Gas-Phase Carbanion Chemistry

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In his 1912 Nobel lecture, Victor Grignard lamented the task of giving an account of organomagnesium compounds as "a subject so specialized in its essence, so vast in its applications...that I should have to survey the entire subject of organic chemistry, with its complicated formulae and with its forbidding names—which are liable to daunt even the initiated".[1] The familiar and time-honored Grignard reagents of which he spoke are perhaps the most widely utilized form of "carbanions" in solution.[2] Actually highly polar organometallic compounds that often exist in aggregated and solvent-sequestered forms,[3] Grignard reagents and their organo-alkali analogs nevertheless exhibit many of the physical characteristics and reactivity patterns expected of the conjugate bases of carbon acids. Truly free carbanions can only exist in the gas phase. Accordingly, experimental studies of gas-phase carbanions are a vital source of information about the *intrinsic* properties and chemical behavior of this important class of reactive organic intermediates.

Gaseous carbanions have been known since the mid-1930s when they were first observed by electron impact (EI) ionization of methane and larger hydrocarbons.[4] Since that time, the gas-phase chemistry of carbanions has been extensively investigated with the use of a variety of experimental methods.[5] Physical studies of gas-phase carbanions have had an important impact on our current understanding of intrinsic acidities,[6] homolytic and heterolytic bond strengths in hydrocarbons,[7] electronic-state splittings in carbenes, carbynes, and biradicals,[8] electron affinities of radicals,[9] energies of temporary anion states,[10] and resonance effects in organic anions.[11] Qualitative studies of the formation, structures, and reactivity of gas-phase carbanions, especially in the last 15 years or so, have provided new insights into carbanion rearrangements and pericyclic chemistry,[12] useful chemical strategies for elucidating carbanion structures and reaction mechanisms,[5,13] and even a look at carbanion stereochemistry.[14] This Account presents a brief summary of recent experimental investigations of gas-phase carbanion chemistry carried out in our laboratory with use of the flowing afterglow and flowing afterglow-triple quadrupole techniques.

The Flowing Afterglow–Triple Quadrupole Technique

It has been nearly 30 years since Ferguson, Fehsenfeld, and Schmeltekopf first described the flowing

afterglow method for investigating the kinetics of gas-phase ion/molecule reactions related to ionospheric chemistry.[15,16] During this period, flowing afterglow has emerged as one of the most versatile methods available for general studies of gas-phase ion chemistry.

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Robert R. Squires was born in Oakland, CA, in 1953. He received his B.S. degree from California State University and his Ph.D. degree in 1980 from Yale University for calorimetric studies of steric effects carried out under the direction of Ken Wiberg. He was a postdoctoral research associate with Chuck DePuy and Veronica Bierbaum at the University of Colorado at Boulder until 1981, at which time he joined the faculty at Purdue University where he is now Professor of Chemistry.
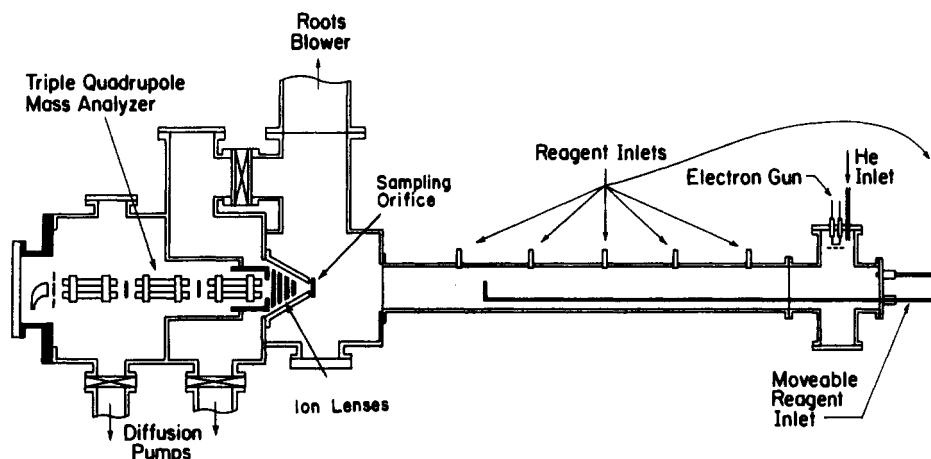
Figure 1. The flowing afterglow–triple quadrupole instrument.

