Tetrabutylammonium Salts of CH-Acidic Carbonyl Compounds: Real Carbanions or Supramolecules?[†]

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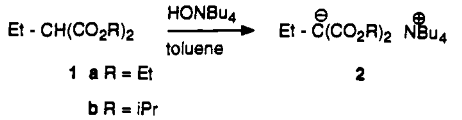
The term "carbanion" is still being used in a loose way to include such synthetically important species as α-lithiated carbonyl compounds, nitriles, sulfones, etc. However, the structural information of these reagents shows that they are *not* real carbanions.[1] Rather, the anionic part of these species is intimately involved with the lithium by way of Li–O, Li–N, or Li–C bonds, the compounds existing often as dimers or tetramers. Carbanions generated by MS methods in the gas phase exist as short-lived species devoid of metals or other counterions.[2] Real carbanions in solution have been postulated to occur as monomeric tetraalkylammonium salts which are believed to be "naked" anions having enhanced nucleophilic reactivity,[3] as in the phase-transfer-catalyzed alkylation of malonates.[4] The aldol addition of certain enolsilanes catalyzed by $FNBu_4$ is also believed to involve highly reactive tetrabutylammonium enolates.[5]

We have previously prepared and isolated the tetrabutylammonium salts of malonic acid dialkyl esters, dicyanomethane, and nitroalkanes.[6] Although not fully characterized, they were used as initiators for the quantitative anionic polymerization of acrylates at room temperature. We now report the first X-ray structural analyses of tetrabutylammonium enolates and also provide information regarding the structure and aggregation state in solution.

We have improved our original procedure[6] for the preparation of ammonium carbanions based on deprotonation by $HONBu_4$ by using toluene to remove the water azeotropically. Thus, the anions of malonates **2a,b** were obtained in >90% yield as hygroscopic crystals. In the absence of moisture they are stable for months in crystalline form and in aprotic solution.



$$\mathrm{Et-CH(CO_2R)_2} \xrightarrow[\text{toluene}]{\mathrm{HONBu_4}} \mathrm{Et-\overset{\ominus}{C}(CO_2R)_2\ \overset{\oplus}{N}Bu_4}$$

1 a R = Et
b R = iPr

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Figure 1 summarizes the results of the X-ray analysis of **2b**.[7] The enolate has a U-shape, just like metal enolates of 1,3-dicarbonyl compounds. The lengths of the two equivalent C–O (carbonyl) bonds are 1.238(2) and 1.232(2) Å, and those of the two C–C bonds in the carbanionic part are 1.415(2) and 1.413(2) Å. Surprisingly, the carbanions are dimeric in the solid state, "held together" by C—H···O hydrogen bonds[8] originating from the α-methylene units of the tetrabutylammonium counterions. As shown in Figure 1, it is a cyclic array of such hydrogen bonds which results in the dimeric nature of the reagent, the distances between the negatively charged oxygen atoms and the α-C atoms of the ammonium ions being in the range of 3.263(2)–3.293(2) Å. Compound **2a** is also dimeric in the solid state.[9]

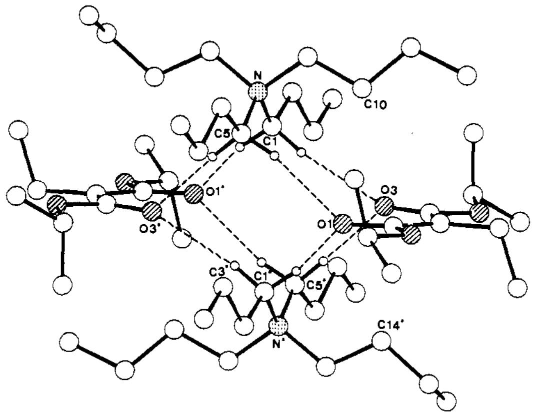

Figure 1. Arrangement of anions and cations in crystalline **2b**. H atoms omitted for clarity, except those bonded to C1(*) and C5(*). Selected interatomic distances (Å): O1···C5 3.263(2), O1···C1* 3.264(2), O3···C1 3.293(2), O3···C5* 3.391(2), O1···C3* 3.238(2), O1···C10 3.389(2), O3···C14* 3.241(2), C1-H1A 0.95(2), H1A···O1* 2.46(2), C1-H1B 0.98(2), H1B···O3 2.36(2), C5-H5A 0.96(2), H5A···O1 2.31(2), C5-H5B 0.98(2), H5B···O3* 2.43(2).

