Gas-Phase Synthesis

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Gas-Phase Synthesis and Reactivity of Lithium Acetylide Ion, $Li{-}C{\equiv}C^-$**

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Dianions in the form of their lithium salts are widely used reagents in organic synthesis.[1] These lithium-rich compounds have a long history going back to Moissan, who first prepared dilithium acetylide (Li_2C_2) in 1896 by reacting coal with lithium carbonate in an electric furnace.[2] Li_2C_2 can also be directly prepared from the relevant elements and is a commercially available solid with a melting point in excess of 550 °C. The nonclassical structure of monomeric Li_2C_2 was initially predicted by Apeloig et al.,[3] while the structure of the aggregate was determined by an X-ray diffraction powder pattern.[4] Li_2C_2 is a useful intermediate produced during radiocarbon dating,[5] and although it is relatively insoluble, it has been found to equilibrate with acetylene to afford lithium acetylide ($Li{-}C{\equiv}CH$, **1H**; see Figure 2) in a synthetically convenient procedure.[6,7] Despite their importance, the investigation of organolithium compounds in solution is difficult because their reactivity often varies with solvent, temperature, and the presence of additives like, for example, HMPA (hexamethylphosphoramide). Gas-phase studies can eliminate these complications and the effects of aggregation. To this end, we have employed in this study a previously developed decarboxylation strategy for the regioselective preparation of radical anions[8,9] and organometallic ions.[10] Herein we report the gas-phase synthesis and reactivity of lithium acetylide ion ($Li{-}C{\equiv}C^-$, **1A**), a species directly related to Li_2C_2 and a valuable synthetic reagent. Its novel properties were studied both experimentally and by high-level G3, G4, and W1 computations.

Electrospray ionization (ESI) of a basic aqueous methanolic solution of acetylenedicarboxylic acid containing a small amount of LiOH in a Fourier-transform mass spectrometer (FTMS) produced the lithium salt of acetylenedicarboxylate dianion ($LiO_2C{-}C{\equiv}C{-}CO_2^-$, *m*/*z* 119; Figure 1). Fragmentation of this ion by activated collisions resulted in the loss of carbon dioxide to afford the conjugate base of lithium propynoate ($LiO_2C{-}C{\equiv}C^-$, *m*/*z* 75). Cleavage of this ion by a second collision-induced dissociation (CID) pulse led to another decarboxylation, thereby generating the desired lithium acetylide ion [Eq. (1); *m*/*z* 31.0166 (obs), 31.0166 (calc)].

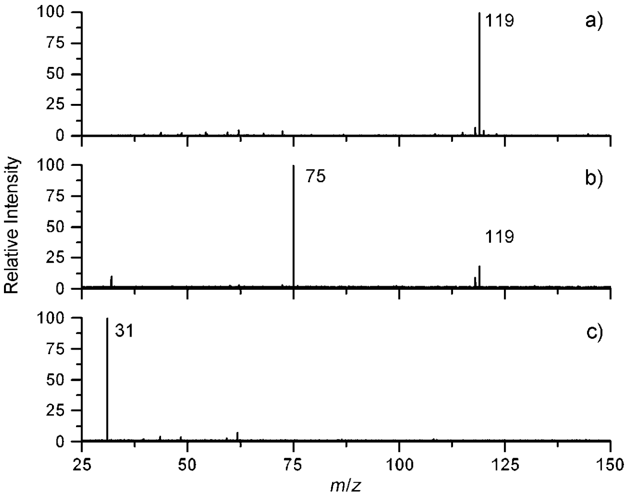

Figure 1. a) Electrospray ionization of acetylenedicarboxylic acid in an FTMS and the subsequent isolation of $LiO_2CC{\equiv}CCO_2^-$ (*m*/*z* 119). b) Formation of $Li{-}C{\equiv}CCO_2^-$ (*m*/*z* 75) by CID of the *m*/*z* 119 ion. c) Formation and isolation of $Li{-}C{\equiv}C^-$ (*m*/*z* 31) by CID of the *m*/*z* 75 ion.

