Hydrates of Organic Compounds. III. The Formation of Clathrate-like Hydrates of Tetrabutylammonium Dicarboxylates

Haruo NAKAYAMA* and Kazuichi WATANABE
Department of Chemistry, Faculty of Engineering, Yokohama National University, Ooka-machi, Minami-ku, Yokohama 232

(Received March 22, 1978)

The solid-liquid phase diagrams for the binary mixtures of water with 20 tetrabutylammonium dicarboxylates, $[(n\text{-}C_4H_9)_4N]_2OOC\text{–}R\text{–}COO$ (R=methylene chain ranging from 0 to 10 carbon atoms; methylene chain containing substituted groups such as $-CH_3$, $-C_2H_5$, $-NH_2$, and $-OH$; and $-C_6H_4-$ (three phthalate isomers)), have been investigated to see the effect of dicarboxylate anions on the formation of clathrate-like hydrates. It has been found that, with only the one exception of the dodecanedioate, all the other salts form hydrates which have large hydration numbers. Judging from these large hydration numbers, they are believed to be clathrate-like hydrates. From the relationship between the hydration numbers and the melting points, these hydrates can be classified into three groups at least. All the hydrates other than those of oxalate and of terephthalate are newly found in this study.

In 1959 McMullan and Jeffrey[1)] pointed out that a series of hydrates formed by tetrabutyl(and tetraisopentyl)ammonium salts, which were originally found by Kraus and his co-workers,[2)] were clathrate-like hydrates similar to the gas hydrates.[3)] Later this reasoning was verified by detailed structural studies.[4—6)]

In general, in these hydrates, each alkyl chain of the ammonium cation (and also each hydrophobic group of an anion, if such exists) is accommodated within a polyhedron (such as 14- or 15-hedron) which is constructed by hydrogen-bonded water molecules. Since most of these hydrates can easily be formed at moderate conditions, they provide us with a suitable model system for studying the nature of the interaction between water and hydrophobic molecules, especially in connection with the structural modification of water molecules in the vicinity of hydrophobic solutes in an aqueous solution.

The previous study[7)] clearly showed that the most suitable alkyl chain of a tetraalkylammonium cation for the formation of stable clathrate-like hydrates was either butyl or isopentyl, and further that a shorter or longer chain than these groups drastically affected the stability of the hydrates. On the other hand, in the case of anions it is well known that many tetrabutyl(or isopentyl)ammonium salts with various anions (such as F^-, Cl^-, Br^-, CH_3COO^-, HCO_3^-, CrO_4^{2-}, WO_4^{2-}, $C_2O_4^{2-}$, and HPO_4^{2-}) can form clathrate hydrates,[1)] and that the effect of an anion on the stability (*i.e.*, the melting points) of these hydrates is not so marked as that of the alkyl-chain length of the cation.

Of the anions which form clathrate-like hydrates, a carboxylate anion seems to be of special importance, since it may have an additional hydrophobic group. The formation of clathrate hydrates of tetrabutylammonium monocarboxylates have been reported for formate,[2)] acetate,[1,2)] propionate,[2)] butyrate,[8)] pentanoate,[8)] benzoate,[2,5)] and *m*-chlorobenzoate.[8)] Such properties as hydration numbers and melting points for these hydrates have been either measured or estimated. The detailed crystal structure is known only for benzoate hydrate.[5)] In this hydrate ($(n\text{-}C_4H_9)_4N\cdot OOCC_6H_5\cdot 39.5H_2O$), not only four butyl groups of the cation but also the benzyl group is enclathrated by the hydrogen-bonded water framework, and the oxygen atoms of the benzoate anion are hydrogen-bonded to the water framework and form part of the polyhedral structure. Essentially similar structures will be expected for the propionate, butyrate, and *m*-chlorobenzoate hydrates. The cases of the formate and the acetate are less simple to predict.[5)]

On the other hand, for tetrabutylammonium dicarboxylates the formation of clathrate hydrate is known only for oxalate[1,2,8)] and terephthalate,[8)] for which hydration numbers have either been measured directly or estimated from the X-ray results (the Laue symmetry, unit-cell dimensions, and so forth). So far no other study has been reported about the formation of clathrate hydrates of a tetrabutylammonium dicarboxylate. In this paper, through the determination of the solid-liquid phase diagrams for the tetrabutylammonium dicarboxylate–water binary systems, an extensive study has been made in order to examine a variety of effects of dicarboxylate anions on the formation of clathrate hydrates: (1) the effect of the length of the methylene chain introduced between two carboxyl groups; (2) the effect of the type and the position of the substituted groups (such as $-CH_3$, $-C_2H_5$, $-NH_2$, and $-OH$); and (3) the effect of the geometrical relationship between the two carboxyl groups.

