
ν	1.402	1.000	0.000	—	1.332	1.000	0.000	—	1.368	1.000	0.000	—
	1.416	1.010	0.202	+0.02	1.252	0.940	0.202	-0.13	1.323	0.967	0.101	-0.14
	1.425	1.016	0.303	+0.02	1.167	0.876	0.505	-0.12	1.275	0.932	0.202	-0.15
	1.433	1.022	0.404	+0.02	Average = -0.13				1.248	0.912	0.276	-0.14
	Average = +0.02								1.203	0.879	0.404	-0.14
Average = -0.14												
(+)	0.744	1.000	0.000	—	0.738	1.000	0.000	—	0.724	1.000	0.000	—
	0.747	1.004	0.101	+0.02	0.729	0.988	0.101	-0.05	0.715	0.987	0.101	-0.06
	0.751	1.009	0.202	+0.02	0.717	0.971	0.202	-0.06	0.692	0.955	0.202	-0.10
	0.758	1.016	0.404	+0.02	0.697	0.945	0.404	-0.06	0.667	0.920	0.404	-0.09
	Average = +0.02				Average = -0.06				Average = -0.08.			
	<i>Ammonium chloride.</i>				<i>Sodium chloride.</i>				<i>Lithium chloride.</i>			
ν	1.356	1.000	0.000	—	1.348	1.000	0.000	—	1.386	1.000	0.000	—
	1.295	0.955	0.101	-0.20	1.254	0.930	0.101	-0.31	1.207	0.871	0.107	-0.56
	1.232	0.909	0.202	-0.21	1.177	0.873	0.202	-0.29	1.037	0.748	0.269	-0.47
	1.171	0.864	0.353	-0.18	1.117	0.828	0.303	-0.27	0.954	0.688	0.403	-0.40
	Average = -0.20				1.027	0.762	0.404	-0.29	Average = -0.48			
Average = -0.29												
(+)	0.721	1.000	0.000	—	0.722	1.000	0.000	—	0.730	1.000	0.000	—
	0.709	0.984	0.101	-0.07	0.694	0.961	0.101	-0.17	0.701	0.961	0.095	-0.18
	0.689	0.956	0.202	-0.10	0.660	0.914	0.202	-0.19	0.681	0.934	0.165	-0.18
	0.677	0.939	0.303	-0.09	0.638	0.884	0.303	-0.18	0.667	0.914	0.197	-0.20
	0.662	0.918	0.404	-0.09	0.611	0.846	0.404	-0.18	0.641	0.878	0.266	-0.21
Average = -0.09				Average = -0.18				Average = -0.19.				
	<i>Barium chloride.</i>				<i>Strontium chloride.</i>				<i>Calcium chloride.</i>			
ν	1.345	1.000	0.000	—	1.292	1.000	0.000	—	(See p. 267.)			
	1.315	0.978	0.101	-0.10	1.214	0.940	0.104	-0.20				
	1.260	0.937	0.202	-0.14	1.129	0.874	0.356	-0.17				
	1.183	0.880	0.303	-0.18	Average -0.18							
	Average = -0.14											
(+)	0.733	1.000	0.000	—	0.724	1.000	0.000	—	0.745	1.000	0.000	—
	0.716	0.977	0.085	-0.12	0.677	0.935	0.202	-0.15	0.725	0.974	0.143	-0.08
	0.680	0.927	0.171	-0.20	0.644	0.889	0.404	-0.16	0.712	0.957	0.221	-0.09
	0.663	0.905	0.341	-0.13	Average = -0.15				0.692	0.929	0.264	-0.12
	Average = -0.15								0.665	0.893	0.327	-0.15
Average = -0.14												
Average = -0.12												

TABLE II (contd.)

