

Supramolecular Structure of the Tetrabutylammonium Salt of 2-Phenylpropionitrile

Manfred T. Reetz*, Stephan Hütte, and Richard Goddard

Mülheim an der Ruhr, Max-Planck-Institut für Kohlenforschung

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Dedicated to Prof. Dr. Fritz Vögtle on the Occasion of his 60th Birthday

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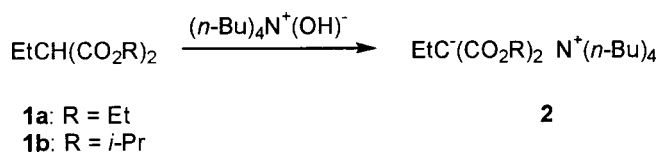
Abstract. The deprotonation of 2-phenylpropionitrile $\text{Ph}(\text{CH}_3)\text{CHCN}$ (**3**) by $(n\text{-Bu})_4\text{N}^+(\text{OH})^-$ results in the corresponding tetrabutylammonium salt (**4**) in excellent yield. An X-ray structural analysis shows that the compound is not a genuine carbanion ("naked anion"). Instead, a dimeric form is found in the crystal in which the nitrogen of the cyano

group in the anion undergoes multiple H-bonding with the α -methylene units of the $(n\text{-Bu})_4\text{N}^+$ cations as a consequence of $\text{CH}\cdots\text{N}$ interactions. A cryoscopic study of the compound in benzene indicates the existence of tetramers, which means that in solution supramolecular ions pairs are involved.

The term "carbanion" has been applied by synthetic organic chemists for decades to denote carbon-based anionic species [1]. In doing so, structural aspects are knowingly ignored. The basis of traditional and modern carbanion chemistry is formed by the many different types of organolithium reagents, including alkyl-lithium compounds, lithiated heterocycles, and deprotonated forms of carbonyl compounds (enolates), nitriles, nitroalkanes, sulfoxides, sulfones, and other CH-acidic precursors [1, 2]. In addition to purely synthetic aspects, considerable effort has gone into the study of the structural properties of these reagents [3]. Indeed, it has long been accepted that carbanions are not involved at all; rather, lithium is intimately bonded to the nucleophilic species which occur as monomers, dimers or higher aggregates.

In contrast to these and other organometallic reagents, the scientific community took a different view of metal-free anionic systems. Specifically, the tetraalkylammonium salts of CH-acidic compounds such as esters, ketones, nitriles, nitroalkanes, and sulfones were believed to be naked anions and therefore true carbanions [4]. Their existence was first postulated in phase transfer catalyzed alkylations and Michael additions [5]. Later, $\text{R}_4\text{N}^+\text{F}^-$ -promoted alkylation [6] and aldol addition [7] reactions of enolsilanes derived from ketones were hypothesized to occur *via* the intermediate formation of genuine enolates. The successful use of pre-formed isolable tetraalkylammonium salts of malonates as initiators in the metal-free polymerization of acrylates also seemed to indicate that true carbanions display unusual reactivity and selectivity quite different from the lithium or sodium counterparts [8, 9]. Such com-

pounds have also been used as metal-free carbon nucleophiles in Pd-catalyzed allylic substitution reactions [10].



However, detailed structural studies in the solid phase and in solution of compounds of the type **2** showed that the concept of naked anions does not apply at all [11]. Indeed, these and other tetraalkylammonium salts of CH-acidic compounds, *e.g.*, those of 2-nitropropane [12], phenylacetic acid ester [13] or phenylpropionic acid ester [13], are not true carbanions. The tetrabutylammonium units are not isolated cations, but are in fact intimately associated with the carbon nucleophiles. This novel phenomenon is based on strong hydrogen bonds originating from the α -methylene units of the tetrabutylammonium cations as H-donors and the negatively charged oxygen atoms in the enolates **2** (or in nitronates) as H-acceptors ($\text{CH}\cdots\text{O}$ interactions) [14]. Relevant are MO calculations on $(\text{CH}_3)_4\text{N}^+$, which show that the positive charge is not localized on nitrogen as traditionally drawn by organic chemists, but delocalized evenly over the four methyl groups [9]. This also means that the methyl groups (or α -methylene groups in R_4N^+) are somewhat acidic. Interestingly, in the case of enolates **2** eight of the $\text{CH}\cdots\text{O}$ interactions occur in such a way that a dimer-

ic form results, as shown by X-ray structural analyses [11]. Two U-shaped enolates lie opposite one another, held together by two tetrabutylammonium cations. Although dimethylsulfoxide (DMSO) might be expected to break up the hydrogen bonds, the dimeric nature of the enolates is in fact maintained upon recrystallization in this solvent, DMSO simply participating as a solvate which can be viewed as the beginning of a type of solvent shell [11] (Fig. 1).