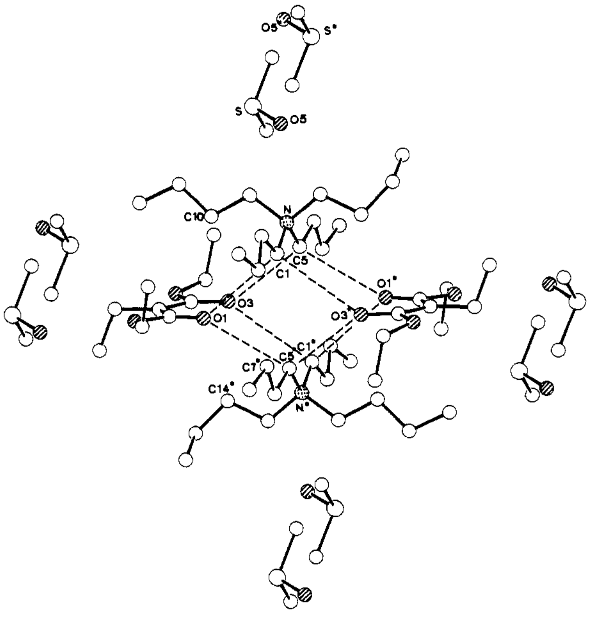

Figure 2. Arrangement of anions, cations, and DMSO in crystalline **2a** + DMSO. Selected interatomic distances (Å): O1···C1 3.440(2), O1···C5* 3.290(1), O3···C1* 3.386(1), O3···C5 3.328(2), O1···C10 3.434(2), O3···C14* 3.316(2), O1···C7* 3.267(2).

[†] Dedicated to Professor Carl Krüger on the occasion of his 60th birthday.

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(3) See, for example: March, J. *Advanced Organic Chemistry*, 3rd ed.; Wiley: New York, 1985, p 322.

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(7) Crystal data for **2b**: $C_{27}H_{55}NO_4$, FW = 457.7, colorless prisms, monoclinic, $P2_1/n$ (No. 14), $a = 11.615(3)$, $b = 17.045(4)$, and $c = 14.710(3)$ Å, $\beta = 90.59(2)°$ (25 automatically centered reflections), $V = 2912.1(3)$ Å^3, $T = 100$ K, $Z = 4$, $d_{\mathrm{calcd}} = 1.04$ g/cm^3, $\mu(\mathrm{Mo\ K}\alpha) = 0.64$ cm^{-1}, Enraf-Nonius CAD4 diffractometer, graphite monochromated Mo Kα radiation $\lambda = 0.710\,69$ Å, 7124 data collected ($[\sin(\theta)/\lambda]_{\max} = 0.65$ Å^{-1}, $[\pm h,+k,+l]$), 6630 independent ($R_{\mathrm{av}} = 0.01$), 4849 observed $[I > 2\sigma(I)]$, 509 parameters, final $R = 0.046$, $R_w = 0.048$ $[w = 1/\sigma^2(F_o)]$, $\Delta/\sigma = 0.86$, largest residual density = 0.38 e/Å^3.

(8) Taylor, R.; Kennard, O. *J. Am. Chem. Soc.* **1982**, *104*, 5063–5070. Desiraju, G. R. *Acc. Chem. Res.* **1991**, *24*, 290–296.

(9) Crystal data for **2a**: $C_{25}H_{51}NO_4$, FW = 429.7, colorless prisms, monoclinic, $P2_1/a$ (No. 14), $a = 15.291(5)$, $b = 18.172(4)$, and $c = 19.095(2)$ Å, $\beta = 93.57(2)°$ (25 automatically centered reflections), $V = 5296(1)$ Å^3, $T = 100$ K, $Z = 8$, $d_{\mathrm{calcd}} = 1.08$ g/cm^3, $\mu(\mathrm{Mo\ K}\alpha) = 0.66$ cm^{-1}, Enraf-Nonius CAD4 diffractometer, graphite monochromated Mo Kα radiation $\lambda = 0.710\,69$ Å, 13 932 data collected ($[\sin(\theta)/\lambda]_{\max} = 0.65$ Å^{-1}, $[\pm h,+k,+l]$), 12 074 independent ($R_{\mathrm{av}} = 0.01$), 9228 observed $[I > 2\sigma(I)]$, C22 and C47 disordered (two positions, isotropic, 0.5 occupancy), H atoms fixed at calculated positions ($U_{\mathrm{H}} = 0.05$ Å^2), 529 parameters, final $R = 0.068$, $R_w = 0.099$ $[w = 1/\sigma^2(F_o)]$, $\Delta/\sigma = 0.52$, largest residual density = 0.82 e/Å^3.