Flowing afterglow and its powerful variant, the selected ion flow tube (SIFT)[17] technique, are currently employed in more than 20 research laboratories worldwide. An impressive variety of chemical and physical research interests is represented in the flow tube community, ranging from atmospheric chemistry and interstellar synthesis to physical organic and organometallic studies.[18] An important feature of ion flow tube methods that may account for their general utility is the flexible, modular design of the basic instrumentation. In its simplest form, a flowing afterglow device consists of an ion source, a relatively high-pressure, flowing-gas reactor, an ion sampling system, and a quadrupole mass analyzer. Over the decades, each of these main elements of the flowing afterglow has been continuously modified and improved, resulting in a variety of useful new experimental capabilities.[18]

In a collaborative effort in 1983 with my colleague R. G. Cooks, we installed a commercial triple quadrupole mass analyzer into the existing flowing afterglow apparatus in my laboratory and demonstrated the viability of a tandem flowing afterglow–triple quadrupole configuration.[19] Soon afterward, we acquired our own triple quadrupole system for permanent installation; the final instrument is illustrated in Figure 1. The flowing afterglow portion of the instrument consists of an electron emission source located at the upstream end of a 1 m long flow tube. High-purity helium enters the system near the electron gun and carries the ions formed by ionization of added neutral precursors down the flow tube at velocities near 100 m/s. At the typical operating pressures of 0.1–1.0 Torr, the ions experience ca. 10^7 collisions per second with the helium and are rapidly brought into thermal equilibrium with the room-temperature flow tube. During their approximately 10-ms residence time in the flow reactor, the ions can undergo spatially and temporally resolved reactions with neutral reagents added through gas inlets located at regular intervals along the tube. At the downstream end of the flow reactor, either the positive or negative ions are gently extracted from the plasma through a sampling orifice

and focused with electrostatic lenses into the triple quadrupole mass analyzer.

The triple quadrupole is one member of a growing family of tandem mass spectrometers developed for performing MS/MS experiments.[20] The EXTREL triple quadrupole analyzer in our instrument consists of three coaxially aligned quadrupole mass filter elements followed by an electron multiplier. The first (Q1) and third (Q3) quadrupoles can be operated in ion mass resolving mode, while the middle quadrupole (Q2) is a gas-tight, rf-only (rf, radio frequency) unit that serves as a collision/reaction chamber for collision-induced dissociation (CID) or ion/molecule reactions with mass-selected ions. The reactant ion translational energies in Q2 are determined by the quadrupole rod offset voltage, which can be varied over a range of ca. 0.1–200 eV. Either inert target gases such as argon or reactive neutral compounds can be added to Q2 at pressures corresponding to single or multiple ion target collisions ((3–30) × 10^{-5} Torr).

The triple quadrupole mass analyzer adds many new capabilities to the basic flowing afterglow experiment. In the conventional instrument utilizing single-stage mass analysis, information about ion structures is normally obtained from consideration of the products formed in ion/molecule reactions with selected neutral reagents.[13] With the triple quadrupole analyzer, CID can provide a fast, convenient means for characterizing ion structures and distinguishing isomeric ions, since different ions often display unique ionic fragments or undergo fragmentation with different collision energy dependence.[21]

CID can also be used to obtain information about the thermochemistry and dynamics of ion fragmentation.[22] For these studies, a CID product ion yield is monitored as a function of the ion target collision energy. From the resulting ion appearance curve, one can extract the threshold energy for the dissociation, E_T, by a modeling procedure that takes into account the Doppler broadening of the collision energy by the nonstationary

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target,[23] the kinetic energy spread of the reactant ion beam, and an adjustable functional form for the energy-dependent CID cross section above threshold.[24,25] For fast dissociation reactions involving a simple bond cleavage that has no reverse activation energy, E_T can be directly equated with the bond dissociation enthalpy.

Carbanion Synthesis by Collision-Induced Decarboxylation

Collision-induced dissociation is widely recognized as a powerful tool for obtaining structural information for gas-phase ions.[21] If we shift our attention specifically to the ionic *products* of a CID reaction, then it is evident that CID can serve as a useful synthetic tool as well. Degradative methods such as pyrolysis or photolysis are commonly employed by synthetic organic chemists to transform one compound into another, or by physical organic chemists to generate reactive intermediates such as carbenes or free radicals by the elimination of small molecular fragments. In recent reports from this laboratory and others,[26] it has been demonstrated that CID of suitable precursor ions can be used to generate novel fragment ions that would be difficult or impossible to prepare by conventional gas-phase ion synthetic methods such as electron impact or chemical ionization.