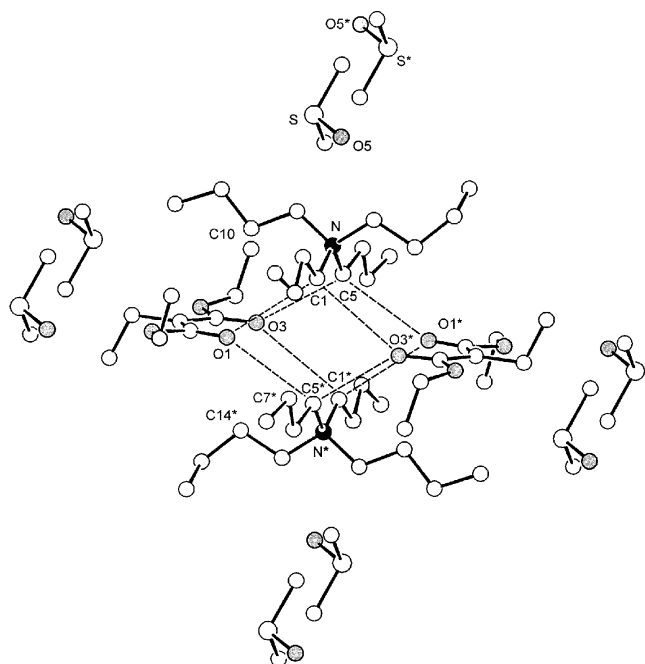


Fig. 1 X-ray crystal structure of enolate **2a** with DMSO as solvate [11]. Indicated interionic C(H)⋯O distances range between 3.290(1) – 3.440(2) Å.

As shown by cryoscopic investigations, enolates **2** are also dimeric in solution (benzene) [11]. In this medium a structure similar to that shown in the crystal is likely, since NMR studies at low temperature reveal the presence of two different types of α -methylene units in the ammonium part of the salts **2**. On the basis of these and other findings [15] we postulated the concept of supramolecular ion pairs [11] (Fig. 2f). These species need to be distinguished from traditional structures [16] such as contact (intimate) ion pairs (Fig. 2a), solvent-shared ion pairs (Fig. 2b), solvent-separated ion pairs (Fig. 2c) and free ion pairs (Fig. 2d). They are also different from penetrated ion pairs (Fig. 2e) which have been postulated recently [17]. Supramolecules of the type shown in Fig. 2f are based on reversible hydrogen bond formation and therefore constitute a novel branch of supramolecular chemistry [18].

We were interested in the structure of tetrabutylammonium salts of nitriles lacking oxygen functionality,

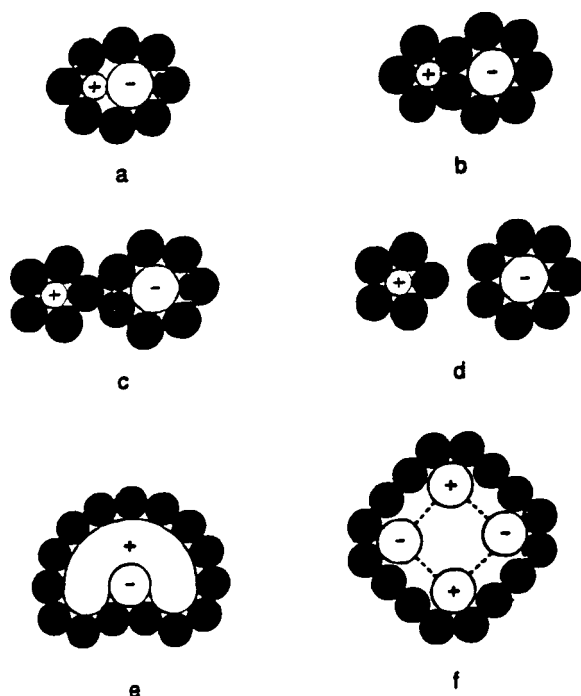
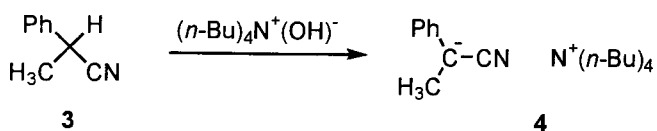