$$HO_2C{-}C{\equiv}C{-}CO_2H \xrightarrow[\text{LiOH}\ CH_3OH/H_2O]{\text{ESI}} \underset{m/z\ 119}{LiO_2C{-}C{\equiv}C{-}CO_2^-}$$

$$\xrightarrow[-CO_2]{\text{CID}} \underset{m/z\ 75}{LiO_2C{-}C{\equiv}C^-} \xrightarrow[-CO_2]{\text{CID}} \underset{\mathbf{1A}}{\underset{m/z\ 31}{Li{-}C{\equiv}C^-}} \qquad (1)$$

Compared with hydrogen, lithium as a substituent has been found to increase the proton affinity of LiO^- and $^-CH_2CO_2Li$ while decreasing their electron binding energies.[10a,11] These properties were therefore examined for the lithium acetylide ion both experimentally and computationally. This aim was accomplished, in part, by reacting **1A** with a wide variety of acids of known strength (Table 1; 1 cal = 4.184 J).[12] Water reacts as one might expect to afford the

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Table 1: Experimental gas-phase acidities at 298 K.

RH	ΔH°_{acid} [kcal mol^{-1}]	RH	ΔH°_{acid} [kcal mol^{-1}]
benzene	401.2 ± 0.2	H_2O	390.27 ± 0.02
$EtNH_2$	399.3 ± 1.1	C_6H_5F	387.2 ± 2.5
iPrNH_2	397.2 ± 3.1	toluene	382.3 ± 1.2
Me_2NH	396.4 ± 0.4	MeOH	381.9 ± 0.5
naphthalene	394.2 ± 1.2	EtOH	378.7 ± 0.8
furan	391.1 ± 0.4		

acetylide ion presumably through the transient intermediate **2** [Eq. (2)]. The more acidic [D$_4$]MeOH behaves similarly, but

$$\mathbf{1A} \xrightarrow{H_2O} \underset{\mathbf{2}}{\left[HC{\equiv}C^- \cdots Li^+ \cdots {}^-OH \right]} \longrightarrow HC{\equiv}C^- + LiOH \qquad (2)$$

the ion analogous to **2** is actually detected and [D$_3$]methoxide serves as a deuteride source, thus leading to the reduction of lithium acetylide [Eqs. (3a) and (3b)].[13] Still more acidic alcohols protonate **1A**, while ethanol [Eq. (4a)], in a similar

$$\mathbf{1A} \xrightarrow{CD_3OD} \underset{\sim 15\%}{DC{\equiv}C^- \cdots Li^+ \cdots {}^-OCD_3} \longrightarrow \underset{\sim 40\%}{DC{\equiv}C^- + LiOCD_3} \qquad (3a)$$

$$\longrightarrow \underset{\sim 45\%}{DC{\equiv}C^- \cdots Li^+ \cdots D^- + CD_2O} \qquad (3b)$$

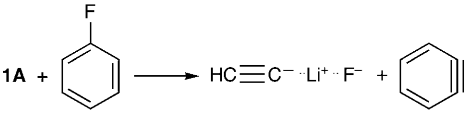
$$\mathbf{1A} \xrightarrow{EtOH} \underset{\sim 60\%}{EtO^-} + Li{-}C{\equiv}CH \qquad (4a)$$

$$\longrightarrow \underset{5\%}{HC{\equiv}C^- \cdots Li^+ \cdots {}^-OEt} \qquad (4b)$$

$$\longrightarrow \underset{25\%}{HC{\equiv}C^- \cdots Li^+ \cdots H^-} + CH_3CHO \qquad (4c)$$

$$\longrightarrow \underset{10\%}{HC{\equiv}C^- \cdots Li^+ \cdots CH_3^-} + CH_2O \qquad (4d)$$