In 1986 we introduced a new method for generating gas-phase carbanions by collision-induced dissociation of organic carboxylate ions (eq 1).[27] In these initial

$$RCO_2^- \xrightarrow{CID} R^- + CO_2 \qquad (1)$$
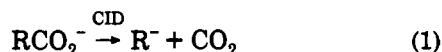
studies, we used a Fourier transform ion cyclotron resonance spectrometer (FT-ICR)[28] that was generously made available to us by my colleague, B. S. Freiser. We showed that four chemically distinct $C_3H_5^-$ ions are produced by decarboxylation of the following isomeric ions:

$CH_2{=}CHCH_2CO_2^-$ $CH_3CH{=}CHCO_2^-$ $CH_2{=}C(CH_3)CO_2^-$ $\triangleright{-}CO_2^-$
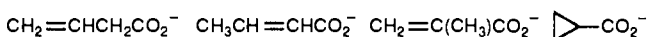
Moreover, the specific reactivity of each $C_3H_5^-$ ion with neutral reagents such as N_2O, CS_2, and others was found to be consistent with the expected structures derived from simple heterolytic cleavage of the $R^-{-}CO_2$ bond without skeletal rearrangements or hydrogen shifts. Therefore, in organic synthetic parlance, collision-induced decarboxylation is a "regioselective" method for preparing gas-phase carbanions. Carboxylate CID

has since been used in other laboratories,[29] and it provides a useful complement to the fluorodesilylation method for gas-phase carbanion synthesis developed by DePuy and co-workers.[30]

Collision-induced decarboxylation can also be carried out in the triple quadrupole analyzer of our tandem instrument.[31,32] In exploring the scope of this method, we discovered that even acetate ion can be decarboxylated to produce the archetypal carbanion, CH_3^-. When CID of acetate ion is carried out in the presence of reactive neutral compounds in Q2, bimolecular reactions of the CH_3^- fragment can be observed.[33] An experimental protocol was developed for identifying products of CH_3^- reactions and distinguishing them from those produced by the translationally excited acetate ion. The methyl anion exhibits reactivity commensurate with its high basicity ($\Delta H_{acid}(CH_4) = 416.6$ kcal/mol)[34] and its low electron binding energy ($EA(CH_3) = 1.8$ kcal/mol).[35] For example, CH_3^- abstracts protons from the weak acids $CH_2{=}CH_2$, NH_3 and C_6H_6 and transfers an electron to O_2, C_6F_6, and SO_2. It also displays interesting condensation reactions with a variety of compounds, such as the addition/H_2-elimination reaction observed with propanal:

$$CH_3^- + CH_3CH_2CHO \rightarrow H_2 + C_4H_7O^- \qquad (2)$$
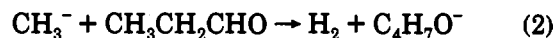
The observation of such a "fragile", weakly bound species as CH_3^- from carboxylate CID suggested to us that this method might provide a means to prepare other alkyl ions. This is an important experimental challenge because simple alkyl carbanions such as ethyl, 1- and 2-propyl, and all of the butyl anions have been predicted by theorists to be thermodynamically unstable with respect to electron detachment[36] and have thus far eluded detection in all deliberate attempts to form them.[37] In agreement with the predictions from both theory[36] and previous gas-phase experiments,[37] we find that none of the C_3–C_5 carboxylate ions produce detectable yields of alkyl anions under the same CID conditions that produce CH_3^- from $CH_3CO_2^-$. However, we do observe trace amounts of the neopentyl anion and other primary pentyl carbanions from the corresponding C_6 carboxylates (e.g., eq 3).[31,32] Here, we are

$$(CH_3)_3CCH_2CO_2^- \rightarrow (CH_3)_3CCH_2^- + CO_2 \qquad (3)$$

witnessing the delicate balance between the destabilizing inductive effects and stabilizing polarizability