Fig. 2 Different types of ion pairs: a) contact (intimate) ion pair; b) solvent-shared ion pair; c) solvent-separated ion pair; d) free ion pair; e) penetrated ion pair; f) supramolecular ion pair.

since these would have to undergo H-bonding of the type CH⋯N, if at all. Furthermore, U-shaped forms as in the anionic part of **2** or in nitronates are not possible, which likewise raises the interesting question of structure in the crystal and in solution.

Synthesis and Structure

Of the many different possible precursors for cyano-stabilized anions, 2-phenylpropionitrile (**3**) was chosen. Upon subjecting this nitrile to a solution of $(n\text{-Bu})_4\text{N}^+(\text{OH})^-$ in THF/toluene and removing the water azeotropically according to a previously described procedure [11–13,15], salt **4** was obtained in 86% yield as a hygroscopic yellowish-green solid.



Recrystallization from toluene afforded crystals suitable for an X-ray structural analysis. The most striking feature is the dimeric nature of the salt (Fig. 3). As in the case of enolates **2**, two anions lie in close proximity to one another, the two ammonium counterions above and below serving as a clamp holding the anions to-

gether. In this case hydrogen bonds of the type $\text{CH}\cdots\text{N}$ [14] originate from the interaction of the basic nitrogen atom of the nitrile function in the anion with the acidic α -methylene moieties of the tetrabutylammonium ions. Table 1 summarizes the most important bond lengths and angles in the anion.

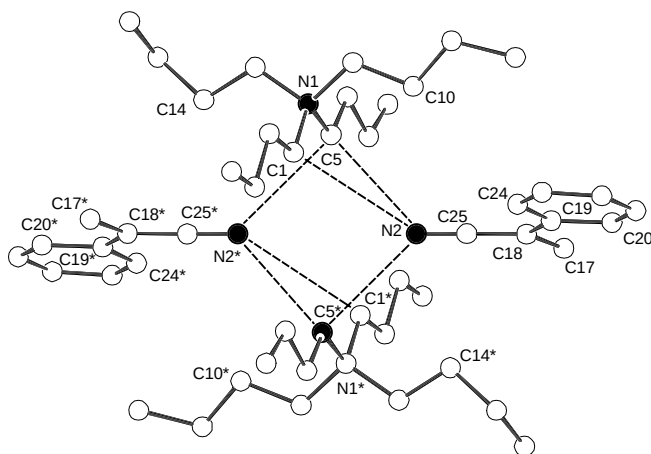


Fig. 3 X-ray crystal structure of tetra-*n*-butylammonium-1-cyano-1-phenylethanide (**4**). Selected interionic distances (Å) and angles (°): $\text{N2}\cdots\text{C1}$ 3.406(2), $\text{N2}\cdots\text{C5}$ 3.590(2), $\text{N2}\cdots\text{C5}^*$ 3.389(2), $\text{N2}\cdots\text{C1}^*$ 4.185(2), $\text{N2}\cdots\text{C5}\cdots\text{N2}^*$ 97.4(1), $\text{N2}\cdots\text{C1}\cdots\text{N2}^*$ 86.8(1).

Table 1 Important bond lengths and bond angles of salt **4**

Bond lengths [Å]		Angles [°]	
$\text{C(18)}-\text{C(17)}$	1.504(2)	$\text{C(17)}-\text{C(18)}-\text{C(19)}$	121.7(2)
$\text{C(18)}-\text{C(19)}$	1.418(2)	$\text{C(17)}-\text{C(18)}-\text{C(25)}$	117.9(2)
$\text{C(18)}-\text{C(25)}$	1.391(2)	$\text{C(19)}-\text{C(18)}-\text{C(25)}$	120.5(2)
$\text{C(25)}-\text{N(2)}$	1.165(2)	$\text{C(18)}-\text{C(25)}-\text{N(2)}$	179.2(2)
		$\text{C(18)}-\text{C(19)}-\text{C(20)}$	121.9(2)
		$\text{C(18)}-\text{C(19)}-\text{C(24)}$	123.0(1)