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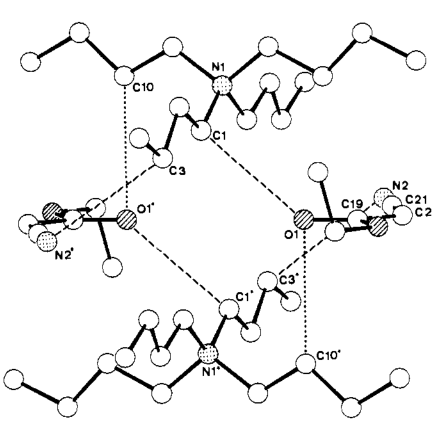


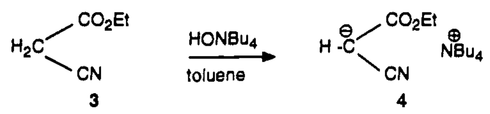
Figure 3. Arrangement of anions and cations in crystalline 4. Selected interatomic distances (Å) and angles (deg): O1···C1 3.268(2), O1···C10* 3.349(2), N2···C3* 3.497(2), O1···C1* 3.437(2), N2-C21 1.165(2), C20-C21 1.392(2), C19-C20-C21 121.2(1).

Hydrogen bonds originating from CH_3 or CH_2 groups are generally weak[8] but are greatly enhanced by the presence of the neighboring ammonium functionality. Indeed, MO calculations of $N^+(CH_3)_4$ ions show that the positive charge is *not* localized on nitrogen, but delocalized over the methyl groups.[10]

When **2a** was added to dimethyl sulfoxide (DMSO), different crystals were grown which contain solvate molecules.[11] In spite of the well-known ability of DMSO to break up hydrogen bonds, the dimeric nature of the anions (Figure 2) is retained. Thus, solvent-separated ion pairs[12] are not formed.

In benzene, the dimeric nature of **2** is retained, as shown by freezing point depression studies (**2a**, $MW_{calcd} = 430$, $MW_{expt} = 872$; **2b**, $MW_{calcd} = 458$, $MW_{expt} = 855$). In toluene-d_8 at room temperature, the ^{13}C NMR spectrum of **2a** displays sharp signals at $\delta = 75.2$ for the carbanion and 57.8 for the α-methylene C atoms of the ammonium counterion. At −83 °C, the four signals of the cation split into two sets of four sharp signals of equal intensity (viz. 57.5 and 55.2 ppm for the α-carbon atoms). The four pairs of peaks coalesce at −60 °C, the energy of site exchange being $\Delta G^\ddagger = 41 \pm 2$ kJ/mol. This phenomenon was also observed for **2b**. The data suggest that two different pairs of α-methylene units in the ammonium salt exist in solution, one pair participating in H-bonding and the other not, probably as in the solid state. Indeed, the solution ^{13}C NMR spectrum is very similar to that obtained in the solid state by MAS ^{13}C NMR spectroscopy. The IR spectra of **2a,b** show absorption at 1677 cm^{-1} due to the enolate moiety. Any effects that would be observed for hydrogen bonding are obscured by the CH absorptions of the alkyl chains.

In a similar reaction we have also obtained crystals of the tetrabutylammonium salt of the cyanoacetic acid ethyl ester **4**. The X-ray structural analysis[13] shows once more a dimeric species in which hydrogen bonding plays the central role (Figure 3). In this case, however, only one terminal carbonyl O atom is available to form a hydrogen bond to the tetrabutylammonium cation. The N atom of the nitrile groups makes a weaker bond to a γ-methylene group, and the dimer is further stabilized by a secondary interaction of the terminal O atom to a β-methylene group. Such an interaction is also seen in the crystal structures of **2a,b** and **2a** + DMSO (Figures 1 and 2).