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Table I. Gas-Phase Acidities Determined from Decarboxylation Threshold Energies[a]

compound[b]	ΔH_{acid} (eq 4), kcal/mol	ΔH_{acid} (lit.),[c] kcal/mol
CH_4	418 ± 4	417 ± 1
(structure)	413 ± 4	
(structure)	411 ± 4	
CH_3F	409 ± 4	
$CH_2=CHC(CH_3)_3$	409 ± 4	
(triangle structure)	409 ± 5	412 ± 2
$CH_2=CH_2$	407 ± 3	409 ± 1
$CF_3CH_2CH_3$	406 ± 4	
$PhCH_2CH_3$	406 ± 5	
(structure)	403 ± 4	401 ± 2
$CH_3C(O)CH_2CH_3$	401 ± 4	
CH_2F_2	389 ± 4	387 ± 7
CHF_3	376 ± 4	377 ± 2
$CH_3C\equiv N$	369 ± 4	373 ± 3

[a] Taken from ref 39. [b] Acidic hydrogen indicated in boldface type. [c] Taken from ref 34.

effects of alkyl groups on a carbanion center.[6,37,38] With the neopentyl anion the combined polarizability effect of three β-methyl substituents is just sufficient to endow the carbanion with a positive electron binding energy since β-alkyl substitution has little effect on radical stabilities. In contrast, with the smaller butyl, propyl, and ethyl anions, the electron-releasing inductive effects and the radical stabilizing effects of the α- and β-alkyl groups are dominant, and the electron binding energies become negative. Thus, the carbanions formed by decarboxylation do not survive the 25-μs minimum observation time of our experiments.

The measured appearance energy (E_T) of the carbanion fragment from reaction 1 can provide good estimates for the R^-–CO_2 heterolytic bond energies, which can be related to the gas-phase acidity of the conjugate acid of the carbanion, RH:[31,39,40]

$$\Delta H_{acid}(RH) = E_T + \Delta H_F(RCO_2H) +$$
$$\Delta H_{acid}(RCO_2H) - \Delta H_f(CO_2) - \Delta H_f(RH) \quad (4)$$

The supplemental thermochemical data needed for eq 4 are either well-known or can be reliably estimated.[34] Insofar as regioselective decarboxylation occurs with virtually all carboxylate ions,[32] this method provides a means to estimate the gas-phase acidity at any site in an organic molecule that is capable of supporting a negative charge. This includes positions with hydrogens that are not normally abstracted in acid–base reactions because of their low intrinsic acidities or because of the presence of other more acidic hydrogens in the molecule. We have determined acidities in this way for over 20 different compounds;[39] a brief listing of selected ΔH_{acid} values is provided in Table I. In cases where comparisons with other values in the literature can be made, the agreement is generally quite good. The well-known acidity-enhancing effects of angle strain in small-ring compounds is clearly evident in the results for bicyclo-

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Scheme I
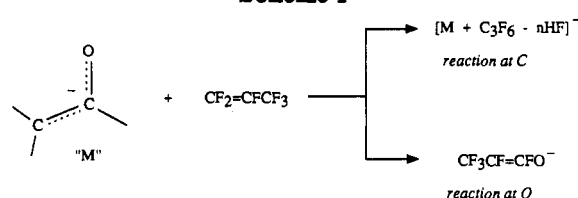
pentane and the two cyclopropanes. α-Fluoro substitution appears to have a highly variable acidifying effect (cf. CH_4, CH_3F, CH_2F_2, and CHF_3), while β-substitution in ethane ($\Delta H_{acid} = 420$ kcal/mol) by CF_3, phenyl, or acetyl leads to pronounced acidity enhancements of comparable magnitude.

Enolate Ions

Of the many different classes of carbanions, enolate ions are probably the most familiar because of their great practical utility in organic synthesis.[2,41] We have been using the flowing afterglow–triple quadrupole technique to investigate three fundamental questions concerning the intrinsic properties and reactivity of enolate ions. What factors control carbon vs oxygen alkylation of these ambident nucleophiles? When do enolate ions behave as nucleophiles and when do they react as bases? Which α-position in unsymmetrical ketones is most acidic thermodynamically, and how do kinetically controlled deprotonations operate in the gas phase?