The anion in **4** is essentially planar, which is also found in α -lithiated forms of related nitriles (e.g., lithio-phenylacetonitrile) [19]. The $\text{C(18)}-\text{C(25)}-\text{N(2)}$ unit is linear and contains a strongly shortened $\text{C(18)}-\text{C(25)}$ bond and a slightly elongated $\text{C(25)}-\text{N(2)}$ bond relative to those of typical neutral nitriles. These trends have also been found in α -lithiated nitriles [19]. The neutral precursor **3** and the dimeric anion **4** were also studied by IR-spectroscopy. Accordingly, compound **3** shows an absorption peak at 2240 cm^{-1} , which shifts to 2080 cm^{-1} upon going to **4**. Thus, the nitrile absorption band of the anion appears close to the absorption band of neutral ketene-imines $\text{R}_2\text{C}=\text{C}=\text{NR}$ ($1995\text{--}2040\text{ cm}^{-1}$) [20].

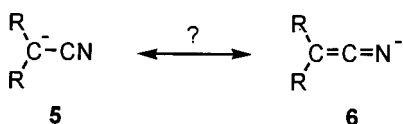
Finally, the question as to whether the dimeric nature of anion **4** is retained in solution was addressed by ex-

amining its cryoscopic behaviour in benzene. If a dimeric form were to exist in solution, then an apparent molecular weight of about 746 g mol^{-1} (2×373) should be found experimentally. Surprisingly, this did not turn out to be the case. Rather, an aggregation state of approximately four was detected. This implies that compound **4** exists as tetramers in solution. However, since the precision of the experimental method declines at such high molecular weights [15], the results need to be interpreted with a certain degree of caution.

Discussion

The most important conclusion of the present study concerns the supramolecular nature of the structure of the cyano-stabilized anion **4**. The X-ray structural analysis of the crystal and a cryoscopic study in solution unambiguously show that “naked anions” (real carbanions) [4] are not involved. This important finding lends further support to our previous conclusions regarding the complex structural characteristics of tetraalkylammonium salts of other CH-acidic compounds [11–13]. Thus far the only “real carbanion” that we have come across is tetrabutylammonium cyclopentadienide; the Cp-anion is so stable that it undergoes essentially no interaction with the $(n\text{-Bu})_4\text{N}^+$ cation in the crystal [12].

The dimeric structure of **4** in the crystal reveals some remarkable features. As delineated above, it is the nitrogen of the cyano function in **4** which participates in several H-bonding interactions with the α -methylene entities of the $(n\text{-Bu})_4\text{N}^+$ cations, whereas no such bonding occurs with the formally negatively charged C-atom in the anion, which would imply $\text{CH}\cdots\text{C}$ interactions. This might be construed as evidence for resonance stabilization of carbon-centered negative charge by a cyano group, as symbolized by the hypothetical resonance forms **5** $\leftrightarrow$ **6**. However, the traditional view of resonance stabilization of negative charge by cyano groups has been contested recently by Boche [19], Pagani [21] and others [22]. These authors consider inductive effects as the true mechanism of stabilization. More work is necessary concerning this interesting question, specifically in the case of ammonium salts.



In solution the salt **4** is neither monomeric nor dimeric. Rather, a cryoscopic study in benzene indicates a significantly higher order of aggregation, possibly a tetrameric form. In this case ion pairs similar to the type

shown in Fig. 2f are relevant. Specifically, giant supramolecules composed of four interconnected $\ominus \cdots \oplus$ units each made up of $\text{Ph}(\text{CH}_3)\text{C}\cdots\text{CN}$ and $(n\text{-Bu})_4\text{N}^+$ ions, appear to exist in solution. Whatever their exact nature may be, upon crystallization they break down to dimers (Fig. 3).

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Experimental

The NMR spectra were recorded on Bruker AC-200 (^1H : 200 MHz) and Bruker AC-300 (^{13}C : 75 MHz) instruments using $\text{DMSO}-d_6$ as solvent and $(\text{CH}_3)_4\text{Si}$ as internal reference. A Perkin-Elmer FT 1600 instrument was used to record the IR-spectrum. The X-ray structural analysis was performed using an Enraf-Nonius-CAD4-Diffractometer. The cryoscopic measurements were performed in dry benzene by the Mikroanalytisches Laboratorium Dornis and Kolbe (Mülheim an der Ruhr, Germany).

