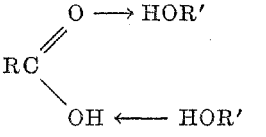
[CONTRIBUTION FROM THE FURMAN CHEMICAL LABORATORY, VANDERBILT UNIVERSITY]

# THE VARIATION OF PARTITION RATIOS IN MIXED SOLVENTS

D. E. PEARSON AND MAX LEVINE[1]

*Received April 3, 1952*

In the preceding paper (1), it was noted that alcohols are unusually effective in the extraction of organic acids from water solution and it was postulated that the effectiveness is due to the dual nature of their hydrogen-bonding processes. Alcohols can act as both acceptors and donors, an oversimplified version of their action being visualized as follows:




Though it is difficult to prove such a postulate, it is profitable to accept this mechanism of solubilization tentatively and investigate means of utilization. One application which has been found worthwhile is the use of mixed solvents, one a preferred hydrogen-bonding acceptor, another a donor, in partition studies. Enhanced solubility in the organic phase is anticipated when such a combination of solvents is used.[2]

Though no literature record of partition ratios using mixed solvents has been found,[3] considerable information is available on the solubility of organic compounds in mixed solvents. Even these data include few examples involving low molecular weight compounds. Highfield (4) has reviewed the literature up to 1926. The interesting solubility properties of picric acid are described by Duff and Bills (5), of helianthine by Dehn (6), and of soaps in glycol-hydrocarbon solvents by Palit (7). Examples, involving high molecular weight compounds which have multiple points for solvent action and consequently more pronounced effects, are more abundant. Older theories of solubilization, such as those of Baker (8), Barr and Bircumshaw (9), and Byron (10) propose interaction of the two solvents to form a new species in which high molecular weight substances, such as cellulose derivatives, are more soluble. Mardles (11) points out that any important interaction between solvent molecules should actually lead to poorer solubility. The more recent theory, apparently the outgrowth of the work and discussions of Esselen (12), Marden and Dover (13), Highfield (4), Grinberg and Shulman (14), McBain (15), and Palit (7, 16), proposes a balanced action between polar and non-polar forces of the mixed solvent operat-

[1] From part of the thesis of Max Levine submitted to the Graduate School, Vanderbilt University, in partial fulfillment of the requirements for the Ph.D. degree, 1951.

[2] Herz and Kuhn (2) have found the solubility of most inorganic salts in mixed solvents to be an average of the solubility in each of the pure solvents.

[3] Craig (3) alludes to such cases.

TABLE I

PARTITION RATIOS OF FORMIC ACID[a] IN THE SYSTEMS, WATER-PURE SOLVENT AND WATER-MIXED SOLVENT

| WATER-SOLVENT I (K) | WATER-SOLVENT II (K) | WATER-EQUAL VOLUMES OF I AND II (K) | CONCENTRATION INCREASE IN ORGANIC PHASE, [b] % |
|---|---|---|---|
| Methyl isobutyl ketone (2.31) | Cyclohexanol (1.41) | 1.01 | 72 |
| Methyl isobutyl ketone (2.31) | 1-Hexanol (2.24) | 1.41 | 62 |
| Methyl isobutyl ketone (2.31) | Methyldibutylcarbinol (2.91) | 1.80 | 42 |
| Methyl isobutyl ketone (2.31) | 1,2-Octanediol (1.59) | 1.43 | 31 |
| Methyl isobutyl ketone (2.31) | Methylisobutylcarbinol (1.69) | 1.29 | 51 |
| Pivalonitrile (4.39) | Methylisobutylcarbinol (1.69) | 1.32 | 84 |
| Isopropyl ether (7.1) | Methylisobutylcarbinol (1.69) | 1.81 | 51 |
| Mesityl oxide (1.22) | Methylisobutylcarbinol (1.69) | 1.05 | 34 |
| Butyl acetate (2.88) | Methylisobutylcarbinol (1.69) | 1.52 | 48 |
| Chloroform (85) | Methylisobutylcarbinol (1.69) | 2.48 | 33 |
| Cyclohexanone (0.91) | Methylisobutylcarbinol (1.69) | 0.88 | 40 |
| Cyclohexanone (0.91) | Cyclohexanol (1.41) | 0.84 | 32 |
| Methyl isobutyl ketone (2.31) | Cyclohexanone (0.91) | 1.39 | −6 |
| Methyl isobutyl ketone (2.31) | Mesityl oxide (1.22) | 1.78 | −10 |
| Methyl isobutyl ketone (2.31) | Butyl acetate (2.88) | 2.59 | 0 |
| Methyl isobutyl ketone (2.31) | Pivalonitrile (4.39) | 2.94 | 2 |
| Methyl isobutyl ketone (2.31) | Isopropyl ether (7.1) | 3.32 | 4 |
| Methyl isobutyl ketone (2.31) | Chloroform (85) | 11.3 | −60 |
| Methyl isobutyl ketone (2.31) | N,N-Dibutylformamide (0.30) | 0.52 | 2 |
| Methylisobutyl carbinol (1.69) | N,N-Dibutylformamide (0.30) | 0.73 | −30 |
| Methylisobutylcarbinol (1.69) | Cyclohexanol (1.41) | 1.53 | 0 |