Experimental

Materials. The following tetrabutylammonium dicarboxylates $[(n\text{-}C_4H_9)_4N]_2OOC\text{–}R\text{–}COO$, were used, where R were: (1) $-(CH_2)_n-$ (n=0—8, and 10); (2) $-CH(C_2H_5)-$; (3) $-CH_2-CH(CH_3)-(CH_2)_m-$ (m=0—2); (4) $-CH(NH_2)-(CH_2)_l-$ (l=1,2); (5) $-CH_2-CH(OH)-$; and (6) $-C_6H_4-$ (*o*-, *m*-, and *p*-). All the salts were prepared by neutralizing tetrabutylammonium hydroxide solutions with the corresponding acids. The hydroxide was prepared from tetrabutylammonium iodide by means of silver oxide,[1,2)] and purified by recrystallization from its dilute aqueous solution in the form of clathrate hydrate crystal.[2)] The tetrabutylammonium iodide was prepared by the reaction between tributylamine and butyl iodide and was purified by repeated recrystallization from ethyl acetate.[7)] All acids were reagent grade commercial materials and used without further purification except phthalic and isophthalic acids and four acids $HOOC(CH_2)_nCOOH$, whose n=3—8: phthalic and isophthalic acids were recrystallized from ethyl alcohol and the latter acids from water. The salts which could form stable hydrates (whose melting points were higher than about 10 °C) were purified by recrystallization from water in the hydrate forms.

Procedures. For each salt, a sample (about 1—2 ml) of known composition was prepared by weighing its concentrated solution and water, and then was sealed in a small glass ampoule. No special care was taken to remove the air dissolved in the solution. The concentrated salt solution was prepared by dehydrating a relatively dilute solution over P_2O_5 in an desiccator; its concentration (water content) was determined by the Karl Fisher titration method on a MK-AII apparatus (Kyoto Electronics Manufacturing Co.). Each ampoule was gradually cooled until the solid phase appeared and was annealed for at least 24 h. After that, the ampoule was slowly warmed (at the rate about 0.3 °C per hour) with vigorous shaking in a constant temperature bath. The solid -liquid phase diagrams were determined by measuring the temperature at which the solid phase completely disappeared. When the temperature determination was somewhat ambiguous, especially at high mole fractions and at low temperatures, the differential scanning calorimeter (DSC) (Shimadzu Seisakusho, SC-20) was also employed.

Results

The solid-liquid phase diagrams for the salts of $[(n\text{-}C_4H_9)_4N]_2OOC\text{-}(CH_2)_n\text{-}COO$ with $n=0$—4 are shown in Fig. 1, and with $n=5$—8, and 10 in Fig. 2. With only one exception, the salt with $n=10$, all the other salts form hydrates with a large number of water molecules. All these hydrates melt congruently.

The oxalate ($n=0$) hydrate is quite stable. Its melting point is 16.6 °C and its hydration number is 58±1. This melting point is in good agreement with 16.8±0.1 reported by Jeffrey and co-workers[1] for the tetragonal structure. The hydration number, however, is greatly different from their values, 67 (by chemical analysis) and 64 (estimated from crystallographic data).[1] On the other hand, their other hydration number, 57.3±2,[8] which has been estimated for the cubic structure ($a=24.58$ Å) is in agreement with ours, though the melting point of this structure has not been reported.