Tetra-*n*-butylammonium-1-cyano-1-phenylethanide (4)

A 250 ml three-necked flask, equipped with two 100 ml dropping funnels and connected to a vacuum pump via a cold trap (cooled by liquid N_2), was charged with commercially available $\text{HON}(n\text{-Bu})_4$ (Aldrich) in methanol (20 mmol of a 1M solution) and 50 ml of dry toluene. An additional 20 ml of toluene were added and vacuum was then applied at room temperature until the total volume was reduced to 70 ml (not less!). This operation was repeated 5 more times. More toluene (50 ml) was added and then freshly distilled **3** (2.9 g; 22 mmol) in 40 ml of toluene was added dropwise (2 h) to the flask. Thereafter, the solution was carefully concentrated to about 20 ml and transferred to a Schlenk tube, which was then pumped to dryness overnight using an oil diffusion pump, affording 6.4 g (86%) of salt **4** as a yellowish-green hygroscopic solid in essentially pure form. – IR (KBr): 2080 cm^{-1} (CN). – ^1H NMR: δ/ppm = 0.93 (t; 3J = 7.0 Hz; 12H; $\text{NCH}_2\text{CH}_2\text{CH}_2\text{CH}_3$); 1.30 (sextet; 3J = 7.3 Hz; 8H; $\text{NCH}_2\text{CH}_2\text{CH}_2\text{CH}_3$); 1.43–1.63 (m; 11H; $\text{NCH}_2\text{CH}_2\text{CH}_2\text{CH}_3$ and CH_3 of anion); 3.14 (m; 8H; $\text{NCH}_2\text{CH}_2\text{CH}_2\text{CH}_3$); 5.68–6.00, 6.40–6.78, 7.08–7.30 (multiplets, 5H; aromatic H). – ^{13}C NMR: δ/ppm = 13.4 ($\text{NCH}_2\text{CH}_2\text{CH}_2\text{CH}_3$); 15.0 (CH_3 of anion); 19.1 ($\text{NCH}_2\text{CH}_2\text{CH}_2\text{CH}_3$); 23.0 ($\text{NCH}_2\text{CH}_2\text{CH}_2\text{CH}_3$); 35.9 (central C-atom of anion); 57.5 ($\text{NCH}_2\text{CH}_2\text{CH}_2\text{CH}_3$); 107.3 (aromatic); 111.7 (aromatic); 116.8 (aromatic); 125.2–128.8 (aromatic); 136.9 (CN); 149.1 (aromatic).

X-ray Analysis of Tetra-*n*-butylammonium-1-cyano-1-phenylethanide (4)

A portion of the above sample of compound **4** was dissolved in toluene. As a consequence of slow removal of the solvent *in vacuo* at room temperature, yellowish-green plate-like crystals of **4** suitable for an X-ray structure analysis were obtained. Crystal data for **4**: $[\text{C}_{16}\text{H}_{36}\text{N}]^+[\text{C}_9\text{H}_8\text{N}]^-$, M_r = 372.62 g mol^{-1} ,

crystal size $0.35 \times 0.32 \times 0.15$ mm, a = 10.479(5), b = 9.734(4), c = 23.380(10) Å, β = 100.32(5)°, U = 2346.2(18) Å³, T = 100 K, monoclinic, $P2_1/n$ [No. 14], Z = 4, d_{calc} = 1.06 g cm^{-3} , μ = 0.06 mm^{-1} , Enraf-Nonius CAD4 diffractometer, λ = 0.71069 Å, ω - 2θ -scan, 4851 reflections, 4724 independent, 3631 observed [$I > 2\sigma(I)$], $[(\sin\theta)/\lambda]_{\text{max}}$ = 0.65 Å^{−1}, direct methods (SHELXS-97, Sheldrick, G. M. *Acta Cryst.* **1990**, A46, 467), least-squares refinement (on F_o^2 , SHELXL-97, Sheldrick, G. M., University of Göttingen, 1997), H riding, 244 refined parameters, R = 0.046 (obs. data), R_w = 0.128 (Chebyshev weights), final shift/error 0.001, residual electron density +0.211 eÅ^{−3}. Atomic coordinates and e.s.d.'s have been deposited at the Cambridge Crystallographic Data Centre, CCDC-113329.

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Address for correspondence:
Prof. Dr. M. T. Reetz
Max-Planck-Institut für Kohlenforschung
Kaiser-Wilhelm-Platz 1
D-45470 Mülheim an der Ruhr
Fax: Internat. code (0)208 306 2985
e-mail: reetz@mpi-muelheim.mpg.de