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The Simplest Azabutadienes in Their N-Protonated Forms. Generation, Stability, and Cycloaddition Reactivity in the Gas Phase

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The simplest azabutadienes, i.e. 1-aza-1,3-butadiene and 2-aza-1,3-butadiene, are generated in their N-protonated forms **1** and **2** via gas-phase dissociative electron ionization of allylamine and piperidine, respectively. Formation of **1** and **2** is suggested by simple dissociation mechanisms, and supported by high-accuracy G2 ab initio calculations, which show the ions to be stable, non-interconverting species. Whereas **1** and **2** are unreactive toward ethylene and cyclohexene, **2** reacts with alkenes activated by electron-donating (OC_2H_5), electron-withdrawing (CN, $COCH_3$), and vinyl and phenyl substituents most likely by polar [$4^+ + 2$] cycloaddition, as suggested by MS^3 experiments and ab initio calculations. The cycloadduct of **2** with ethyl vinyl ether is unstable and dissociates promptly by ethanol loss; hence, net C_2H_2 addition occurs. This novel vinylation reaction is proposed as a potential structurally diagnostic test for both 2-azabutadienes and vinyl ethers. Isomer **1** is in general much less reactive, and abundant adducts are only formed in reactions with alkenes activated by electron-withdrawing substituents. In reactions of **1** and **2** with esters (methyl acetate and dimethyl carbonate), hydrogen-bridged ion−neutral complexes are formed as the most abundant and stable products, as suggested by the ab initio calculations. Acetone, fluoroacetone and acetonitrile form abundant adducts with both **1** and **2**; however, the experimental and theoretical results on these adducts provide no clear structural information. Reactions of **1** with DMSO occur almost exclusively by proton transfer, whereas **2** forms an abundant complex with DMSO. Limited reactivity is observed for **1** and **2** with acetyl chloride and thionyl chloride; the minor products observed were those of either dissociative proton transfer or charge exchange. The distinctive reactivities of **1** and **2** with styrene, ethyl vinyl ether, and dimethyl sulfoxide contrast to their identical low energy CID behavior, and allow their straightforward differentiation in the gas phase.

Introduction

Cycloadditions are reactions of remarkable importance and great synthetic use in condensed phase chemistry.[1] Polar cycloadditions,[2] i.e. those in which ionic reactants such as even-electron negatively (M^-) and positively charged (M^+) species are employed, are used with success in many synthetic strategies in solution chemistry. Odd-electron cations ($M^{\bullet+}$) generated in solution participate in "hole"-catalyzed polar cycloaddition reactions,[3] which often display extremely low activation barriers such that even forbidden reactions can be initiated.[3e]

In the gas phase, cycloadditions have been systematically studied for a variety of ionic species[4] via different multiple-stage mass spectrometric (MS^n) techniques.[5] Recent pentaquadrupole MS studies[6] have suggested the occurrence of novel gas-phase cycloaddition reactions, i.e. [3 + 2] 1,3-cycloaddition of the simplest ionized carbonyl ylide ($CH_2{=}O^+CH_2^{\bullet}$) with carbonyl compounds,[6a] and polar [4 + 2^+] cycloaddition of acylium ($RC^+{=}O$),[6b] thioacylium ($RC^+{=}S$),[6b] nitrilium ($RC{\equiv}N^+CH_3$),[6c] and sulfonium ($RS^+{=}CH_2$)[6d] ions with several "*s-cis*" conjugated dienes. Polar [4 + 2^+] cycloadditions, which are

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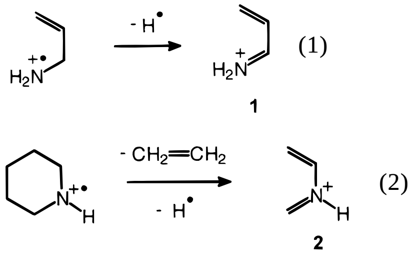
well-known in solution, have also been observed and studied in the gas phase by multiple stage MS. They include those of immonium ions ($CH_2{=}NH^+R$),[6c] and of protonated and methylated carbonyl compounds.[6e]

Neutral azabutadienes and analogues, often under acid catalysis, or complexed cationic azabutadienes react promptly in solution with several dienophiles by [4 + 2] and polar [4^+ + 2] Diels–Alder cycloadditions, respectively, and these reactions have been used as key steps in important routes to heterocyclic systems.[2,7] Simple dissociation mechanisms[8] suggest that the N-protonated forms of the simplest members of the azabutadienes, i.e. 1-aza-1,3-butadiene (**1**) and 2-aza-1,3-butadiene (**2**), are generated in the gas phase by dissociative electron ionization (EI) of allylamine and piperidine, respectively (eqs 1 and 2).



Protonated azabutadienes are likely the key reactive species in solution acid-catalyzed cycloadditions, or alternatively they are good models for the cationic azabutadienes. Hence, if **1** and **2** are indeed formed as stable species in the gas phase, MS^n experiments[5] could be applied for the study of their intrinsic gas-phase reactivity. Additionally, characteristic gas-phase reactivities could allow distinction between **1** and **2**, while suggesting potential structurally diagnostic ion/molecule reactions for their higher homologues and derivatives.

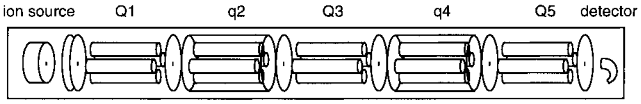


Figure 1. A simple schematic representation of the pentaquadrupole (QqQqQ) mass spectrometer. Q1, Q3, and Q5 are ion mass-analyzer quadrupoles, whereas the q2 and q4 quadrupoles function as ion-focusing reaction chambers. In a typical sequence of experiments, an ion is generated in the source, mass-selected by Q1, and further reacted under controlled conditions (collision energy and pressure) with a neutral gas introduced in q2. Product ions of interest are then subsequently mass selected by Q3, and structurally analyzed by either collision-induced dissociation or structurally diagnostic ion/molecule reactions in q4, while Q5 is scanned to acquire the triple-stage mass spectra. For more details see ref 5c.