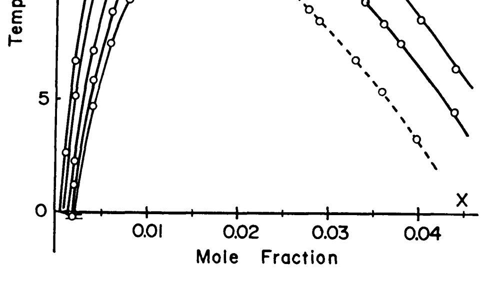

Fig. 1. The solid-liquid phase diagrams for the water-$[(n\text{-}C_4H_9)_4N]_2OOC(CH_2)_nCOO$ systems; $n=0$—4.

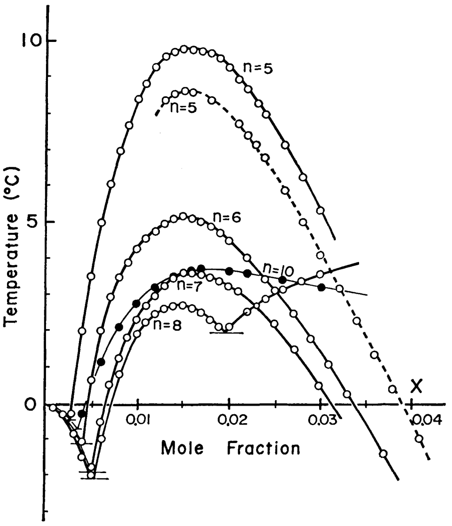

Fig. 2. The solid-liquid phase diagrams for the water-$[(n\text{-}C_4H_9)_4N]_2OOC(CH_2)_nCOO$ systems; $n=5$—8, and 10.

As is seen from Figs. 1 and 2, the stabilities (*i.e.*, melting points) of these hydrates decrease, as a general trend, upon increasing the length of the methylene chain located between the two carboxyl groups. However, the hydrates of glutarate ($n=3$) and adipate ($n=4$) are exceptionally stable, indicating that $OOC\text{-}(CH_2)_3\text{-}COO$ and $OOC\text{-}(CH_2)_4\text{-}COO$ anions are most suitable for being accommodated within the hydrogen-bonded water framework. For the pimelic salt ($n=5$), another metastable phase appears when its aqueous solution is cooled rapidly. The stable phase appears only when the solution is maintained at temperatures around 0 °C for several days. The salt concentration of the hydrates (*i.e.*, the concentration of maximum temperature in each phase diagram) slightly decreases with increasing n from 0 to 2, shifts to a high (and almost the same) value for the salts with $n=3$ and 4, and again decreases and holds an approximately constant value for the salts with $n=5$—8 (Fig. 2).

In the case of the salts with $n=2$, 4, and 8, another solid phase appears at high mole fractions, around 0.02 for $n=2$ and 8 and 0.04 for $n=4$. It is not certain whether these phases are lower hydrates or anhydrous solids. For the salt with $n=10$, the phase diagram (Fig. 2) shows a very broad peak in the vicinity of $X=0.016$—0.018. This solid phase, however, does not seem to be a hydrate similar to those of the other salts, judging from the fact that the shape of the phase diagram differs from the others and that it takes a long time to attain the dissolution equilibrium, as compared with other salts.

All the melting points and hydration numbers obtained in this paper are summarized in Table 1. The phase diagrams of such salts as ethylmalonate, methylsuccinate, aminosuccinate (L-asparate), hydroxysuccinate (L-malate), 3-methylglutarate, 2-aminoglutarate (L-glutamate), and 3-methyladipate have essentially similar shapes to those of each parent salt, as shown in Fig. 1. Therefore, for the hydrates of these salts, only the melting points and hydration numbers which are read off each phase diagram are listed in Table 1.

Figure 3 gives the phase diagrams of three isomeric (*o*-, *m*-, and *p*-) phthalates. The phthalate gives the most stable hydrate among the salts studied in this paper. Although the water content of these hydrates is approximately identical, their melting points decrease in intervals of 4.0 degrees in the order of phthalate, isophthalate, and terephthalate. In the case of terephthalate, another solid phase appears at high mole fractions around 0.04; its composition is not known. The observed melting point and hydration number for the terephthalate hydrate, 12.3 °C and 62±2 (Table 1), are in disagreement with those reported by Jeffrey *et al.*,[8] 9.5 °C and 84±4. The latter hydration number has been deduced by inference from the structures already known.