manner to methanol, also affords acetylide–lithium ethoxide [Eq. (4b)] and acetylide–lithium hydride [Eq. (4c)] clusters. Ethanol reacts also via a novel methide-transfer pathway [Eq. (4d)]. Such a process has been reported by Schröder and Schwarz for the reactions of iron alkoxide cations (FeOR$^+$) with ketones,[14] and the decarboxylation of metal acetates to afford methylmetal anions carried out by O'Hair and coworkers can be viewed as a formal methide shift.[15] Amines such as $EtNH_2$, Me_2NH, and iPrNH_2 also react via hydride- and methide-transfer pathways to give the same ionic products as those shown in Equations (4c) and (4d). Fluorobenzene and furan behave in a similar manner, although in the former case fluoride ion is transferred to lithium while in the latter case lithium–hydrogen exchange takes place [Eqs. (5) and (6)].[16] In contrast, benzene does not react with **1A**, toluene simply protonates **1A**, and naphthalene undergoes addition (44%), addition–H_2 (42%), acetylide formation (7%), and proton transfer (7%).



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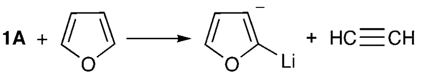


(6)

Naphthalene is the weakest acid that was examined that protonated lithium acetylide ion. The overall reaction rate constant was found to be $(1.3 \pm 0.5) \times 10^{-10}$ cm^3 molecule^{-1} s^{-1}, which corresponds to seven out of every 100 collisions leading to products given that the collision rate constant (i.e. k_{ADO})[17] is 1.93×10^{-9} cm^3 molecule^{-1} s^{-1}. If one assumes that the inefficient proton transfer ($k_{P.T.} = (9.1 \pm 3.8) \times 10^{-12}$ cm^3 molecule^{-1} s^{-1}, which corresponds to a reaction efficiency of 0.5%) is a result of the reaction endothermicity, then the thermokinetic method[18] can be used to derive the acidity of lithium acetylide. That is, the Arrhenius equation is employed to derive the endothermicity of the proton transfer by solving Equation (7), where $k_{P.T.}/A$ is 0.5% and $T = 300$ K.

$$E_a = -RT\ln(k_{P.T.}/A) \qquad (7)$$

The resulting activation energy is (3.2 ± 0.6) kcal mol^{-1}, which leads to $\Delta H^\circ_{acid}(\mathbf{1H}) = (391.0 \pm 1.3)$ kcal mol^{-1}. This result indicates that the substitution of a hydrogen atom in acetylene by a lithium atom leads to a (12.7 ± 1.3) kcal mol^{-1} decrease in acidity, which is similar to what was observed for lithium acetate (CH_3CO_2Li, (16.7 ± 4.3) kcal mol^{-1}).[10a]

To probe the acidity of **1H** further, G3,[19] G4,[20] and W1[21] computations were carried out because these methods are well established and known to generally be very accurate. The lowest energy structures for **1H** and **1A** are given in Figure 2, and the latter species is found to have a nonclassical bridging structure, as is typical for lithium.[22] The predicted acidities at 298 K for acetylene and lithium acetylide are given in Table 2, and reproduce the experimental measurements to within 1.9 kcal mol^{-1}. This outcome provides strong support for our experimental determination.

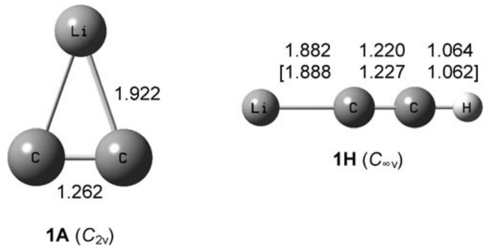


Figure 2. B3-LYP/cc-pV(T+d)Z structures of lithium acetylide ion (**1A**) and its conjugate acid (**1H**). Bond lengths are in Å, and experimental values from an X-ray crystal structure (Ref. [4c]) are in brackets.