This article describes a systematic study via pentaquadrupole (QqQqQ) MS^2 and MS^3 experiments,[9] in conjunction with ab initio theoretical calculations, of the gas-phase generation and stability of **1** and **2** (as compared with 13 alternative isomers **3**–**15**), and of their intrinsic gas-phase reactivities toward a number of dienophiles, i.e. alkenes, nitriles, ketones, esters, sulfoxides, and acetyl chloride. In several cases adducts are formed extensively, and MS^3 experiments and ab initio calculations have been performed in the hope that they could lead to structural elucidation. The results suggest that polar [4^+ + 2] cycloaddition occurs across the C=C double bond of activated alkenes, whereas loosely bonded hydrogen-bridged ion–neutral complexes, i.e. the "*mono*-solvated" ions, are the most likely adducts for the neutral reactants known to be poor dienophiles in solution. Experimental and theoretical evidence suggest the occurrence, via polar [4^+ + 2] cycloaddition, of an interesting "vinylation" (C_2H_2 addition) reaction between **2** and ethyl vinyl ether, thus the potential of this novel gas phase reaction as a general structurally diagnostic test for both 2-azabutadienes and vinyl ethers is discussed.

Experimental Section

The MS^2 and MS^3 experiments were performed using an Extrel [Pittsburgh, PA] pentaquadrupole (QqQqQ) mass spectrometer (Figure 1), which is described in detail elsewhere.[10] The QqQqQ consists of three mass-analyzing quadrupoles (Q1, Q3, Q5), by which mass-selection and mass-analysis are performed, and by two rf-only "full" ion-transmission reaction quadrupoles (q2, q4), in which ion/molecule reactions or collisional dissociations occur. For the MS^2 experiments, the ion was generated by dissociative 70 eV electron ionization (EI) of allylamine (**1**) or piperidine (**2**), or by methane chemical ionization (CI) of ethyl cyanide (**6**) or methyl iodide CI of acetonitrile (**8**), and mass-selected by Q1. After ion/molecule reactions in q2 with the neutral reagent of choice, Q5 was used to record the product spectrum, while Q3 and q4 were operated in the "full" ion-transmission rf-only mode.

Nominal sample and neutral gas pressures were typically 5×10^{-6} and 5×10^{-5} Torr, respectively, as monitored by a single ionization gauge located centrally in the vacuum chamber. The target gas pressure corresponds to a typical beam attenuation of 50–70%, viz., to multiple collision conditions. However, lower reaction yields but similar sets of products were always observed at lower pressure, mainly single collision conditions in q2. Instrument parameters such as quadrupole offset potentials and lens voltages were adjusted to maximize the abundance of the ion/molecule products, and the same reaction conditions were used when reacting either **1** or **2** with the same neutral.

For the MS^3 experiments, a reaction product of interest was selected in Q3 and dissociated by collisions with argon in q4, while Q5 was scanned across the desired m/z range to record the sequential product triple stage (MS^3) spectra. The collision energies, calculated as the voltage difference between the ion source (grounded) and the collision quadrupole, were typically near 0 eV for ion/molecule reactions and 15 eV for CID, in both MS^2 and MS^3 experiments.

Molecular orbital calculations were performed using GAUSSIAN94.[11] Structure optimizations using gradient techniques

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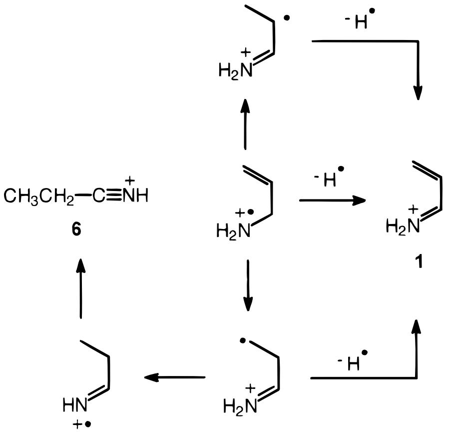
Scheme 1



were performed at either the G2 level[12] or at the Hartree–Fock (HF)[13] level of theory using the 6-31G(d,p) basis set. In the latter case, improved energies were obtained by using single point calculations at the MP2/6-31G(d,p) level, including valence electron correlations calculated by second-order Mϕller–Plesset perturbation theory,[14] a procedure denoted as MP2/6-31G(d,p)//6-31G(d,p).

Results and Discussion

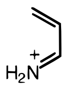
Making 1 and 2. As mentioned, dissociative EI of allylamine and piperidine are expected to produce the N-protonated forms of 1-aza-1,3-butadiene (**1**) and 2-azabutadiene (**2**), respectively, as the primary *m/z* 56 fragments of $C_3H_6N^+$ composition (eqs 1 and 2).[8] Isomerization of the ionized molecules prior to dissociation could lead, however, to formation of other isomeric $C_3H_6N^+$ ions. This seems not to be the case for piperidine; high-resolution mass spectrometric measurements, deuterium labeling, and metastable ion experiments[8a,15] have firmly supported the direct dissociation mechanism of piperidine depicted briefly in eq 2.

The case of allylamine is more complex because a series of H-shifts may occur (Scheme 1). Isomerization of ionized allylamine to the two distonic ions $CH_3\dot{C}HCH{=}NH_2^+$ and $\dot{C}H_2CH_2CH{=}NH_2^+$ should, however, not change the $C_3H_6N^+$ composition because both isomeric ions are expected to dissociate by H loss to also yield **1** (Scheme 1). H loss dissociation from the imino ion $CH_3CH_2CH{=}NH^{\bullet+}$ would be expected to form another isomer, i.e. **6**, but **6** is ruled out from the chemical reactivity with isoprene of the *m/z* 56 fragment of allylamine.[6c] The authentic **6** (formed by CI protonation of propiononitrile) reacts largely and exclusively with isoprene by proton transfer,[6c] whereas the *m/z* 56 fragment ion from allylamine is much less reactive, forming with isoprene a modest but unique adduct.[6c] Further distinction via reactions with ethyl vinyl ether between the authentic **6** and the ion thought (and demonstrated) to be **1** is described in the ion/molecule reactivity section that follows.

Table 1. Total and Relative Energies of $C_3H_6N^+$ Isomers from G2 ab Initio Calculations

ion	G2 energy (hartree)	relative energy (kcal/mol)
1	−172.05712	**Zero**
2	−172.03674	**12.8**
3	−172.03505	13.8
4	−172.01971	23.5
5	−172.02237	21.8
6	−172.04231	9.3
7	−172.02887	17.7
8	172.05543	1.1
9	−171.94382	71.1
10	−171.97686	50.4
11	unstable	- -
12	−171.98661	44.2
13	−171.98717	43.9
14	−171.99807	37.1
15	−171.99481	39.1