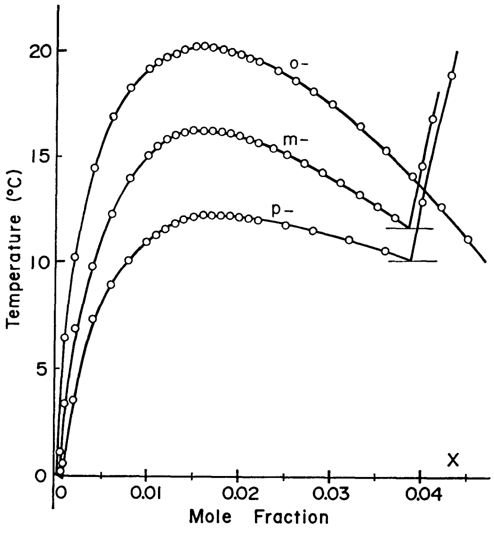

Fig. 3. The solid-liquid phase diagrams for the water-tetrabutylammonium phthalate systems.

Table 1. The melting points and the hydration numbers of the hydrates formed by a series of tetrabutylammonium dicarboxylates $[(n\text{-}C_4H_9)_4N]_2OOC\text{-}R\text{-}COO$

R	Melting point (°C)	Hydration number
None (oxalate)	16.6	58±1
$-CH_2-$	14.4	59±1
$-CH(C_2H_5)-$	15.9	62±1
$-CH_2-CH_2-$	12.1	61±1
$-CH_2-CH(CH_3)-$	14.9	63±1
$-CH_2-CH(NH_2)-$ (L)	9.8	63±2
$-CH_2-CH(OH)-$ (L)	11.1	63±1
$-CH_2-CH_2-CH_2-$	20.2	55±1
$-CH_2-CH(CH_3)-CH_2-$	16.2	55±1
$-CH(NH_2)-CH_2-CH_2-$ (L)	15.8	55±1
$-CH_2-CH_2-CH_2-CH_2-$	19.0	55±1
$-CH_2-CH(CH_3)-CH_2-CH_2-$	12.0	55±2
$-(CH_2)_5-$ (stable)	9.8	63±2
(metastable)	8.6	65±2
$-(CH_2)_6-$	5.2	65±3
$-(CH_2)_7-$	3.7	65±3
$-(CH_2)_8-$	2.7	65±3
$-C_6H_4-$ phthalate	20.3	62±1
isophthalate	16.3	62±1
terephthalate	12.3	62±2

Discussion

These results show that all the salts, except dodecanedioate, form hydrates which have large hydration numbers ranging from 55 to 65 and melt congruently. Although there is no evidence about the structure of these hydrates, they are believed to be clathrate-like hydrates for the following reasons. In general, arguing from the structure of several tetraalkylammonium salt hydrates,[1,4–7] 7—8 water molecules per one alkyl group, such as butyl and isopentyl, are needed in order to accommodate it by making a hydrogen-bonded water framework. Since the salts used in this study have 8 or 9 hydrophobic groups, the hydration numbers for these salt hydrates are expected to have values around 60 if they form similar types of hydrates, in good agreement with the values actually found.

As mentioned earlier, the detailed crystal structure of tetrabutylammonium carboxylate hydrates is known only for benzoate hydrate,[5] in which two oxygen atoms of the benzoate anion occupy two adjacent polyhedral sites. Thus it may be reasonably anticipated that, in the dicarboxylate hydrates found in this paper, four oxygen atoms of two terminal carboxyl groups will likewise occupy the appropriate hydrogen-bonded sites of the polyhedral vertices. This restriction will be one of the factors which will affect the stabilities of these hydrates. In addition, we may list other stability-controlling factors, such as (1) how well a hydrophobic group existing between two carboxyl groups is