Acid concn.	s/s_0 .	c .	K .	Acid concn.	s/s_0 .	c .	K .	Acid concn.	s/s_0 .	c .	K .	
<i>Magnesium chloride.</i>				<i>Cæsium nitrate.</i>				<i>Thallous nitrate.</i>				
1.339	1.000	0.000	—	1.402	1.000	0.000	—	1.430	1.000	0.000	—	
	0.826	0.285	-0.29	1.464	1.044	0.101	0.19	1.571	1.099	0.101	0.41	
(+)	0.709	1.000	0.000	—	1.567	1.118	0.202	0.24	1.674	1.170	0.202	0.34
	0.644	0.909	0.216	-0.19	1.581	1.128	0.303	0.18	1.923	1.345	0.404	0.32
	0.589	0.830	0.411	-0.20	1.670	1.191	0.404	0.19	Average = 0.36			
	Average = -0.19			0.744	1.000	0.000	—	0.758	1.000	0.000	—	
Average = -0.19			0.762	1.024	0.101	0.10	0.804	1.061	0.101	0.25		
Average = -0.19			0.783	1.052	0.202	0.11	0.858	1.132	0.202	0.27		
Average = -0.19			0.810	1.089	0.303	0.12	0.951	1.255	0.404	0.24		
Average = -0.19			0.836	1.124	0.404	0.13	Average = 0.25					
Average = -0.19			Average = 0.20				Average = 0.12					
<i>Rubidium nitrate.</i>				<i>Potassium nitrate.</i>				<i>Ammonium nitrate.</i>				
(+)	1.382	1.000	0.000	—	1.373	1.000	0.000	—	1.380	1.000	0.000	—
	1.408	1.019	0.101	0.08	1.390	1.013	0.101	0.06	1.385	1.003	0.101	0.0
	1.431	1.035	0.202	0.08	1.408	1.025	0.202	0.05	1.385	1.003	0.202	0.0
	1.456	1.054	0.303	0.08	1.432	1.043	0.404	0.05	1.382	1.001	0.303	0.0
	1.490	1.076	0.404	0.08	Average = 0.05				1.370	0.991	0.404	0.0
Average = 0.08			0.738	1.000	0.000	—	0.732	1.000	0.000	—		
Average = 0.08			0.747	1.013	0.101	0.05	0.735	1.005	0.101	0.02		
Average = 0.08			0.759	1.028	0.202	0.06	0.738	1.009	0.202	0.02		
Average = 0.08			0.764	1.035	0.303	0.05	0.740	1.011	0.404	0.01		
Average = 0.08			0.774	1.048	0.404	0.05	Average = 0.02					
Average = 0.05			Average = 0.05				0.733	1.000	0.404	0.0		
<i>Sodium nitrate.</i>				<i>Lithium nitrate.</i>								
(+)	1.348	1.000	0.000	—	1.342	1.000	0.000	—				
	1.324	0.983	0.101	-0.08	1.276	0.950	0.101	-0.22				
	1.305	0.968	0.202	-0.07	1.227	0.915	0.202	-0.19				
	1.236	0.917	0.404	-0.09	1.121	0.835	0.404	-0.19				
	Average = -0.08			Average = -0.20								
Average = -0.08			0.722	1.000	0.000	—	0.722	1.000	0.000	—		
Average = -0.08			0.715	0.991	0.101	-0.04	0.707	0.978	0.101	-0.09		
Average = -0.08			0.700	0.969	0.202	-0.07	0.688	0.953	0.202	-0.10		
Average = -0.08			0.676	0.937	0.404	-0.07	0.652	0.903	0.404	-0.11		
Average = -0.06			Average = -0.10				Average = -0.10					

The foregoing results are summarised in Table III, in which a and b represent the difference between the value of K for the metal mandelate (K_M) and for its chloride (K_{MCl}) or nitrate respectively.

For the data of Table I, with certain of the metallic ions only a small range of concentrations of mandelic acid can be investigated, as acid salts are deposited at relatively low concentrations (see also original curves, *loc. cit.*). On this account the values of K are not so constant as in the data of Table II, where a larger range of concentrations is available. In particular, with r -mandelic acid and calcium mandelate no values of K can be calculated.

We may take K_M as representing the salting-out effect of the metallic ion + compound formation (salting-in effect), and K_{MCl} as denoting the joint salting-out effects of the metallic ion and of the chloride ion. The differences a and b will then represent the compound formation effect + the salting-out effect of the chloride and nitrate ion respectively, and will be independent of the salting-out effect of the metallic ion. Since the values obtained for a and b are approximately constant, we may conclude that the compound formation effect is independent of the metallic ion present. The effect of the metallic mandelates is therefore due to a combination of the mandelic acid with the mandelate ion of the types: HA, A' , $2HA, A'$, and $3HA, A'$, where A represents the mandelate ion.

It is generally agreed that the size of the ions determines the extent of the salting-out effect of a salt, and since potassium and chloride ions are approximately of the same size, we may assume, with Larsson (*loc. cit.*, 1931), that $K_K = K_{Cl}$. Since $K_{KCl} = -0.14$,