Stabilities of 1 and 2. Although **1** and **2** are most likely the primary $C_3H_6N^+$ fragments of allylamine and piperidine, respectively, higher thermodynamic stability of other $C_3H_6N^+$ isomers[16] (see structures below) could drive rapid isomerization of the nascent ions. To verify whether **1** and **2** are thermodynamically stable regarding isomerization, ab initio calculations at the high accuracy G2 level[12] were performed. Ten $C_3H_6N^+$ ions (**1**−**10**) found as the most stable at the MP4/6-31G(d) + ZPE level[16a] as well as five additional structures (**11**−**15**) were considered.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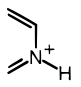
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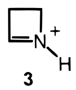
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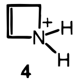
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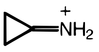
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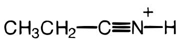
$CH_3CH_2{-}C{\equiv}\overset{+}{N}{-}H$

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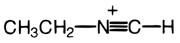
$CH_3CH_2{-}\overset{+}{N}{\equiv}C{-}H$

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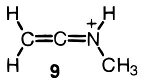
$CH_3{-}C{\equiv}\overset{+}{N}{-}CH_3$

8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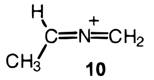
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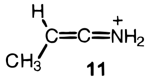
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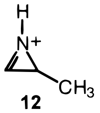
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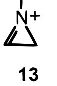
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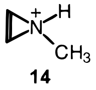
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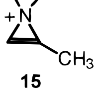
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At the high accuracy G2 level, **1** is *the most* stable $C_3H_6N^+$ isomer (Table 1), whereas **2** is the fourth most stable, being placed only 12.8 kcal/mol above **1**. Ion **11** is found unstable at the G2 level. Ions **3**−**5** and **12**−**15**, which could be formed from **1** and **2** through several

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Table 2. Ionic Products of Reactions of 1 and 2 with Several Neutral Dienophiles

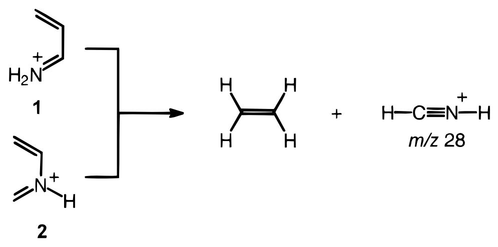
		m/*z* (relative abundance)			
neutral	ion	adduct	protonated neutral[a]	proton-bound dimer	other products
$CH_2{=}CH_2$	**1**	none	none	none	none
	2	none	none	none	none
cyclohexene	**1**	none	none	none	none
	2	none	none	none	none
$CH_2{=}CHPh$	**1**	160(37)	none	none	131(100)
	2	160(100)	none	none	none
$CH_2{=}C(CH_3)CH{=}CH_2$[b]	**1**	124(15)	81(100)[c]	none	none
	2	124(100)	81(8)[c]	none	none
$CH_2{=}CHC({=}O)CH_3$	**1**	126(100)	71(2)	141(47)	none
	2	126(82)	71(3)	141(100)	none
$CH_2{=}CHC{\equiv}N$	**1**	109(100)	none	107(31)	none
	2	109(100)	none	107(53)	none
$CH_2{=}CHOCH_3$	**1**	128(36), 82(32)[d]	none	none	101(100)
	2	82(100)[d]	none	none	101(22)
$CH_3C{\equiv}N$	**1**	97(100)	42(1)	83(27)	none
	2	97(100)	42(9)	83(65)	none
$(CH_3)_2C{=}O$	**1**	114(100)	59(2)	117(64)	none
	2	114(100)	59(5)	117(52)	none
$CH_3C({=}O)CH_2F$	**1**	132(100)	none	153(12)	none
	2	132(100)	none	153(10)	none
$CH_3OC({=}O)CH_3$	**1**	130(100)	none	149(6)	none
	2	130(100)	none	149(8)	none
$(CH_3O)_2C{=}O$	**1**	146(100)	91(1)	181(26)	none
	2	146(100)	91(13)	181(22)	none
$CH_3C({=}O)Cl$	**1**	none	none	none	43(100)[e]
	2	none	none	none	43(100)[e]
$(CH_3)_2S{=}O$	**1**	134(95)	79(2)	157(100)	none
	2	134(1)	79(13)	157(100)	none
$Cl_2S{=}O$	**1**	none	none	none	83(100), 85(33)[e]
	2	none	none	none	83(100), 85(33)[e]

[a] Owing to multiple collisions, proton transfer may occur from either the reactant ion or its product or fragment ions. [b] Data taken from ref 6c. Note that an overall reactivity factor of 0.02 and 2.4 are reported for **1** and **2**, respectively. [c] The most abundant secondary product of proton-transfer reaction to isoprene. [d] A product ion that correspond to loss of ethanol (46 mu) from the intact aduct of *m*/*z* 128. [e] Formed as minor products, whereas the signal of the surving reactant ion dominates the product spectra.

cyclization processes combined some cases with hydrogen shifts, are placed higher in energy than **1** and **2**; hence, these endothermic and thermodynamically unfavorable cyclizations are excluded. As **1** is the most stable isomer, all of its isomerization processes including that involving H-shift to **6** are endothermic and thermodynamically unfavorable. Of the H-shift isomerizations of **2** to **7**−**9**, only the one that forms **8** is thermodynamically favorable, i.e. it represents a −11.7 kcal/mol exothermic processes (Table 1). The **2** → **8** isomerization is, however, likely connected by considerably energetic intermediates (and transition states) such as $CH_2{=}CHN^+CH_3$;[16] hence, this isomerization should occur only under considerable energy activation.

Therefore, the G2 results suggest that the primary **1** and **2** are both kinetically and thermodynamically stable gaseous species, i.e. they lie in deep potential wells that prevent isomerization. Note that several, energy-demanding skeleton rearrangements would be involved in **1** ↔ **2** interconvertions, which are therefore also unexpected.

MS Characterization of 1 and 2. The double-stage (MS^2) collision-induced dissociation (CID) spectra of **1** and **2** (not shown) are very simple and similar. They display an ion of *m*/*z* 28 (most likely $HC{\equiv}NH^+$) as the exclusive fragment. The similar dissociation behaviors of **1** and **2** make them indistinguishable by low-energy CID. Further, although ethene loss can be easily rationalized for both isomeric structures (eq 3), it cannot be used for their structural assignments. This restriction applies because isomers **6** and **8** also display ethene loss as their main dissociation channel.[16a,b] Strong evidence that excludes formation of **6** and **8** is obtained, however, when comparing the behavior of the putative **1** and **2** in ion/molecule reactions with ethyl vinyl ether to that of the authentic **6** and **8**. As will be discussed later, **1** and **2** behave differently in reactions with ethyl vinyl ether (see Figures 3a,b), whereas both **6** and **8** react mainly by proton transfer to afford the *m*/*z* 73 and 101[17] products (spectra not shown). Distinctive reactivity of **1** and **2** with isoprene compared to that of **6** and **8** has also been observed.[6c]



(3)

Cycloaddition Reactivity of 1 and 2. Product ion spectra, i.e. mass spectra which record the products of ion/molecule reactions of the mass-selected reactant ions **1** and **2** with several alkenes, ketones, nitriles, and sulfoxides, are reported in Table 2, whereas some typical examples are shown as figures. In general, two competitive reactions occur, as exemplified in Figure 2: (i) adduct formation (*m*/*z* 146) and (ii) primary proton transfer (*m*/*z* 91) with the subsequent formation of the proton-bound dimer of the neutral reactant (*m*/*z* 181); a secondary

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(17) The product ion of *m*/*z* 101 arises from ethylation of ethyl vinyl ether by protonated ethyl vinyl ether (*m*/*z* 73); see Kenttämaa, H. I.; Cooks, R. G. *J. Am. Chem. Soc.* **1989**, *111*, 4122.