[a] Formic acid was 0.0977 $N$. Partition ratios were also run at 0.05 $N$ and 0.025 $N$, but these data illustrated no further point and are not recorded. [b] Direct comparison of partition ratios is misleading. The theoretical concentration in the organic phase was calculated as follows (for first example): 2.31 g. of formic acid in water is in equilibrium with 0.5 g. of formic acid in one-half the volume of solvent I; 2.31 g. of formic acid in water is in equilibrium with 0.82 g. of formic acid in one-half the volume of solvent II; the theoretical concentration in the combined solvent is, therefore, 1.32 g.; Found, 2.28 g. in combined solvent in equilibrium with 2.31 g. of formic acid in water or 72% increase.

ing directly on the solute. For example, alcohols would form a hydrogen bond with a cellulose derivative, aiding in dispersion and covering some polar parts

of the aggregates sufficiently to permit solubility in non-polar solvents. In other words, the process of solubilization appears to be a dynamic, balanced action between polar and non-polar forces.

Thus, the mixed solvent theory, as applied to partition ratios, is an extension of the more recent theory of solubilization. The solubilization theory proposes dual action of polar and non-polar forces, whereas the results of this paper suggest that, in some cases, the polar forces are of a dual nature in themselves — specifically, that two types of hydrogen bonding are involved in the solubilization of organic acids. Though no proof of this extension can be found in the experimental section, the results are best explained on this basis.

TABLE II

PARTITION RATIOS OF VARIOUS SOLUTES IN WATER-MIXED SOLVENTS SYSTEMS

| SOLUTE[a] | WATER-METHYL ISOBUTYL KETONE, K | WATER-METHYL ISOBUTYL-CARBINOL, K | WATER-EQUAL VOLUMES OF I AND II K | CONCENTRATION INCREASE IN ORGANIC PHASE, % |
|---|---|---|---|---|
| Oxalic acid | 12.3 | 6.9 | 4.4 | 100 |
| 1-Naphthalenesulfonic acid | 24.1 | 1.93 | 2.21 | 61 |
| Succinic acid[b] | 4.94 | 1.62 | 1.36 | 81 |
| N-Acetyl-D-valine | 2.83 | 0.59 | 0.67 | 45 |
| Acetic acid | 2.07 | 1.09 | 1.02 | 40 |
| Propionic acid | 0.58 | 0.32 | 0.30 | 32 |
| Acrylic acid | 0.42 | 0.27 | 0.23 | 43 |
| Ammonia[c] | 20.1 | 9.1 | 9.5 | 32 |
| Methylamine[d] | 2.06 | 3.54 | 1.39 | 87 |
| Dimethylamine[e] | 8.4 | 1.59 | 2.70 | 1 |
| Trimethylamine[f] | 1.88 | 0.44 | 0.83 | −13 |

[a] All solutes were about 0.1 $N$ unless otherwise noted. [b] 0.0489 $N$. [c] 0.0717 $N$. [d] 0.0609$N$. [e] 0.0836 $N$. [f] 0.0661 $N$. Other concentrations were also used but the results not recorded.

## EXPERIMENTAL

The procedures of the preceding paper (1) were followed except as noted in the results. All mixed solvents were purified separately by washing with sodium bicarbonate solution, drying, and fractionating. They were mixed in a 50–50 ratio by volume except as noted and then presaturated with water. The 50–50 ratio by volume was chosen on the basis of results obtained in the extraction of formic acid (0.05 $N$) using mixtures of methyl isobutyl ketone and methylisobutylcarbinol. The following partition ratios were obtained (% ketone by volume in carbinol given in brackets): 1.75 [0]; 1.55 [10]; 1.44 [20]; 1.33 [30]; 1.32 [40]; 1.28 [50]; 1.30 [60]; 1.38 [70]; 1.56 [80]; 1.88 [90]; 2.39 [100]. This experiment indicated maximum transfer to the organic phase at a 50–50 ratio by volume. The temperature of equilibration 26° ± 2°, did not seem to affect the relative maximum transfer on the basis of the following results (formic acid 0.05 $N$): methyl isobutyl ketone, 0° (K = 2.26); 25° (K = 2.31); 40° (K = 2.63); methylisobutylcarbinol, 0° (K = 1.76); 25° (K = 1.68); 40° (K = 1.80); equal volumes of methyl isobutyl ketone and methylisobutylcarbinol, 0° (K = 1.08); 25° (K = 1.28); 40° (K = 1.49). The results are recorded in Tables I and II.