In order to examine the first of these issues, one would normally require some means for analyzing the *neutral* products of a gas-phase alkylation reaction with the usual electrophiles such as the methyl halides.[42] We developed an alternative procedure based on analysis of the mass spectrometrically distinct *ionic* products of condensation reactions between enolate ions and perfluoropropylene, $CF_2=CFCF_3$.[43] This reagent displays remarkably consistent reactivity wherein a single ionic product, $CF_3CF=CFO^-$, is produced when it reacts with pure oxyanions such as alkoxides, carboxylates, or HO^-, while addition accompanied by multiple HF loss characterizes its reactions with pure carbanions such allyl, benzyl, or phenide. Thus, by determining the yields of these two types of products formed in reactions with ambident enolate ions, one can obtain a quantitative measure of the intrinsic preference for reaction at the carbon or oxygen terminus (Scheme I). We have applied our probe to a variety of cyclic and acyclic enolates derived from ketones, aldehydes, esters, and amides.[43] Acyclic enolates display the full range of behavior—from nearly 100% reaction at oxygen to 100% reaction at carbon. Enolates derived from aldehydes and acyclic ketones react mainly or exclusively at oxygen, while enolates with electronegative or π-donating substituents at the carbonyl center yield predominately carbon condensation products. A general preference for reaction at carbon is evident for the

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Scheme II
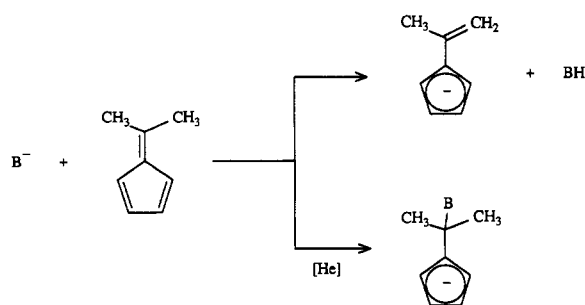
cyclic ketone enolates, which appears to diminish with increasing ring size.

6,6-Dimethylfulvene also displays remarkable selectivity in its gas-phase reactions with enolate ions.[44] This hydrocarbon undergoes competing proton transfer and addition reactions with a wide variety of organic and inorganic anions (Scheme II). Proton transfer (Bronsted acidity) dominates in its reactions with aldehyde enolates, acyclic ketone enolates, and most cyclic ketone enolates, while addition (Lewis acidity) dominates in its reactions with small-ring ketone enolates and all ester enolates. There is a striking similarity in the behavior of the various enolates toward both CF_2=$CFCF_3$ and dimethylfulvene which suggests a common cause. The same enolates that behave as good Bronsted bases toward dimethylfulvene also display a propensity to react with CF_2=$CFCF_3$ at oxygen. Similarly, the best nucleophiles (Lewis bases) toward dimethylfulvene show a general preference for reaction with CF_2=$CFCF_3$ at their carbon terminus.

In the original reports on these reactions,[43,44] we identified the keto–enol energy differences of the parent carbonyl compounds as a useful correlate for the observed variations in enolate reactivity. Thus, enolates derived from carbonyl compounds such as aldehydes and ketones with small keto–enol energy differences (ca. 10 kcal/mol) will tend to have lower barriers for the kinetically preferred protonation or alkylation at oxygen, while enolates from compounds such as esters, amides, and small-ring ketones that have larger keto–enol energy differences (>20 kcal/mol) will be constrained to react through carbon. Because this is an inherently slower process with carbon acids such as dimethylfulvene, nucleophilic addition predominates. Although this model satisfactorily accounts for the behavior of the majority of the enolates examined, there are some notable exceptions, such as $PhCOCH_2^-$, $^tBuCOCH_2^-$, and c-$C_3H_5COCH_2^-$, which all show mainly carbon attack despite the fact that their parent ketones have relatively small keto–enol energy differences.
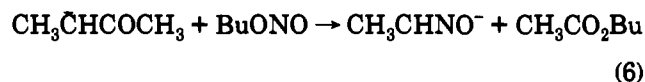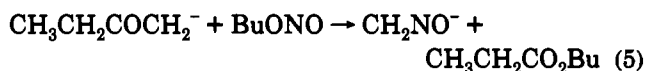
Recently, Nibbering and co-workers made use of our approach to evaluate the ambident reactivity of acyclic enolates in an FT-ICR.[45] With C_3F_6 as the probe reagent, the C/O product distributions measured in the FT-ICR were found to be in excellent accord with our flowing afterglow results. However, with the related perfluorohydrocarbon, C_6F_6, the C/O reactivity ratios differed significantly, such as in the case of acetone enolate where the 5:1 oxygen attack preference found with C_3F_6 switches to a 5:1 carbon preference with C_6F_6.