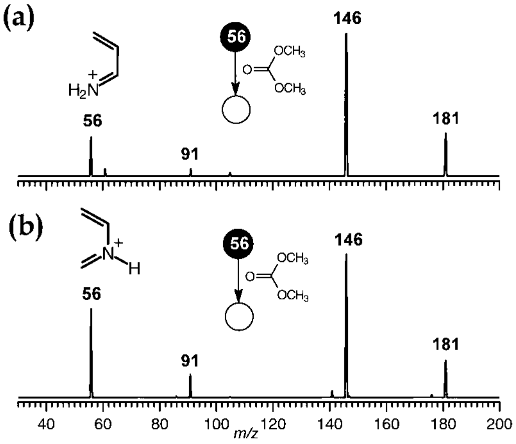

Figure 2. Double-stage (MS^2) product spectra for reaction of (a) **1**, and (b) **2** with dimethyl carbonate. Note the surviving reactant ion of *m/z* 56, protonated dimethyl carbonate of *m/z* 91, the dimethyl carbonate proton-bound dimer of *m/z* 181, and the ion−neutral complex of *m/z* 146. In the terminology used to describe the type of MS^n experiment and scan mode employed, a filled circle represents a fixed (or selected) mass; an open circle, a variable (or scanned) mass, whereas the neutral reagent or collision gas that causes the mass transitions are shown between the circles. For more details on this terminology see ref 5b.

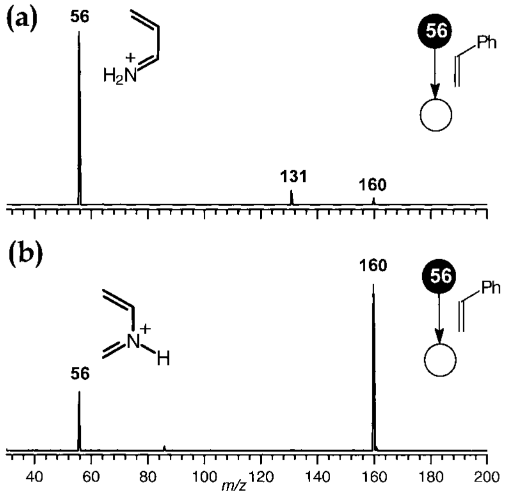

Figure 3. Double-stage (MS^2) product spectra for reaction of (a) **1** and (b) **2** with styrene. Note that **2** forms a very abundant adduct of *m/z* 160, whereas **1** is much less reactive.

reaction that is favored due to the multiple-collision conditions employed. Proton transfer may occur, however, also from secondary product or fragment ions.

(1) Alkenes. Both **1** and **2** are practically unreactive toward the "nonactivated" dienes ethylene and cyclohexene (Table 2). However, activation by the cyano and acetyl electron-withdrawing substituents greatly favors adduct formation of **1** and **2** with both acrylonitrile and methyl vinyl ketone.

Remarkably different reactivities of **1** and **2** are observed in reactions with the phenyl- and vinyl-substituted alkenes, i.e. styrene (Figure 3) and isoprene (Table 2). Reactions occur promptly between **2** and styrene, and the adduct of *m/z* 160 (Figure 3a) is formed exclusively. In contrast, **1** reacts with styrene under the same conditions to a very limited extent, and most of the reactant ion of *m/z* 56 survives the collisions (Figure 3b). The adduct of *m/z* 160 and an ion corresponding to loss of 29 u from the adduct (*m/z* 131*)* are the products observed at low abundance. Distinctive behaviors for **1** and **2** are also observed in reactions with isoprene (Table 2).

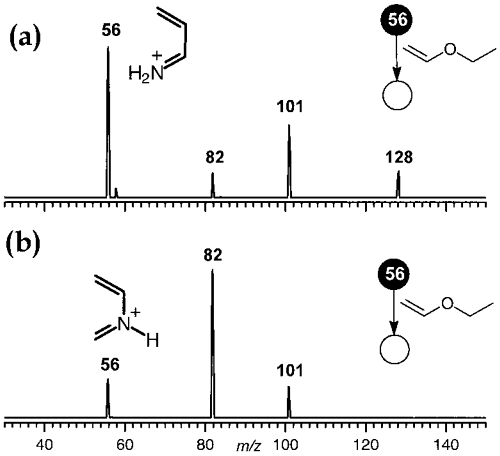

Figure 4. Double-stage (MS^2) product spectra for reaction of (a) **1** and (b) **2** with ethyl vinyl ether. The product of *m/z* 82 corresponds to net C_2H_2 addition, which is rationalized in terms of $[4^+ + 2]$ cycloaddition followed by rapid ethanol loss dissociation.

Very distinctive reactivity is also observed in reactions of **1** and **2** with ethyl vinyl ether, an electron-rich ethoxy-substituted alkene. In reactions with **2** (Figure 4b), no intact adduct is formed, and an ion of *m/z* 82 corresponding to loss of ethanol from the adduct is the most abundant product. Reactions of **1** with ethyl vinyl ether (Figure 4a) occur again to a much more limited extent; the intact adduct of *m/z* 128 and the ethanol loss fragment of *m/z* 82 are minor, whereas the secondary proton-transfer product[17] of *m/z* 101 dominates.

(2) Nitriles. Two nitriles were studied: acrylonitrile (a cyanoalkene already addressed) and acetonitrile, which reacts largely by adduct formation with both **1** and **2** (Table 2). A slightly greater adduct formation reactivity, when compared to proton-transfer reactivity, is observed for **1**.

(3) Ketones and Esters. Adducts and proton-transfer products are formed in reactions of **1** and **2** with the ketones and esters (Table 2), as exemplified for dimethyl carbonate in Figure 2. Acetone reacts promptly by proton transfer and adduct formation, whereas the adducts dominate the product ion spectra of fluoroacetone, methyl acetate, and dimethyl carbonate. No adduct is observed in reactions with acetyl chloride, and only a minor product of *m/z* 43[18] is formed (Table 2).