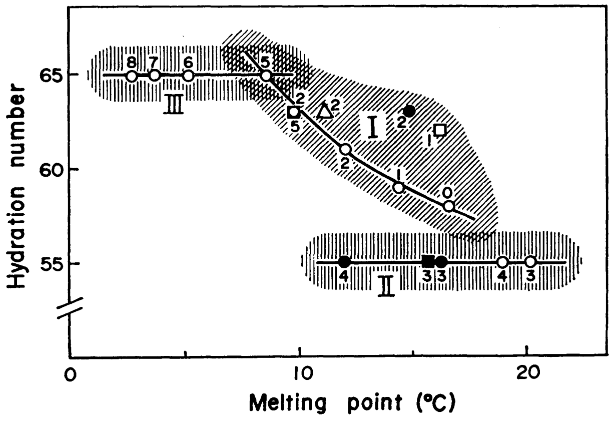

Fig. 4. The correlations between the hydration numbers and the melting points of the hydrates of tetrabutylammonium dicarboxylates. ○: Anions with no substituted group; ●: anions with methyl group; □: anions with ethyl group; ■: anions with $-NH_2$ group; △: anion with –OH group. A numeral attached to each point indicates the number of carbon atoms in the methylene chain of the dicarboxylate anion.

accommodated within a hydrogen-bonded framework of waters and (2) the change in electrostatic potential due to the positional change of carboxyl anions with respect to a central $(n\text{-}C_4H_9)_4N^+$ cation.

Figure 4 gives the relationship between the hydration numbers and the melting points observed for our series of hydrates. The number attached to each point stands for the number of carbon atoms of the methylene chain in a dicarboxylate anion. From this figure we may tentatively classify these hydrates into three groups: I, II, and III.

Group I consists of the hydrates of the salts with $n=$ 0, 1, 2, and 5 and all their derivatives. In this group of hydrates the hydration number varies within the range of 58 and 63 depending upon the size and/or shape of the hydrophobic group of the anion and increases, in general, with decreasing the melting points. Of these hydrates, oxalate hydrate is the most stable and the stability gradually decreases upon increasing the length of the methylene chain. This fact will suggest that neither a small methylene chain as in the malonate ($n=1$) and the succinate ($n=2$) nor a large one as in the pimelic salt ($n=5$) is suitable in size to be encaged stably by a hydrogen-bonded water framework. The stabilities of these hydrates seem to be strongly influenced by the relative difficulty of fixing four oxygen atoms of two carboxyl groups into appropriate polyhedral sites. From the fact that oxalate (and also phthalate hydrate, Fig. 3 and Table 1) is fairly stable, it may be said that the existence of two carboxyl groups in the vicinity of one tetrabutylammonium cation is favorable for forming a stable hydrate. Thus in the oxalate hydrate, for example, the hydrate is made up by $[(n\text{-}C_4H_9)_4N\cdot OOC\text{–}COO]^-$ anions and $(n\text{-}C_4H_9)_4N^+$ cations, each surrounded by a hydrogen-bonded water framework.

It is interesting to note that the ethylmalonate hydrate is more stable than that of the malonate itself; the same relation is found between methylsuccinate and succinate hydrates. This indicates that the introduction of an ethyl or methyl group onto such small hydrophobic anions makes them more suitable in size to be surrounded by the hydrogen-bonded framework of water. The substitution of polar groups like $\text{–}NH_2$ and –OH onto the succinic acid anion causes a slight decrease in the melting points of their hydrates. This presumably occurs as a result of the overlapping of two conflicting factors: a favorable factor of increasing the molecular volume of such a small anion; and a inconvenient factor of the disturbance in the stable formation of water polyhedra due to the occurrence of directional interaction (hydrogen-bonding) between these polar groups and water molecules which construct polyhedral cages. This effect of the introduction of a polar group into a guest molecule on the stability of its hydrate is, however, much less than expected; salts such as $(n\text{-}C_4H_9)_3(C_3H_6OH)NF$ and $(n\text{-}C_4H_9)_3(CH_3COOCH_2)NF$ cannot form stable hydrates at all,⁹⁾ in striking contrast to a very stable $(n\text{-}C_4H_9)_4NF$ hydrate.⁷⁾

Group II consists of the hydrates of the salts having $n=3$ (glutarate) and $n=4$ (adipate) which are fairly stable and have the smallest hydration number of 55; these salts are favorable for water molecules to form the hydrogen-bonded framework most efficiently by sharing common faces of adjacent polyhedra as much as possible. The fact that the hydrates of these salts, including their methyl and amino derivatives, have almost the same hydration number will suggest that these hydrates have essentially the same structures, although their melting points are considerably changed by the type of anions. In contrast to the case of the malonate and succinate hydrates mentioned above, the introduction of a methyl group onto the methylene chain of a glutaric or adipic acid anion causes a decrease in the melting point of its hydrate. As pointed out above, since the dicarboxylate anion having three or four methylene groups with no substituted groups seems to be the optimum anion for the formation of a stable hydrate, the presence of the substituted group will either make the hydrophobic group unfavorably large or disturb the best fit of the methylene chain by reducing the degree of positional freedom of occupation. The effect of the substituted amino group on the stability of hydrate is relatively slight, just as in the case of the succinate.