Nibbering and co-workers formulated an insightful frontier orbital argument to rationalize this behavior, in which it is proposed that the energy of the low-lying LUMOs of C_3F_6 and C_6F_6 relative to the two highest-lying π-orbitals of the enolate controls the kinetic preference for carbon vs oxygen attack.[45] This frontier orbital model nicely accounts for the otherwise aberrant behavior of the three acetyl enolates mentioned above, which all have relatively low-energy HOMOs.

Kinetic vs thermodynamic control in the formation of isomeric enolates from unsymmetrical ketones is an important issue in organic synthesis.[46] Kinetic control generally prevails when strong, sterically bulky bases such as lithium diisopropylamide (LDA) are employed and deprotonation is rapid and irreversible. Thermodynamically controlled deprotonations usually require some means for the enolate regioisomers to equilibrate.[46] We developed an experimental protocol for distinguishing and quantitating isomeric enolates in a gas-phase mixture without the use of deuterium labeling and for determining their relative stabilities by direct acid-catalyzed equilibration.[47] Acyclic enolates react with n-butyl nitrite in the gas phase to produce condensation products that are characteristic of the charge-bearing carbon.[48,49] For example, the primary enolate ion from 2-butanone produced by fluorodesilylation of the corresponding trimethylsilyl enol ether yields CH_2NO^-, while the isomeric secondary enolate produces CH_3CHNO^- (eqs 5 and 6).

$$CH_3CH_2COCH_2^- + BuONO \rightarrow CH_2NO^- + CH_3CH_2CO_2Bu \quad (5)$$

$$CH_3\overset{-}{C}HCOCH_3 + BuONO \rightarrow CH_3CHNO^- + CH_3CO_2Bu \quad (6)$$

By determining the absolute cross sections for these two reactions and then measuring the yield ratio of the two characteristic products formed in Q2 of the triple quadrupole when BuONO reacts with a mixture of isomeric 2-butanone enolates sampled from the flow tube, we can reliably assay the composition of the mixture. In this way we directly monitored the MeOH-catalyzed equilibration of the isomeric enolates formed by proton abstraction from 2-butanone by OH^- (Scheme III).[47] The secondary enolate **A** is the more stable of the pair with a measured free energy difference from **B** of 1.0 kcal/mol, as determined from the 5:1 mixture of enolates at equilibrium. Interestingly, enolate **A** is also the kinetic enolate, formed in greater initial abundance from 2-butanone with OH^-, NH_2^-, and all other reagent bases we have examined. In solution, the kinetic enolate is usually the *least* substituted enolate since it is the most sterically accessible to the bulky alkyl amide bases that are usually employed.[46] In the gas phase, $^iPr_2N^-$ and OH^- have identical

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Squires

Scheme III
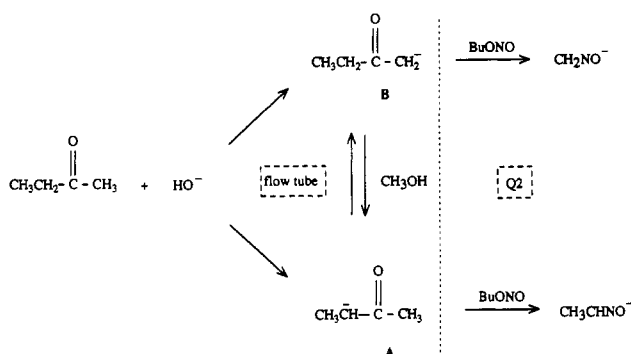
thermodynamic basicities,[50] and they produce identical yields of the two enolates of 2-butanone in proton abstraction reactions that are ca. 20 kcal/mol exothermic:

$$CH_3CH_2COCH_3 \xrightarrow{\text{OH}^- \text{ or } ^i\text{Pr}_2\text{N}^-} A{:}B = 82{:}28 \quad (7)$$
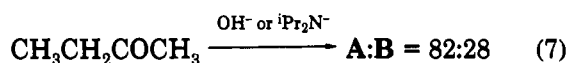
Using this same protocol, we also determined that the primary α-position in methyl isopropyl ketone and the secondary α-position in ethyl isopropyl ketone are both kinetically and thermodynamically more acidic than the respective tertiary α-positions. These intrinsic stability orderings for the enolate regioisomers are at variance with the commonly held view based on enolate chemistry in solution that more substituted enolates are more stable.[46,51] While this may still be true for cyclic enolates and for the neutral enol ethers that are often used to model enolate stability, it clearly does not hold for simple acyclic enolate ions in the gas phase, where solvation and ion pairing are absent.