## DISCUSSION

Table I summarizes the effect of various mixed solvents on the extraction of formic acid from aqueous solution. The solvents which show enhanced solubility

of formic acid in the organic phase (31–84%) are always a combination of a hydrogen-bonding acceptor and donor. Combinations of ketones with other ketones or with esters, nitriles, or ethers (all hydrogen-bonding acceptors) result in little or no enhanced solubility in the organic phase and, in some cases, less solubility than calculated. The combination of two alcohols likewise results in no enhanced solubility. These results were anticipated on the basis of the theory that organic acid solutes are solubilized by two independent types of hydrogen bonding as discussed in the Introduction. This theory can be further utilized in typing solvents whose characteristics are difficult to analyze by observation. For example, the data indicate that chloroform, an exceedingly poor solvent for the extraction of organic acids by itself, acts as a weak proton acceptor which is contrary to its behavior in non-aqueous solution (17). Also, the data indicate that N,N-dibutylformamide is such a strong acceptor and donor molecule that admixture with other solvents does not enhance solubility in the organic phase.

Table II records the partition ratios of various solutes in a given, mixed solvent system. The sequence in the water-mixed solvent system: oxalic acid (100% increase in solubility in the organic phase), succinic acid (81%), formic acid (51%), acetic acid (40%), propionic acid (32%), is exactly the order to be expected from the opposing effect of van der Waals forces. In the series of amines, it is noted that neither trimethylamine nor dimethylamine show enhanced solubility in the mixed solvent. Certainly, an enhancement was not expected with trimethylamine since it has no hydrogen for donor action, and dimethylamine is such a relatively strong base that its hydrogen may not be available for similar action.

Though the work of this paper refers to partition ratios, the theory is also applicable to solubility. For example, the solubility of succinic acid (g./l.) at 30° was as follows in: methyl isobutyl ketone (8.02 g.), methylisobutylcarbinol (42.95 g.), equal volumes of ketone and carbinol (41.18 g.); the solubility of water (% by weight) at 26° was as follows in: methyl isobutyl ketone (2%), methylisobutylcarbinol (6.5%), and equal weights of ketone and carbinol (5.5%).

## SUMMARY

A study of the partition ratios of some organic acids and bases in water-mixed solvent systems has been made. Enhanced solubility in the organic phase of the order of 30–100% takes place whenever a hydrogen-bonding acceptor solvent and a hydrogen-bonding donor solvent are combined. The results are best explained on the theory that the organic solute is solubilized by two types of hydrogen bonding.

NASHVILLE 4, TENNESSEE

## REFERENCES

(1) PEARSON AND LEVINE, *J. Org. Chem.*, **17**, preceding paper (1952).
(2) HERZ AND KUHN, *Z. anorg. Chem.*, **60**, 152 (1908).
(3) CRAIG AND CRAIG in WEISSBERGER, *Technique of Organic Chemistry*, Interscience Publishers, New York, N. Y., 1950, Vol. III, p. 171.
(4) HIGHFIELD, *Trans. Faraday Soc.*, **22**, 57 (1926).
(5) DUFF AND BILLS, *J. Chem. Soc.*, 881 (1932).

(6) DEHN, *J. Am. Chem. Soc.*, **39**, 1399 (1917).
(7) PALIT, *J. Am. Chem. Soc.*, **69**, 3120 (1947) and previous papers.
(8) BAKER, *J. Chem. Soc.*, **101**, 1409 (1912).
(9) BARR AND BIRCUMSHAW, *Trans. Faraday Soc.*, **16**, 98 (1921).
(10) BYRON, *J. Phys. Chem.*, **30**, 1116 (1926).
(11) MARDLES, *J. Oil & Colour Chemists' Assoc.*, **26**, 15 (1943).
(12) ESSELEN, *Ind. Eng. Chem.*, **12**, 801 (1920).
(13) MARDEN AND DOVER, *J. Am. Chem. Soc.*, **30**, 239 (1908).
(14) GRINBERG AND SHULMAN, *Ann. inst. platine (U.S.S.R.)*, **11**, 111 (1933).
(15) MCBAIN, *J. Phys. Chem.*, **30**, 239 (1926).
(16) PALIT, *J. Phys. & Colloid Chem.*, **51**, 837 (1947).
(17) ZELLHOFER, COPLEY, AND MARVEL, *J. Am. Chem. Soc.*, **61**, 3161 (1939).