The C–N bond in **4** is slightly elongated (1.165(2) Å) with respect to normal C≡N bonds found in a number of nitriles (typically, 1.136(10) Å),[14] whereas the C–C bond length of the C–CN entity is at 1.392(2) Å slightly shorter than that in neutral nitriles (typically, 1.443(8) Å).[14] The bond lengths are similar to those reported for [(α-cyanbenzyllithium tetramethylethylenediamine)$_2$·benzene].[15a] Boche[1a,15a] and Pagani[15b] have concluded that in α-lithiated nitriles, stabilization results mostly from inductive and less from resonance effects. Presently we are uncertain whether our data allow for an unambiguous decision regarding this interesting question. Calculations by Schleyer on metalated acetonitrile show that MCH_2CN is 9.7 kcal/mol more stable than the N-metalated form $CH_2{=}C{=}NM$.[16] In solution the reagent **4** is also dimeric, as shown by freezing point depression studies in benzene ($MW_{calcd} = 356$, $MW_{expt} = 730$). The IR spectrum of **4** shows an absorption at 2140 cm^{-1} due to the $>C^-{-}CN$ moiety.

In conclusion, we have demonstrated for the first time that tetraalkylammonium enolates are not truly "naked" carbanions. Rather, the anions and cations interact with one another via hydrogen bonds in a highly ordered manner. Self-organization results in supramolecular[17] structures both in solution and in the solid state. Along with the inherent structural and theoretical interest, the present study may provide help in the rational design of chiral phase-transfer catalysts.[4,18] We also believe that hydrogen bonding involving tetraalkylammonium ions occurs in biological systems.[19]

Acknowledgment. We thank the Deutsche Forschungsgemeinschaft (Leibniz Program).

Supplementary Material Available: Experimental procedures NMR data, tables of fractional atomic coordinates, thermal parameters, and bond distances and angles for **2a**, **2b**, **2a** + DMSO, and **4** (44 pages); tables of observed and calculated structure factors (116 pages). Ordering information given on any current masthead page.

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(11) Crystal data for **2a** + DMSO: $C_{27}H_{57}NO_5S$, FW = 507.8, triclinic, $P\bar{1}$ (No. 2), $a = 11.729(3)$, $b = 12.151(3)$, and $c = 12.819(2)$ Å, $\alpha = 101.85(2)$, $\beta = 100.56(2)$, $\gamma = 115.90(2)°$ (25 automatically centered reflections), $V = 1529(1)$ Å^3, $T = 100$ K, $Z = 2$, $d_{calcd} = 1.10$ g/cm^3, μ(Mo Kα) = 1.32 cm^{-1}, Enraf-Nonius CAD4 diffractometer, graphite monochromated Mo Kα radiation $\lambda = 0.710\,69$ Å, 21 160 data collected ($[\sin(\theta)/\lambda]_{max} = 0.81$ Å^{-1}, $[\pm h, \pm k, \pm l]$), 13 468 independent ($R_{av} = 0.03$), 9542 observed [$I > 2\sigma(I)$], 535 parameters, final $R = 0.053$, $R_w = 0.055$ [$w = 1/\sigma^2(F_o)$], $\Delta/\sigma = 1.02$, largest residual density = 0.57 e/Å^3.

(12) Boche, G. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 731.

(13) Crystal data for 4: $C_{21}H_{42}N_2O_2$, FW = 426.4, colorless prisms, orthorhombic, *Pccn* (No. 56), $a = 16.849(2)$, $b = 18.316(2)$, and $c = 14.561(1)$ Å (25 automatically centered reflections), $V = 4493.5(4)$ Å^3, $T = 100$ K, $Z = 4$, $d_{calcd} = 1.05$ g/cm^3, μ(Mo Kα) = 0.62 cm^{-1}, Enraf-Nonius CAD4 diffractometer, graphite monochromated Mo Kα radiation $\lambda = 0.710\,69$ Å, 9558 data collected ($[\sin(\theta)/\lambda]_{max} = 0.65$ Å^{-1}, $[+h, +k, \pm l]$), 5137 independent ($R_{av} = 0.02$), 3716 observed [$I > 2\sigma(I)$], H atoms fixed at calculated positions ($U_H = 0.05$ Å^2), 226 parameters, final $R = 0.046$, $R_w = 0.052$ [$w = 1/\sigma^2(F_o)$], $\Delta/\sigma = 0.04$, largest residual density = 0.11 e/Å^3.

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