Anionic Homoaromaticity

Homoconjugation, i.e., delocalization of electrons between π-systems that are not directly connected by a single bond, is a fascinating effect in organic chemistry that has inspired elegant experiments as well as lively debate.[52] The extent of stabilization (or destabilization) attending homoconjugation in carbanions has been especially controversial in the last 30 years.[53] We recently reported measurements of gas-phase acidities for a series of cyclic and bicyclic hydrocarbons related to the question of homoaromaticity in the bicyclooctadienyl anion D.[54] In principle, transannular interactions between the allylic and olefinic moieties in this

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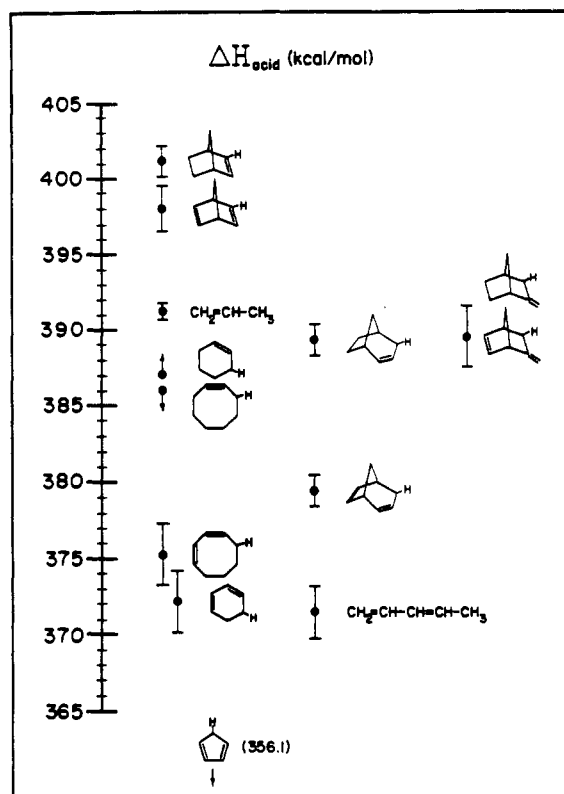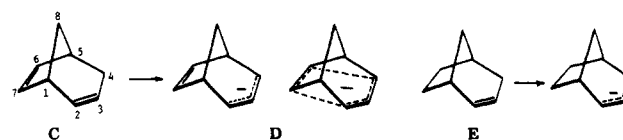(54) Lee, R. E.; Squires, R. R. *J. Am. Chem. Soc.* 1986, *108*, 5078.

Figure 2. Partial gas-phase acidity scale for hydrocarbons relevant to anionic homoaromaticity.

carbanion can create a bishomoconjugated, 6-electron aromatic system, i.e., a "bishomocyclopentadienyl anion".[55]

Indeed, pronounced stabilization effects of this kind are known in analogous bicyclic carbocations such as the 7-norbornenyl cation,[56] and bicyclo[3.2.1]octadiene C does display a marked acidity enhancement over the corresponding bicyclic monoene E in solution (ca. 9 pK_a units).[57] Our measured gas-phase acidities for C, E, and various unsaturated hydrocarbon model systems are illustrated in Figure 2. Bicyclo[3.2.1]octadiene possesses an extraordinarily high gas-phase acidity (low ΔH_{acid}) for an allylic hydrocarbon that is nearly 10 kcal/mol greater than that of bicyclo[3.2.1]octene. The nearly identical acidities of methylene norbornane and methylene norbornene and the fact that the acidities of norbornadiene and norbornene differ by less than 3 kcal/mol indicate that inductive stabilization of the allylic moiety by the remote double bond in D is relatively small.[54]

Nevertheless, our claim that bishomoaromaticity accounts for most of the unusual stability of D has