The series of salts having $n=5$ (metastable phase), 6, 7, and 8 form fairly unstable hydrates whose hydration numbers lie about 65. These are classified as group III hydrates. From the fact that their hydration number is large and almost constant, and that the anions of these salts have rather long methylene chains which must be too large to be accommodated within a typical water polyhedron, and further that the salt with $n=5$ forms two kinds of hydrates (stable and metastable phases), this group of hydrates will presumably have a different crystal structure from the other two groups. Although there is no evidence about the crystal structure, we may imagine the following structure.

The principal constituents of these hydrates may be the tetrabutylammonium cations, each butyl group of which is encaged by a hydrogen-bonded water framework; an anion which has a long methylene chain is accommodated within a fairly distorted void made between the two adjacent cation sheaths. These hydrates will owe a considerable part of their stability to the closeness of fit in the cages of butyl groups of the cation. The long methylene chain of the anion will considerably distort the water framework in which it is accommodated, and therefore it will make the hydrates unstable rather than stabilize them, owing to its hydrophobic nature. These concepts are consistent with the experimental results that the melting points of these hydrates decrease with increasing the length of the methylene chain and that the salt with $n=10$ is no longer able to form a stable hydrate. It is uncertain whether this estimated structure has some correlation with the structure of fairly stable clathrate-like hydrates¹⁰,¹¹⁾ made by a series of salts having the general formula $[(n\text{-}C_4H_9)_3N\text{–}(CH_2)_m\text{–}N(n\text{-}C_4H_9)_3]F_2$ ($m=5$, 6, and 8).

Three isomers of the phthalate also form hydrates which have almost the same hydration number of 62, indicating that they are isostructural. Although the benzene ring of the anion is large enough to be accommodated within a hydrogen-bonded framework, the distortion caused by the restriction that the four oxygen atoms of the two carboxyl groups, which are fixed at the specific position of the benzene ring, must be placed at one of the hydrogen-bonded sites of the polyhedral vertices seems to be the dominant factor which determines the stability of the hydrates. Because of this distortion effect, the water framework around the benzene ring could not be constructed as efficiently as in the group II hydrates, giving a fairly large hydration number as compared with 55 of the group II hydrates. It is not certain whether these hydrates should be included in group I or be classified as another group.

This work was partially supported by a Grant-in-Aid for Scientific Research from the Ministry of Education.

References

1) R. McMullan and G. A. Jeffrey, *J. Chem. Phys.*, **31**, 1231 (1959).
2) D. L. Fowler, W. V. Loebenstein, D. B. Pall, and C. A. Kraus, *J. Am. Chem. Soc.*, **62**, 1140 (1940).
3) M. von Stackelberg, *Z. Elektrochem.*, **58**, 24 (1954).
4) D. Feil and G. A. Jeffrey, *J. Chem. Phys.*, **35**, 1863 (1961).
5) M. Bonamico, G. A. Jeffrey, and R. K. McMullan, *J. Chem. Phys.*, **37**, 2219 (1962).
6) R. K. McMullan, M. Bonamico, and G. A. Jeffrey, *J. Chem. Phys.*, **39**, 3295 (1963).
7) H. Nakayama and K. Watanabe, *Bull. Chem. Soc. Jpn.*, **49**, 1254 (1976).
8) G. Beurskens, G. A. Jeffrey, and R. K. McMullan, *J. Chem. Phys.*, **39**, 3311 (1963).
9) Unpublished data.
10) H. Nakayama and K. Watanabe, to be published.
11) T. L. Broadwater and D. F. Evans, *J. Phys. Chem.*, **73**, 164 (1969).