(4) Sulfoxides. The differences in chemical reactivities of **1** and **2** toward DMSO are remarkable. Whereas **1** (Figure 5a) forms an abundant adduct of *m/z* 134, **2** reacts predominantly by proton transfer (*m/z* 79 and *m/z* 157, Figure 5b). Reactions of **1** and **2** with thionyl chloride, similarly to the reactions with acetyl chloride (Table 2), produce only $SOCl^+$ of *m/z* 83 as a minor product.

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[18] The product ion of *m/z* 43 can be rationalized as the acetyl cation (CH_3CO^+) formed by either dissociative (HCl loss) proton transfer (with either the reactant ions or their *m/z* 28 fragments), or dissociative (Cl loss) charge exchange, see: Abboud, J.-L. M.; Mó, O.; de Paz, J. L. G.; Yáñez, M.; Essefar, M.; Bouad, W.; El-Mouhtadi, M.; Mokhlisse, R.; Ballesteros, E.; Herreros, M.; Homan, H.; Lopez-Mardomingo, C.; Noatario, R. *J. Am. Chem. Soc.* **1993**, *115*, 12468.

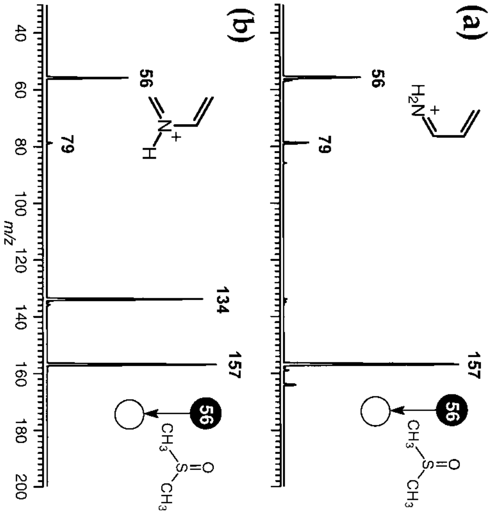


Figure 5. Double-stage (MS^2) product spectra for reaction of (a) **1** and (b) **2** with DMSO. Proton transfer (*m*/*z* 79 and 157) dominates for **1**, whereas **2** reacts largely by proton transfer and adduct (*m*/*z* 134) formation.

Triple Stage (MS^3) Spectra. In trying to obtain structural information on the adducts, their on-line mass selection was performed by Q3 (Figure 1) and their CID behavior investigated by 15 eV collisions with argon in q4, while scanning Q5 to record triple-stage sequential product spectra. As exemplified in Figures 6, the mass-selected adducts were observed to dissociate exclusively by the retro-addition process most likely reforming the reactant ions.

Ab Initio Calculations. Considering the limited structural information provided by the MS^3 experiments, and to obtain more insight into the structure of the gas-phase adducts of **1** and **2**, ab initio calculations at the MP2/6-31G(d,p)//6-31G(d,p) level were performed (Table 3). As depicted in Schemes 2 and 3 for a general RC═X neutral reactant, the most probable alternative structures were considered. They are the two possible *ortho*-(**1a** and **2a**) and *meta*-cycloadducts (**1b** and **2b**), the simple nucleophilic addition products (**1c**,**d** and **2c**), and the ion−neutral hydrogen-bridged complexes (**1e** and **2d**).

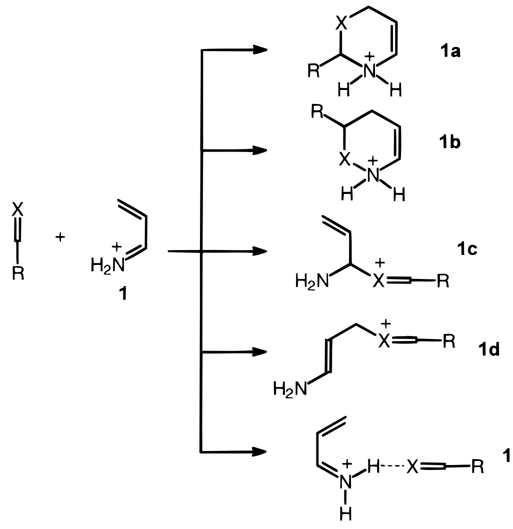
General Discussion. (1) MS^3 Experiments. As shown in Schemes 2 and 3, three reaction pathways were considered for adduct formation: (i) polar [4$^+$ + 2] cycloaddition; (ii) nucleophilic addition; and (iii) a "solvating" process leading to loosely bonded ion−neutral hydrogen-bridged complexes. The triple-stage (MS^3) mass spectra of the adducts, which show exclusive "retro-addition" dissociation, do not provide evidence in favor of any of the three possible structures. This ambiguity occurs because retro-addition is the dissociation pathway expected to dominate for both the polar [4$^+$ + 2] cycloadducts and simple addition acyclic adducts. Many related [4$^+$ + 2] azabutadiene cycloadducts, formed as intermediates of dissociation of ionized alkaloids and other nitrogen heterocycles,[19] fragment extensively via retro Diels−Alder, as exemplified in Scheme 4 for 2-hydroxyquinolizidine[20] and a heterocycle related to Erythrina alkaloids.[21] Retro-Diels−Alder dissociation is also the main process for the [4+2$^+$] isoprene cycloadducts of acylium, thioacylium, nitrilium, and immonium ions.[6b,c] The dissociation of the adducts to afford exclusively **1** and **2** is consistent even with ion−neutral hydrogen-bridged com-

Table 3. Total (hartree) and Relative (to the starting reactants in kcal/mol) Energies from Structure Optimization MP2/6-31G(d,p)//6-31G(d,p) ab Initio Calculations