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been challenged by Schleyer et al.,[58] who propose instead *anionic hyperconjugation* between the ends of the allylic anion and the adjacent C(1)–C(7) and C(5)–C(6) vinyl bonds, and by Lindh et al.,[59] who proffer electrostatic stabilization due to *ion/quadrupole interactions* between the allylic group and the C(6)–C(7) double bond. However, these counterproposals are ultimately unconvincing. The 5.8 kcal/mol ion/quadrupole stabilization energy estimated by Lindh et al. was derived from a $1/r^3$ electrostatic potential calculation involving the Mulliken partial charges computed for the allylic carbons in **D** placed at their respective distances from the experimental quadrupole moments of ethylene vs ethane.[59] This value should be considered an unrealistic upper limit at best, since the actual quadrupole moment of the C(6)–C(7) bridge in **D** will be somewhat smaller than that of ethylene[60] and its orientation with respect to the delocalized charges in the allyl group is nonoptimal. Furthermore, although Lindh et al. employed a higher level of MO theory than has been used in all previous computational studies of carbanion **D**,[53] gas-phase acidities for **C** and **E** were not calculated, so that it is difficult to gauge the reliability of their results.

The homoallyl anion model system used by Schleyer et al. to illustrate anionic hyperconjugation is similarly flawed.[58] Conformer **X**, which allows hyperconjugation but precludes homoconjugation, was stated by Schleyer et al. to be stabilized by 6.6 kcal/mol relative to *n*-butyl anion at the 4-31+G/3-21G level.[61]
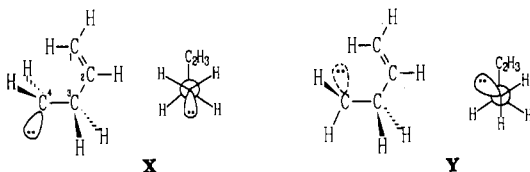
However, a more complete examination[62] at a higher level of theory that includes estimates for the correlation energies (MP4SDQ/6-311+G*/6-31+G*)[61] clearly shows the conformational energy profile for rotation about the C(3)–C(4) bond to be quite flat, with the arguably homoconjugative conformation **Y** essentially identical in energy to **X**. Moreover, the stabilization of conformer **X** (which is actually not the global minimum on the conformational energy surface) relative to *n*-butyl anion is purely inductive and/or electrostatic in origin, as this species displays *none* of the characteristic features of a hyperconjugated system in terms of its electron distributions, orbital compositions, and bond distor-

tions.[63] Hyperconjugation between a carbanion lone pair and an adjacent C–C vinyl bond is unimportant. Accordingly, we maintain that homoconjugation is still a viable explanation for the unusual stability of **D**. Until such time that MO calculations are able to reproduce correctly the measured gas-phase acidities of **C** and **E**, inferences derived from them concerning the origins of the stabilization in **D** are considered tenuous.

Concluding Remarks

In closing his Nobel address, Grignard speculated about the occurrence of organomagnesium compounds in nature, citing the then recent discovery by Willstätter of magnesium in chlorophyll as possible evidence for their role in biosynthesis. He stated: "[Willstätter] concluded that compounds analogous to the organic magnesium compounds must form and that the absorption of carbon dioxide gas by chlorophyll would in every way be comparable to the Grignard reaction. He thus came to compare the chlorophyll of leaves with the haemoglobin of animals; hence, for living matter there would apparently be two transformation cycles—life due to synthesis by means of magnesium and life due to oxidation by means of iron".[1] Although the prospects for gas-phase carbanions may not be nearly so lofty as they might have seemed for Grignard reagents back in 1912, the outlook for the forseeable future is certainly excellent. A number of new developments in our lab and others appear just on the horizon, including direct measurements of carbanion inversion barriers, the rational synthesis and chemical characterization of a variety of interesting new species such as triplet carbyne anions, distonic radical anions, organoalkali negative ions, and small-ring carbanions, and perhaps an indirect look at "unbound" carbanions such as $CH_3CH_2^-$ by combining efficient hydrocarbon radical sources with electron transmission spectroscopy. Experimental studies of gas-phase carbanions, along with parallel theoretical investigations, will continue to shape our knowledge of the intrinsic properties and reactivity of these species. Convergent efforts to delineate the details of ion pairing and solvation effects on carbanion chemistry in solution will ultimately lead us to a complete understanding of this important class of reactive organic intermediates.

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