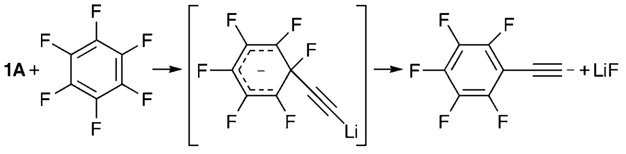
The electron affinity of the radical corresponding to **1A** provides another thermodynamic benchmark, but it could not

Table 2: Computed thermochemical properties for acetylene and lithium acetylide at 298 K.

RH	Method	ΔH°_{acid} [kcal mol^{-1}] (RH)	EA [eV] (R$^{\bullet}$)	BDE [kcal mol^{-1}] (RH)
HC≡CH	G3	378.7	3.00 [69.2][a]	133.5
	G4	378.6	2.96 [68.4][a]	132.3
	W1	378.6	2.97 [68.5][a]	133.4
	expt	378.3 ± 0.1	2.969 ± 0.006 [68.466 ± 0.138][a]	133.32 ± 0.07
LiC≡CH	G3	389.1	1.73 [40.0][a]	114.6
	G4	388.9	1.76 [40.5][a]	114.8
	W1	390.4	1.69 [38.9][a]	115.6
	expt	391.0 ± 1.3		

[a] Values in brackets are in kcal mol^{-1}. BDE = bond dissociation energy, EA = electron affinity.

be reliably measured with our experimental setup. Reactions with electron-transfer reagents were very fast, and the pressure in the reaction region is approximately 10 times greater than at the ionization gauge used to measure the pressure. Therefore, neutral reagent pressures below our measurable and controllable range ($\geq 1 \times 10^{-9}$ Torr) were required to slow the reactions down sufficiently so that there was time to collisionally cool the reactant ion without it being entirely depleted. Consequently, high-level ab initio methods were employed to compute this quantity. The G3, G4, and W1 electron affinities are included in Table 2, and the CCSD(T), BD(T), and CAS-AQCC results with the aug-cc-pVQZ basis set are provided in Table S4 of the Supporting Information. Our best estimate is the W1 value of 1.69 eV (38.9 kcal mol^{-1}). This value can be combined with the experimental acidity of **1H** to obtain the homolytic C–H bond energy of LiC≡CH (115.6 kcal mol^{-1}). These results reveal that replacing an acetylene hydrogen atom by a lithium atom decreases the BDE by 17.7 kcal mol^{-1} and the EA by 29.6 kcal mol^{-1}. Notably, these differences are about 15 kcal mol^{-1} smaller than what was reported for CH_3CO_2Li.[10a] This difference can be attributed to greater stabilization of $LiC_2^{\bullet}$ relative to $HC_2^{\bullet}$ compared with the Li/H difference for $^{\bullet}CH_2CO_2X$ because of the more favorable interaction between the radical and negative charge center (i.e. there is more charge and spin delocalization at the radical-bearing carbon center in $LiC_2^{\bullet}$ relative to $HC_2^{\bullet}$ than in $^{\bullet}CH_2CO_2Li$ relative to $^{\bullet}CH_2CO_2H$, see Table S5 in the Supporting Information). In accord with this explanation, computations at the G3 and G4 levels indicate that the C–H BDE of acetylide ion is smaller than that for acetylene by 26.7 and 25.4 kcal mol^{-1}, respectively, whereas the C–H BDE of acetate ion is only 0.6 (G3 level) and 1.1 (G4 level) kcal mol^{-1} less than for acetic acid. The reactions of dilithium acetylide with electrophiles is synthetically useful, so the reactivity of **1A** with additional electron-deficient reagents was explored. Nucleophilic addition and subsequent loss of hydrogen was observed with anthracene, styrene, and 3-fluorobenzaldehyde. However, this pathway is precluded with hexafluorobenzene, and consequently LiF was lost, presumably to afford pentafluorophenylacetylide ion [Eq. (8)]. The highly reactive nature of **1A** is also seen in its reaction with carbon disulfide. Three products are formed, $S^{\bullet -}$ (≈8 %), sulfur-atom transfer (Li-C≡C-S^{-}, 48 %), and addition with subsequent loss of lithium ($C_3S_2^{\bullet -}$, 45 %). The last species may be the radical anion of carbon subsulfide (S=C=C=C=S$^{\bullet -}$)[23] rather than a distonic ion ($^{\bullet}$C≡C–CS$_2^{-}$) because the former structure is predicted to lie 35.0 kcal mol^{-1} lower in energy at the G4 level (0 K).