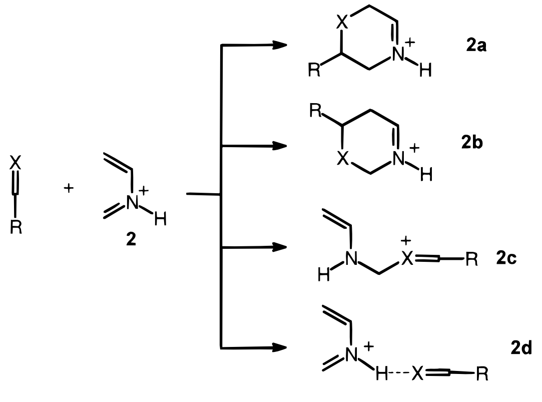
neutral	reagents (1 + neutral)	1a	1b	1c	1d	1e	reagents (2 + neutral)	2a	2b	2c	2d
$CH_3CH_2OCH{=}CH_2$	−403.57302	−403.64702	−403.64899	−403.59517	−403.59322	−403.60517	−403.54963	−403.66230	−403.66207	−403.58146	−403.58522
	0	−46.4	−47.7	−13.9	−12.7	−20.2^a	0	−70.7	−70.6	−20.0	−22.3^a
$CH_2{=}CHCN$^{b}	−342.18365	−342.22522	−342.23564	unstable	unstable	−342.21873	−342.16026	−342.25343	−342.25415	unstable	−342.19931
	0	−26.1	−32.6	–	–	−22.0^c	0	−58.5	−58.9	–	−24.5^c
$CH_2{=}CHCOCH_3$	−402.39902	−402.47451	–	–	–	−402.43555	−402.37563	−402.48463	–	–	−402.41508
	0	−47.4^d	–	–	–	−22.9^d	0^d	−68.4	–	–	−24.8^e
$CH_2{=}CHPh$	−480.54543	−480.58094	–	unstable	−480.54789	–	−480.52341	–	−480.59440	−480.51078	–
	0	−22.3	–	–	−1.5	–		–	−44.5	+7.9	–
$CH_3C({=}O)CH_3$	−364.43316	−364.46581	−364.40575	unstable	−364.43810	−364.47264	−364.40977	−364.47118	−364.47261	unstable	−364.45198
	0	−20.5	−17.2	–	−0.9	−24.8	0	−38.5	−41.7	–	−26.5
$CH_2FC({=}O)CH_3$	−463.43306	−463.46573	–	–	–	−463.47652	−463.40967	–	−463.47253	–	−463.45677
	0	−20.5	–	–	–	−27.3	0	–	−39.4	–	−29.5
$CH_3OC({=}O)CH_3$	−439.46837	−439.48915	–	–	–	−439.51500	−439.44498	–	−439.50022	–	−439.49901
	0	−13.0	–	–	–	−29.3	0	–	−34.7	–	−33.9
$CH_3OC({=}O)OCH_3$	−514.51310	−514.51880	−514.45643	unstable	−514.50339	−514.53363	−514.48971	−514.52007	−514.52426	unstable	−514.53755
	0	−3.6	+35.6	–	+6.1	−12.9	0	−19.1	−21.7	–	−30.0
CH_3CN	−304.22440	−304.23114	−304.21437	unstable	−304.23005	−304.25951	−304.20101	−304.24891	−304.25423	−304.22756	−304.23988
	0	−4.2	+6.3	–	−3.5	−22.0	0	−30.1	−33.4	−16.7	−24.4
$(CH_3)_2S{=}O$	−724.02606	unstable	unstable	−724.06312	−724.06204	−724.07412	−724.00267	−724.01160	unstable	−724.05223	−724.05835
	0	–	–	−23.3	−22.6	−30.2	0	+5.6	–	−31.1	−34.9

[a] The $CH_2{=}CH(C_2H_5)O$- - -**1**(**2**) ion−neutral complexes. [b] The C≡N cycloadducts of acrylonitrile are considerably less stable than the C═C cycloadducts, i.e. **1b′** (−342.21632, −20.5) and **2a′** (−342.19378, −21.0). [c] The $CH_2{=}CHCN$- - -**1**(**2**) ion−neutral complexes. [d] The C═O cycloadducts of methyl vinyl ketone are considerably less stable than the C═C cycloadducts, i.e. **1a′** (−402.42350, −15.4) and **2a′** (−402.43583, −37.8). [e] The $CH_2{=}CH(CH_3)C{=}O$- - -**1**(**2**) ion−neutral complexes.

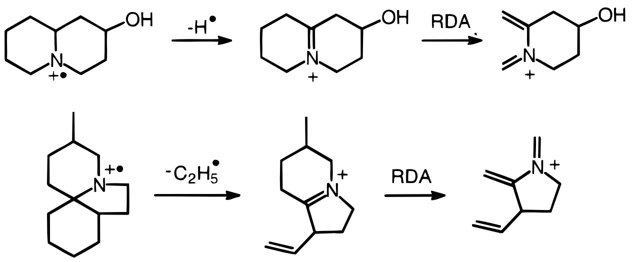
Scheme 2



Scheme 3



Scheme 4



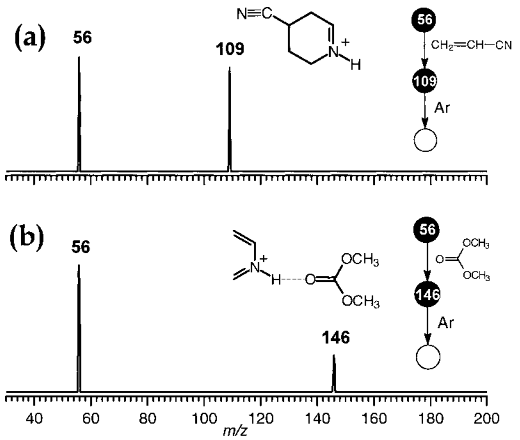


Figure 6. Triple-stage (MS^3) spectra for the adducts formed in reactions with **1** and **2** with (a) acrylonitrile and (b) dimethyl carbonate. Note in both cases exclusive dissociation that reforms the reactant ion. The structures shown have been suggested by the ab initio calculations, see the respective section.

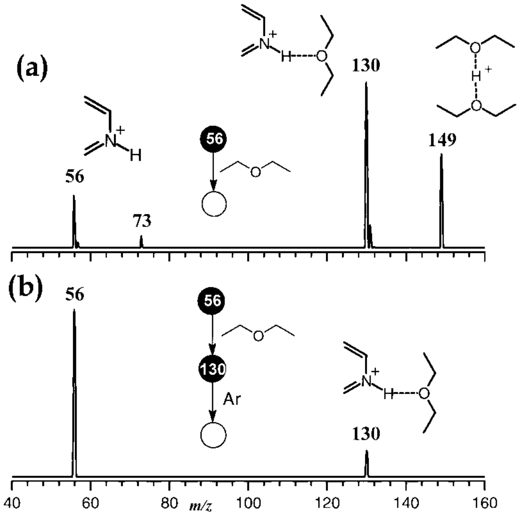


Figure 7. (a) Double-stage (MS^2) product spectra for reaction of **2** with dimethyl ether. An abundant adduct is formed (*m*/*z* 130), whereas no ethanol loss occurs; (b) triple-stage (MS^3) spectrum for the *m*/*z* 130 adduct. The adduct shows no ethanol loss even when activated by 15 eV collisions with argon; it dissociates exclusively to reform **2**.

plexes since the neutral azabutadienes display much higher proton affinities (see the ab initio section that follows); thus, the azabutadienes should held the proton preferentially on collision dissociation.