(8)

In summary, lithiated anions can be generated in the gas phase by the decarboxylation of appropriate precursors. This work demonstrates that a double decarboxylation can be used to prepare a synthetically useful organolithium anion of a hydrocarbon, thus enabling the reactivity of the monomeric species to be probed without complicating solvent effects. A similar strategy should enable the corresponding sodiated species to be examined. Its reactivity differences will be interesting to explore, particularly since the PA (proton affinity), EA, and BDE are similar to those for LiC_2^{-} or $LiC_2^{\bullet}$ at the G3 level (for more details, see Table S6 in the Supporting Information). The G3 and W1 computations also indicate that the reaction Li–C≡C–Li + HC≡CH → 2 Li–C≡CH is exothermic by 2.2 and 2.8 kcal mol^{-1}, respectively, which accounts for the finding of Mortier et al. that dilithium carbide can be used to generate lithium acetylide.[6]

Experimental Section

Gas-Phase Experiments. These studies were carried out using an FTMS consisting of an IonSpec electrospray ionization (ESI) cart with a six-inch gold-plated cylindrical cell and a 3 T superconducting magnet. The inlet system was modified for greater flexibility by incorporating several leak valves, a gas ballast, and an additional pulse valve. As a result, several reagents can be used in succession this way, and kinetic studies can readily be carried out too. Data acquisition and analysis was performed with a PC running the Omega 9 software package. ESI of a MeOH/H_2O (3:1) solution containing acetylenedicarboxylic acid (200–500 μM) and a small amount of LiOH was carried out at a flow rate of 10 μL mL^{-1} into a Z-spray (Micromass) ESI source at 80 °C; the sample cone, extraction cone, and probe high voltage were −18.5 V, −2.2 V, and 2200 V, respectively. The resulting anions were extracted into a hexapole to build signal intensity and then were transported into the FTMS cell through an rf-only quadrupole ion guide. A pulse of argon was used to facilitate ion trapping and assist in vibrationally cooling them. Lithium acetylenedicarboxylate (*m*/*z* 119) was isolated using an arbitrary waveform excitation and subsequently fragmented by two sequential off-resonance excitations to afford $^{-}$C≡CCO$_2$Li (*m*/*z* 75) and then LiC≡C^{-} (*m*/*z* 31). The latter ion was cooled with a pulse of argon, isolated, and then allowed to react with different neutral reagents. Exact mass values of all of the ions studied herein were determined to secure their chemical compositions, which was particularly valuable for differentiating species containing two oxygen atoms versus one sulfur atom.

Computational studies. G3,[19] G4,[20] and W1[21] computations were carried out as described in the literature using the Gaussian 03,[24] Gaussian 09,[24] or MOLPRO[25] programs. Some density functional theory calculations were also carried out using B3-LYP[26] and M06-2X[27] along with the aug-cc-pVDZ and 6-31G(2df,p) basis sets, and subsequent single-point energies were computed at the CCSD(T), BD(T),[28] and CAS-AQCC[29] levels of theory with the aug-cc-pVQZ basis set. All of the resulting energies are reported as enthalpies at 298 K where small vibrational frequencies contributing more than 0.5 RT to the thermal energy were replaced by 0.30 kcal mol^{-1}. Selected Cartesian coordinates and energies are provided in the Supporting Information.

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