(2) Vinylation of 2 by Ethyl Vinyl Ether. In the very particular case of reaction of **2** with ethyl vinyl ether, experimental evidence for polar [$4^+ + 2$] cycloaddition is attained. Loss of ethanol occurs promptly from the nascent adduct to afford the *m*/*z* 82 product (Figure 4b), a process that is best rationalized if cycloaddition occurs (Scheme 5). Cycloaddition is also overall greatly exothermic, see the ab initio section that follows. In contrast, ethanol loss is not consistent with the formation of the corresponding nucleophilic addition product **2c** (Scheme 3), particularly if attack occurs via the oxygen atom, neither with the loosely bonded hydrogen-bridged ion−neutral complex **2d**. A MS^3 experiment (spectrum not shown) shows the *m*/*z* 82 product ion to be very resistance toward collision dissociation, a behavior that is consistent with the cyclic, resonance-stabilized structure expected for the vinylation product (Scheme 5). Formation to a much more limited extent of a net C_2H_2 addition product of *m*/*z* 82 is also observed in reactions of **1** with ethyl vinyl ether (Figure 4a).

Evidence against formation and fast ethanol loss dissociation of loosely bonded hydrogen-bridged ion−neutral complexes (**2d**, Scheme 3) is obtained when reacting **2** with diethyl ether (Figure 7a), i.e. the saturated analogue of ethyl vinyl ether. An adduct of *m*/*z* 130 (most likely the hydrogen-bridged ion−neutral complex) is formed abundantly together with the dimethyl ether proton bound dimer of *m*/*z* 149, but no ethanol loss dissociation of the adduct is observed whatsoever. Even

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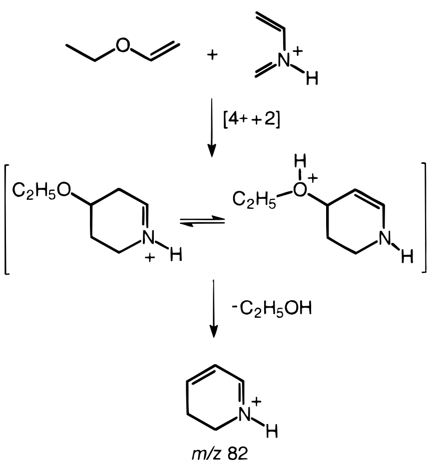
(19) Turecek, F.; Hanus, V. *Mass Spectrom. Rev.* **1984**, *3*, 85.

(20) Hussain, M.; Robertson, J. S.; Watson, T. R. *Org. Mass Spectrom.* **1970**, *4*, 109.

(21) Migron, Y.; Bergmann, E. D. *Org. Mass Spectrom.* **1977**, *12*, 500.

Scheme 5



upon 15 eV collision activation, the adduct shows no proclivity to lose ethanol (Figure 7b); it fragments extensively and exclusively to reform the reactant ion of *m*/*z* 56.

These findings suggest the occurrence of an interesting vinylation (C_2H_2 addition) reaction between **2** and ethyl vinyl ether. The ultimate goal of gas-phase ion/molecule reactions when dealing with structural elucidation is to provide reactions that serve as structurally diagnostic and general methods for the identification of classes of both ions and neutrals. Although ion/molecule reactions have been used successfully to characterize many isomeric ions, just a few have shown the desired generality. A recent example is transacetalization[9f,22] of acylium ions with cyclic acetals and ketals, and ketalization[9e] of acylium ions with diols and analogues, which have been proven as selective tests for both the ions and the neutrals in the gas phase. Kenttämaa and Cooks[23] have also reported a vinylation reaction with ethyl vinyl ether, which was shown to occur extensively for model ions and to serve as a gas phase structurally diagnostic test for several protonated polyfunctional organic molecules containing the specific functional groups, i.e. a carbonyl and a β-hydroxy group. A molecule that displays the proper functionality, and therefore reacts by vinylation with ethyl vinyl ether, is the diterpenoid dilactone shown in Scheme 6a. The vinylation reaction reported herein, which occurs promptly for the simplest N-protonated 2-aza-1,3-butadiene (**2**), shows promise as a general gas phase, structurally diagnostic test for both 2-azabutadienes and vinyl ethers (Scheme 6b).

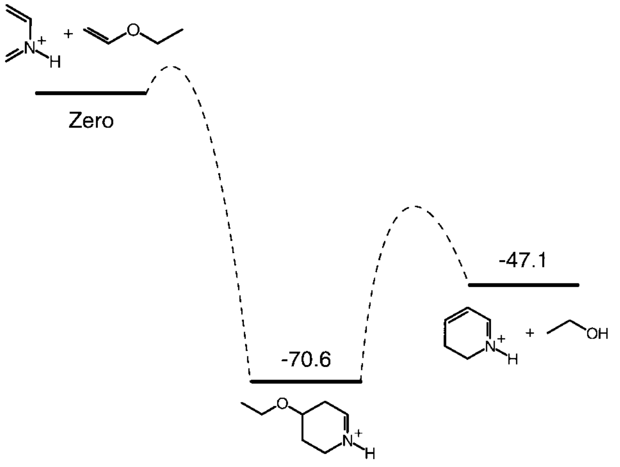
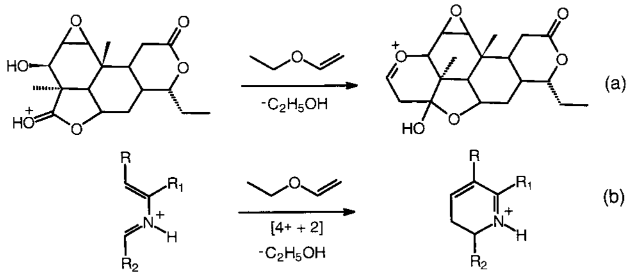


Figure 8. Ab initio potential energy surface diagram for polar [$4^+ + 2$] cycloaddition between **2** and ethyl vinyl ether followed by ethanol loss. Energies are given in kcal/mol. Note the exothermicity of the overall vinylation (C_2H_2 addition) reaction.

Scheme 6



(3) Ab Initio Results. The MO calculations (Table 3) are invaluable in addressing the most likely structures of the gaseous adducts. The [$4^+ + 2$] cycloadducts of **1** and **2** with the activated alkenes ($CH_2{=}CHCN$, $CH_2{=}CHCOCH_3$, $CH_3CH_2OCH{=}CH_2$, and $CH_2{=}CHPh$) are predicted to be by far the most thermodynamically favorable, i.e. formed by the most exothermic reactions. In the case of ethyl vinyl ether, for instance, for which experimental evidence for polar [$4^+ + 2$] cycloaddition is provided, the cycloaddition reactions are −47.7 (**1**) and −70.7 kcal/mol (**2**) exothermic from the reactants, whereas the second most favorable process of ion−neutral complex formation is considerably less exothermic by −20.2 and −22.3 kcal/mol, respectively. Further, the dissociation threshold for ethanol loss from **2a** is calculated to be only 23.3 kcal/mol endothermic from the cycloadduct,[24] thus making the overall process still quite exothermic by −47.1 kcal (Figure 8). The energy barrier for intramolecular proton transfer was not estimated, but such barriers are known to be low.[25] Hence, the high exothermicity of the vinylation reaction explains the rapid dissociation by ethanol loss of the polar [$4^+ + 2$] cycloadduct of **2** with ethyl vinyl ether.

The ab initio results for the alternative adducts of both **1** and **2** with the two esters and DMSO (poor dienophiles in solution) are also clear. The calculations (Table 3) strongly suggest that ion−neutral hydrogen-bridged complexes, or simply the "*mono*-solvated ions" (**1e** and **2d**, Schemes 2 and 3), are the most likely, thermodynamically favorable adducts. These ion−neutral complexes are also predicted by the calculations to be very loosely bonded. As exemplified in Figure 9, the optimized structure of the **2**−methyl acetate complex displays a long NH- - -O hydrogen bond (1.74 A); compare this length to that of the OH- - -O bond (1.40 A) calculated for the methyl acetate proton bound dimer. Such loosely bonded structures likely result from the much higher proton affinity of the azabutadienes, which also drives exclusive dissociation of the ion−neutral complexes to

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[22] Eberlin, M. N.; Cooks, R. G. *Org. Mass Spectrom.* **1993**, *28*, 679.

[23] Kenttämaa, H. I.; Cooks, R. G. *J. Am. Chem. Soc.* **1989**, *111*, 4122.

[24] MP2/6-31G(d, p)/6-31G(d, p)//6-31G(d, p) energies (in hartrees) are ethanol (−154.56810) and the *m*/*z* 82 product (−249.05660). The O-protonated cycloadduct was found to be unstable with respect to dissociation to ethanol and the *m*/*z* 82 product.

[25] Uggerud, E. *Mass Spectrom. Rev.* **1992**, *11*, 389.

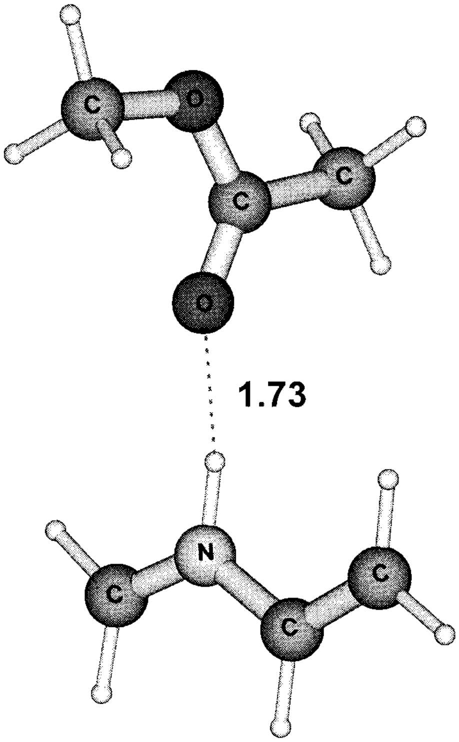

Figure 9. Ab initio optimized structure of the hydrogen-bridged ion−neutral complex between N-protonated 2-aza-1,3-butadiene (**2**) and methyl acetate. Note the long NH- - -O bond length of 1.72 Å, which characterizes a very loosely bonded structure.

reform the N-protonated azabutadiene. G2 ab initio calculations predict proton affinities for 1-aza-1,3-butadiene and 2-azabutadiene of 218.5 and 211.5 kcal/mol, respectively,[26] values that are considerably higher than those of all the neutrals employed.[27]

For the ketones (acetone and fluoroacetone) and acetonitrile, the calculations suggest the respective ion−neutral complexes **1e** to be favored for **1**, whereas for **2** the most stable products are the $[4^+ + 2]$ cycloadducts **2a**,**b** (Table 3). However, the differences in the exothermicity of the competing processes are small, on the range of 5−10 kcal/mol. These small differences most likely fall within calculation errors, specially considering that ZPE energies and BSSE errors[28] were not estimated.

Conclusions

The N-protonated forms of the two simplest azabutadienes, i.e. N-protonated 1-aza-1,3-butadiene (**1**) and N-protonated 2-aza-1,3-butadiene (**2**), are easily accessible and kinetically and thermodynamically stable in the gas phase. The gaseous **1** and **2** are characterized by their distinctive reactivities toward styrene, ethyl vinyl ether, and DMSO, which contrast to their indistinguishable low-energy collision dissociation behavior. Whereas **1** and **2** are both unreactive toward ethylene and cyclohexene, **2** reacts promptly by adduct formation with alkenes activated either by electron-donating, electron-withdrawing, or vinyl and phenyl substituents. According to the ab initio predictions, these adducts are formed via polar $[4^+ + 2]$ Diels−Alder cycloaddition.

Loosely bonded hydrogen-bridged ion−neutral complexes (common gas-phase species[29]) are formed in reactions of **1** and **2** with esters, and of **2** with DMSO. Abundant adducts are often formed in reactions of **1** and **2** with ketones and nitriles, but whether they are cycloadducts or simply ion−neutral complexes could not be determined based on the present experimental and theoretical results.

The nascent $[4^+ + 2]$ cycloadduct with ethyl vinyl ether of **2** is unstable and dissociates rapidly by ethanol loss to afford an abundant C_2H_2 addition product of *m*/*z* 82. This novel and efficient vinylation reaction shows potential as a structurally diagnostic test for both 2-azabutadienes and vinyl ethers in the gas phase, and a study of its generality is underway in our laboratory. Isomer **1** is in general much less reactive with alkenes, forming adducts to considerable extents only with alkenes bearing electron-withdrawing substituents. Such contrasting reactivities are also potentially useful for the distinction between the two classes of azabutadienes in the gas phase.

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[26] G2 total energies (in hartrees) of 1-aza-1,3-butadiene and 2-aza-1,3-butadiene are −171.70883 and −171.69968, respectively.

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